Towards a 5G Satellite Communication Framework for V2X

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***Abstract*—In recent years, satellite communication has been expanding its field of application in the world of computer networks. This paper aims to provide an overview of how a typical scenario involving 5G Non-Terrestrial Networks (NTNs) for vehicle to everything (V2X) applications is characterized. In particular, a first implementation of a system that integrates them together will be described. Such a framework will later be used to evaluate the performance of applications such as Vehicle Monitoring (VM), Remote Driving (RD), Voice Over IP (VoIP), and others. Different configuration scenarios such as Low Earth Orbit and Geostationary Orbit will be considered.**

***Index Terms*—5G, Non-Terrestrial Networks, satellite communication**

I. Introduction

The significant increase of use cases in the automotive industry shows that vehicular communication is becoming an increasingly important requirement and its combination with the 5G technology has the potential to revolutionize the transportation industry, enabling the development of intelligent transportation systems (ITS) and autonomous vehicles.

At the same time, the deployment of Low Earth Orbit (LEO) satellite megaconstellations which consist of a large number of small satellites in orbit around the earth, can provide high-speed Internet connectivity also to remote and unserved regions of the world. Therefore combining megaconstellations with 5G networks, would offer several advantages in handling large amounts of data with low latency [1]. Although terrestrial networks are highly functional and efficient, especially in urban environments, there remains a problem in many areas where the lack of connection is predominant [2], mostly in rural and motorway scenarios.

The development of Non-Terrestrial Networks (NTNs), and in particular, their integration into the already existing terrestrial ones, would entail a large number of advantages such as improvements in the coverage areas and providing connectivity for emergencies. Satellites are therefore in an prominent position to compensate for this coverage gap, but there are several drawbacks to consider when we also want to meet the low latency requirements demanded by real-time applications.

A. Satellite Communication

The basic idea behind satellite communication is to use an orbiting satellite as a relay station to transmit signals over long distances. This type of communication can be used for a wide range of applications, including voice and data communication, broadcasting, navigation, and remote sensing. The main difference is made by the type of orbit described by the satellite, which implies having different altitudes, orbital periods, and coverage areas, Fig. 1 shows a representation of them.

Geostationary Orbit (GEO) satellites, are placed in a circular orbit around the Earth at an altitude of 35,786 kilometers. This altitude allows the satellite to maintain a fixed position relative to the Earth's surface. This makes GEO satellites ideal for applications that require continuous coverage over a fixed geographic area, such as satellite television broadcasting, weather forecasting, and global communications. However, round trip times (RTTs) are estimated to be in the order of $600\,\mathrm{ms}$ [3] because of the long distance from Earth and the resulting high propagation delay makes them unsuitable for time-sensitive applications.

LEO satellites are placed in a circular orbit around the Earth at an altitude of approximately 2,000 kilometers or less. This lower altitude requires LEO satellites to orbit the Earth much faster than GEO satellites, completing a full orbit in just a few hours. Due to the lower altitude, LEO satellites ensure lower latency times, between $30\,\mathrm{ms}$ and $50\,\mathrm{ms}$, ideal for applications that require fast data transmission and low latency, such as satellite Internet and remote sensing.

Medium Earth Orbit (MEO) satellites are placed in a circular orbit around the Earth at an altitude between LEO and GEO. MEO satellites are commonly used for global positioning system (GPS) applications, as well as mobile satellite communication systems.

B. 5G NTN

Non-Terrestrial Networks (NTNs) are an emerging approach in the 5G ecosystem, which refers to the use of satellites, high-altitude platforms (HAPs), and unmanned aerial vehi-

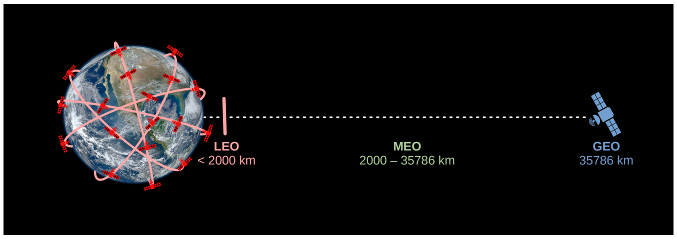

Fig. 1. Satellite orbits

cles (UAVs) to complement terrestrial 5G networks. During the integration phase of NTNs with 5G technology several challenges need to be addressed, such as managing handoffs between different satellite beams and managing the interaction between the satellite and terrestrial networks.

