Poster: Simulating Hybrid LEO Satellite and V2X Networks

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***Abstract*—Low Earth Orbit (LEO) satellite constellations are attracting a lot of interest in research as they promise high-throughput low-latency communication all over the world. This aspect makes them perfect candidates for including them in existing vehicular networks. In this paper we motivate a holistic simulation model for hybrid LEO satellite and ground-based Vehicle-to-Everything (V2X) networks, then present its challenges, approaches to overcome them, and a proof of concept simulation.**

I. Introduction

Vehicle-to-Satellite (V2S) communication [1] is a research field that has received a lot of attention in the past. Already back in 1991, Lutz et al. [2] and, later, Scalise et al. [3] demonstrated the feasibility and presented highly-cited channel models for vehicle-to-satellite communication. Such early results, however, were based on experiments with Geostationary Earth Orbit (GEO) satellites. Due to their great altitude, GEO satellites can cover large areas, thus requiring only small constellations of satellites; moreover, because their position relative to Earth is fixed, topology dynamics are very low.

However, as Kodheli et al. [1] note, GEO constellations are costly to build (and, thus, to use) and propagation delays are high (approx. 120 ms, too high for many applications in the vehicular networking domain); therefore, enabled by modern manufacturing and launch techniques, multiple companies like SpaceX, Amazon, and OneWeb are now, for the first time, deploying very large, (comparatively) affordable Low Earth Orbit (LEO) satellite constellations.

These large LEO satellite constellations promise high throughput and low latencies while still offering close to universal coverage. Their downside lies in the very high relative speeds of nodes, creating high topology dynamics.

It is thus very worthwhile to shift the focus to LEO constellations for vehicle-to-satellite communication research, but also challenging. An important step towards exploration of this field are good system simulation models, capable of capturing satellites' and vehicles' mobility as well as modeling inter-vehicle, inter-satellite, and vehicle-to-satellite communication. This would make it possible to holistically investigate the performance of complete systems up to and including full network architectures consisting of ground, air, and space segments [4].

Dedicated simulation models for individual domains are widely available [5], [6]. However, these simulation models typically take advantage of incompatible abstractions, relegating research to consider each domain in isolation.

In this paper we motivate a holistic simulation model for hybrid LEO satellite and ground-based Vehicle-to-Everything (V2X) networks, then present its challenges, approaches to overcome them, and a proof of concept simulation.

II. Combining Coordinate Systems

While both LEO satellite and V2X simulators model mobility and communication, the motion patterns of nodes differ in all of scale, speed, distance, and dimensionality. For example, the road traffic simulator Eclipse SUMO, which is very popular in V2X research, requires map projection (e.g., Universal Transverse Mercator, UTM) to be applied to coordinates, then internally uses a Cartesian coordinate system to represent a scenario. Conversely, as is typical, the LEO satellite network simulator presented by Henderson and Katz [6] uses a spherical coordinate system which represents Earth as an ellipsoid. In the following, we discuss four alternatives of combining these coordinate systems.

a) Map projection of satellite coordinates: As a first, obvious solution, each LEO satellite position can be map projected to Cartesian coordinates. This has the big drawback of potentially needing to choose between *(1)* a map projection that is valid for only a small region of Earth (such as UTM) for satellites that are far away from that region or *(2)* a map projection that is valid for all of Earth, but not very precise in the near field – each alternative leading to projection errors.

b) Inverse map projection of vehicle coordinates: As an alternative solution, each Cartesian vehicle position can be inverse-map-projected back to a longitude, latitude, and altitude tuple. This has the big drawback of being computation heavy as all model calculations (e.g., for radio propagation in cities) must now take place in non-Cartesian coordinates.

c) Maintaining positions in two coordinate systems: Yet another solution is to maintain two positions for each object, one in each coordinate system. Many computations, such as for inter-vehicle and inter-satellite links can then be performed in their native coordinate systems using unmodified models, but the aforementioned drawbacks for V2S communication are retained.