In the NTNs 3GPP standards [4] two main types of payload configurations have been defined: regenerative and transparent. A regenerative payload receives the incoming signal, demodulates it, and regenerates a new signal that is retransmitted back to Earth. This process allows the satellite to amplify the signal and remove any noise or interference that may have been introduced during the transmission. On the other hand, a transparent payload does not regenerate the signal that it receives, but acts as a simple frequency repeater. This type of payload is typically used for applications where signal delay and latency must be minimized, such as in real-time video or voice communications. Within this work, the integration of NTNs into the 5G ecosystem is being designed through a hybrid network architecture that combines cellular base stations and non-terrestrial ones (regenerative and transparent payload are both considered) to provide seamless connectivity. The use cases for 5G NTN can be grouped into three main categories. The first is service continuity, which aims to provide access through NTNs in areas where it is not feasible to use terrestrial networks. The second is service ubiquity, which seeks to improve the availability and connection resilience of NTN in the event of disasters that cause temporary outages or destruction of terrestrial networks. The third is service scalability, which aims to offload traffic from terrestrial networks during busy hours [5]. In the context of Cellular Vehicle-to-Everything (C-V2X), the authors in [4] presented six categories of Vehicle-to-Network (V2N) use cases in which the usage of satellite communication is feasible. In this section, we describe some of the most common use case categories concerning vehicular communication.

1) Vehicle Monitoring: It is one of the use cases of V2N which involves the collection of real-time data from vehicles, such as location, speed, and vehicle health to send it to the network for analysis and processing so that this data can be used to improve traffic management, optimize routing and scheduling of vehicles, and enhance safety by identifying potential hazards or incidents on the road [6].

2) Remote Driving: Involves the remote operation of a vehicle using a network connection. Remote driving can be useful in a variety of scenarios, such as in hazardous environments or for long-distance transportation. To support remote driving, V2N communication can enable real-time transmission of high-quality video and audio data, as well as other sensor data such as GPS and radar information. This allows the remote operator to have a clear view of the vehicle's surroundings and to make decisions based on the information received. To ensure safety in remote driving scenarios, V2N communication systems must be highly reliable and have low latency, to minimize the time delay between the remote operator's commands and the vehicle's response [7].

3) Voice over IP: VoIP could be used in a variety of scenarios in V2N communication, such as vehicular communications, communication between drivers and passengers or communication between drivers and remote operators, in this latter case, the remote control of the vehicles could be enabled. To support VoIP in V2N communication, high-quality audio transmission must be ensured, with minimal delay, jitter, and packet loss. Quality of Service (QoS) mechanisms may be used to prioritize voice traffic over other types of traffic, such as data or video, to ensure that voice communication remains clear and uninterrupted [8].

4) Video Streaming: One application of video streaming in V2N is for instance real-time monitoring of traffic conditions. Vehicles equipped with cameras can capture and transmit video footage of the road which can then be used to analyze the traffic flow and detect accidents and other situations that may be causing delays. This information can be relayed to other vehicles and drivers, allowing them to adjust their routes or driving behavior in response enhancing overall road safety. Another typical application of video streaming in V2N is entertainment. Vehicles equipped with screens and streaming capabilities can allow passengers to watch movies, or other content during their journey [9].

C. Vehicular Communications

In the context of vehicular communications, several existing frameworks refer to the set of protocols, architectures, and technologies used to support communication between vehicles and between vehicles and other infrastructures. Our research focus regards mainly the Vehicle-to-Everything (V2X) communication, which is a type of wireless communication technology that enables vehicles to communicate with other vehicles, infrastructure, and other connected devices in their environment. V2X supports a wide range of applications, including safety-related applications, traffic management, and infotainment [10]. To exploit the communication capabilities between vehicle and infrastructure (V2I) or among vehicles (V2V), we considered here the well-known framework Veins [11] for the simulation of vehicular ad-hoc networks (VANETs) in a realistic environment, in combination with the road traffic simulator SUMO [12].

In this work, we want to describe the simulation framework that allows us to test different automotive use cases for V2X communication. In particular, our research focus regards the communication protocols at the transport layer (such as UDP and TCP) that are suitable for vehicular communication and 5G networks. Our simulations allow us to evaluate different application-level quality of service (QoS) metrics such as packet loss, latency (end-to-end packet delay), and goodput.

The next sections are organized as follows. We will describe the framework we use to merge the 5G ecosystem with NTNs, we will discuss some of the applications that could be tested with this framework, and at the end, we will give some insight into the subsequent studies.

II. Framework Description

In the literature, there are already some related projects, such as the simulation framework 5G-Sim-V2I/N [13] used for testing Cellular-Vehicle-to-Everything communications in different scenarios with terrestrial-only networks. Recently also the Open Air Interface (OAI) has been used as a platform for developing and testing 5G communication systems for both ground-based and LEO satellite-based applications.

In particular, the authors in [14] used the software-defined radio (SDR) demonstrator 5G Global Open Access (5G-GOA) based on the Open Air Interface (OAI) where several adaptations are being done to support 5G-NTN use-cases to enable direct-access between UE and gNB via transparent payload for geostationary (5G-GOA) and non-geostationary satellites (5G-LEO) [15]. However, to the best of our knowledge, currently no V2X 5G satellite communication framework exists and no experimental tests were performed at the transport layer for the evaluation of different use cases in this context.

To test the feasibility of the system in a realistic traffic scenario, the simulation framework Simu5G [16] for the discrete event simulator OMNeT++ [17] is being considered to enable the simulation of the 5G user plane protocol stack. Furthermore, the coupling with the open-source vehicular network simulation framework Veins and its interaction with the road traffic simulator SUMO has been performed.

A relevant consideration to highlight in this framework is the limitation of considering only the user plane. The control plane, responsible for signaling and managing the network resources performing tasks such as session setup or mobility management is therefore not considered. The choice of neglecting the control plane from a simulation scenario might imply achieving incomplete network functionality or a lack of network resource management, therefore potentially leading to improper resource allocation, and inefficient utilization of network resources. On the other side, excluding signaling traffic also has advantages.

In particular, considering an abstraction of the control-plane, functions like signaling could be easily substituted with queries to the specific modules containing the global information within a simulation, then these modules will be called every time such information need to be obtained. Furthermore, a similar structure would speed up the set-up of a simulation scenario and favor the integration of new functionalities with future implementations, therefore making the framework more easily evolvable. A similar user plane analysis has also been performed in [18].

Simu5G is aimed at a scenario characterized only by terrestrial nodes, therefore the first necessary modification concerned the channel model according to the International Telecommunication Union (ITU-R) guidelines P.681-11 and 3GPP standards [4]. In this context, reference has been made to a scenario involving a regenerative payload where the base station (gNB) is on board the satellite. Fig. 2 shows a representation of this system when no Inter-Satellite-Links (ISL) are considered. Furthermore, in its original version, Simu5G includes

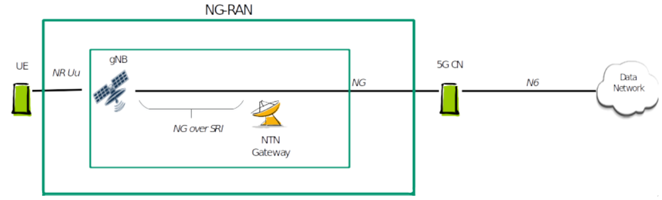

Fig. 2. Regenerative satellite base station (gNB) processed payload [4].

by default indoor rural and urban scenarios, which are also considered within this work.

Within Veins, the communication is based on messages, which are transmitted and received by vehicles and roadside units (RSUs). The overall system works by running in parallel the enhanced Simu5G for satellite communication, Veins (through the OMNeT++ simulation environment), and SUMO. In particular, both simulators are connected via a TCP socket using the standardized communication protocol known as Traffic Control Interface (TraCI) to allow a bidirectional and coupled simulation of road and network traffic. Fig. 3 shows a representation of how the frameworks interact with each other.

Simu5G reflects the characteristics of ground-based communication where the terrestrial base station provides coverage within a relatively small area, typically ranging from a few kilometers to several tens of kilometers, depending on the infrastructure deployment and the specific technology used.

Within this framework, an important difference with respect to the terrestrial case of Simu5G is the coverage region provided by satellite systems. In particular, the coverage is measured as a footprint that contains multiple cells. The typical footprint of GEO satellites is between $200\,\mathrm{km}$ and $3500\,\mathrm{km}$, depending on the satellite's position [4]. LEO satellites, on the other hand, could provide a relatively small coverage when compared to GEO satellites, but still much larger than ground-based communications. For LEO satellites the footprint area varies in the range of $100\,\mathrm{km}$–$1000\,\mathrm{km}$ [4]. The Radio Access Network (RAN) within this enhanced version of Simu5G is composed of satellite footprints under the control of a single or multiple gNBs (depending on the type of configuration considered) to which the User Equipments (UEs–vehicles in this case) are attached. For a hybrid terrestrial/NTN scenario, both cellular and footprint coverages are considered. The core network, as in Simu5G consists of IP routers connecting an entry point, the Packet GateWay (PGW), to the gNBs. The feeder link toward

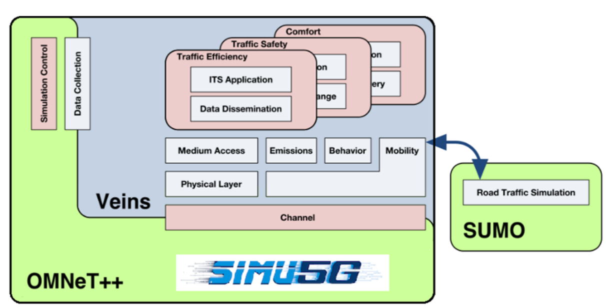

Fig. 3. Framework Architecture (adapted from [19]).