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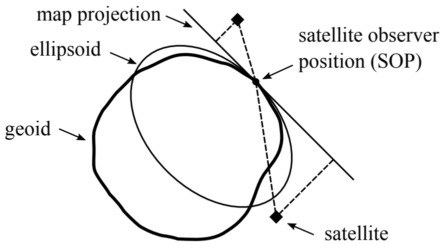

Figure 1. Satellite Observer Position (SOP) centric approach.

d) Satellite Observer Position (SOP) centric approach: An alternative solution illustrated in Figure 1 is to transform satellite positions into an {azimuth angle, altitude angle, distance} tuple relative to a static Satellite Observer Position (SOP) that is chosen well (e.g., lies in the center of the road traffic scenario) – and to then position satellites in the Cartesian coordinate system of the road traffic scenario according to these measures. This has the benefits of (after conversion) using Cartesian coordinates for all model calculations, the (inverse) map projection of the SOP always matching the region it is in (thus minimizing projection error), and closely maintaining exactly the measures most relevant to channel modeling: relative {azimuth angle, altitude angle, distance} of a satellite.

III. Updating Channel Models

Adapting the aforementioned channel models for V2S communication [2], [3] from GEO to LEO satellite communication is another challenge. Scalise et al. [3] also point out the necessity of incorporating obstacles like buildings, bridges, and trees. Furthermore, Kodheli et al. [1] point to atmospheric fading as yet another factor that needs to be modeled. This requires adaptations of existing channel models – or, indeed, entirely new models – to be researched.

IV. Proof of Concept

We are making available a proof-of-concept implementation of a combined simulation of LEO satellite and V2X communication that adapts the SOP-centric approach discussed in Section II to demonstrate its feasibility. This implementation, *space_Veins*,[1] is developed as an extension of Veins [5] and adds models specific to V2S communication.

It includes a dedicated simulator of LEO satellite mobility which is bidirectionally coupled to the other simulation components (Eclipse SUMO for road traffic simulation and OMNeT++ for network simulation). The dedicated server is written in Python, based on the *Skyfield*, *Google Protocol Buffers*, and *ZeroMQ* libraries. Its input data are NASA/NORAD Two-line Element Sets (TLEs), each of which contains, e.g., orbital inclination, ascension, and eccentricity of a satellite. For each combination of SOP and a satellite it can then return the aforementioned {azimuth angle, altitude angle, distance} tuple relative to the SOP allowing the other simulator components to position the satellite in their coordinate system while avoiding the pitfalls discussed in Section II.

[1] https://sat.car2x.org

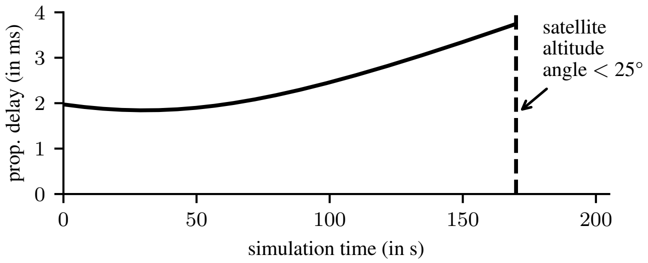

Figure 2. Propagation delay between a single vehicle and Starlink-1528 over time. At 170 s the satellite dips below an altitude angle of 25°.

The V2S channel model of the proof-of-concept implementation is highly idealistic: Data exchange of two nodes is only allowed at altitude angles of 25° or higher, then subject to only a free space path loss and propagation delay model.

Figure 2 shows the propagation delay of a single vehicle sending ping messages to a single satellite. The vehicle is driving in the Veins 5.1 tutorial example and communicating with satellite Starlink-1528 (with simulation time $t = 0$ being 16 Aug 2021 9:00:41 UTC). As can be seen in the figure and as expected, delay is minimal when the satellite is at its shortest distance to the vehicle, that is, when it culminates at $t = 30\,\mathrm{s}$; when its altitude angle dips below 25°, connectivity is lost. The figure also serves to illustrate the generally low, but variable delay and the need for dynamic topology management.

V. Conclusion

Recent advances regarding satellite constellations enable new promising communication possibilities. In this paper we motivated a holistic simulation model for hybrid Low Earth Orbit (LEO) satellite and ground-based Vehicle-to-Everything (V2X) networks, presented its challenges, approaches to overcome them, and a proof of concept simulation. As first indicator for plausible abstractions, we showed the impact of mobility on propagation delay of transmissions between a single vehicle and a single satellite.

References

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