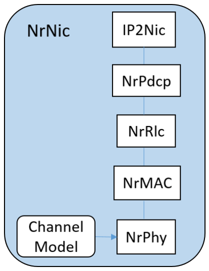

Fig. 4. Structure of the NR NIC modules in Simu5G (adapted from [16]).

the Core Network is carried out using the GPRS tunneling protocol (GTP).
In the protocol stack of Simu5G the communications between the gNB and the vehicle occur at the Data Link Layer (DLL) of the OSI reference model. An illustrative diagram about the layers of this system is shown in Fig. 4.
The Physical and DLL are implemented using a stack of four protocols, on both the gNB and UE side. On top there is the Packet Data Convergence Protocol (PDCP), which receives IP datagrams, and sends them to the Radio Link Control layer (RLC). The RLC Service Data Units (SDUs) are stored in the RLC buffer and they are used by the Media Access Control (MAC) layer when a transmission needs to be made.
The MAC assembles the RLC Protocol Data Units (PDUs) into Transport Blocks (TBs), adds a MAC header, and sends everything through the physical layer for transmission [16].
At the lower layers, the primary modification regarding the channel model involves incorporating two significant factors that contribute to signal attenuation. Unlike Simu5G, only the Free Space Path Loss (FSPL) and the shadowing have been considered. Currently also the attenuation due to atmospheric effects has been neglected following the choice to carry out experiments in the S-Band frequency range. In order to simulate applications in Downlink (DL) and Uplink (UL), we are using the related classes from the INET library. The configuration in the UL is characterized by a sender (the vehicle) which according to the `starting_time` (initialized in the application configuration) starts sending packets with a certain sending interval towards the gNB which in its turn forward them towards the core network. The downlink works in a similar way, where the sender is the server and the flow is mirrored. Fig. 5 shows a screenshot of the urban scenario configuration when a GEO satellite is considered. With the help of OpenStreetMap, we have selected an area of the German city of Erlangen to fit the default scenario with Veins. During the simulation the vehicles move on different lanes in both directions. In this case, one GEO satellite is capable to connect to all the involved vehicles.

III. Conclusion and Future Work

In this paper, we have introduced the concept of non-terrestrial networks and motivated the reasons for which their use can be advantageous within the 5G technology in the context of hybrid connectivity. We adapted the OMNeT++ Simu5G framework to be usable and compliant with the 3GPP

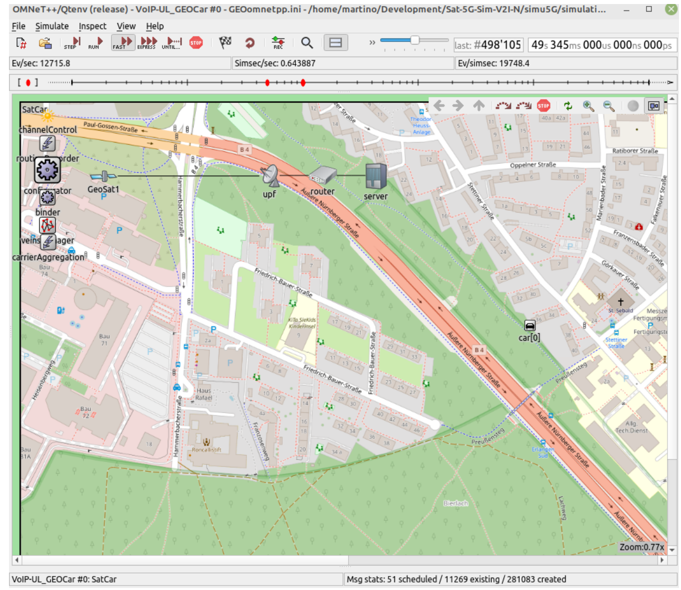

Fig. 5. NTN scenario with a GEO satellite (Screenshot from OMNeT++).

specifications for experiments with non-terrestrial nodes. We gave a high-level description of the different frameworks involved in our simulations and their integration to be able to test several automotive applications. In the future, it is envisaged to evaluate the performances in terms of Quality of Service at the application layer and the performance comparison through the use of different protocols at the transport layer. These experiments will be provided for both satellite configurations, such as GEO and LEO, including a scenario characterized by a higher degree of complexity with multiple cars running several applications in parallel and considering also the movement of LEO satellites.

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