Obstacle Shadowing in Vehicle-to-Satellite Communication: Impact of Location, Street Layout, Building Height, and LEO Satellite Constellation

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Abstract—**Future cooperative mobile systems all commonly share three characteristics: High reliance on stable and performant network connectivity, high mobility of involved nodes, and operation in both cities and remote/rural areas, where uninterrupted availability of the required infrastructure cannot be guaranteed. Researchers and industry alike are thus looking towards Vehicle-to-Satellite (V2S) communication with Low Earth Orbit (LEO) satellites to bridge connectivity gaps. Yet, the interplay of many parameters impacting system performance is frequently overlooked. In this paper, we present an extensive simulation study investigating the impact of all of: ground station location on Earth, small-scale ground station position in the overall city layout (regarding both neighboring building locations and heights), and properties of LEO satellite constellations (in terms of both density and inclination). We found that each of these many parameters substantially impacts the performance of V2S communication. At the same time we could confirm that street and building geometry in the overall city layout give rise to systematic patterns in V2S connectivity on the ground.**

I. Introduction

Uninterrupted end-to-end connectivity or, in general, Internet access is becoming increasingly important in current and, especially, future technologies and applications; to give just a few examples: Future mobility concepts include autonomous or teleoperated vehicles and truck platooning. More efficient technologies in logistics make use of Unmanned Aerial Vehicle (UAV) delivery systems [1] and autonomous ships [2] that deliver goods around the globe. Post disaster emergency communication systems that connect first responders with each other as well as with their tools like UAVs and robots attract more and more interest. All these use cases share three common characteristics: (i) high reliance on stable and performant network connectivity, (ii) high mobility of involved nodes, and (iii) operation in both cities and remote/rural areas.

At the same time, these use cases often operate in areas that cannot guarantee uninterrupted availability of the required infrastructure, e.g., cellular network technologies [3]. To compensate this aspect, standardization bodies like the 3GPP aim to integrate Non-Terrestrial Networks (NTNs) [4], often consisting of Low Earth Orbit (LEO) satellite constellations, with existing technologies. Private companies like SpaceX, OneWeb, or Iridium already operate these kinds of constellations and offer services like Internet connectivity or asset tracking. Due to decreasing cost of satellite launches, more and more private companies are planning to build their own LEO satellite constellations. One example is the car manufacturer Porsche [5] who decided to invest into Isar Aerospace, a company that plans to launch their own satellites. Another example is the automotive company *Geely* [5] that launched its first 9 LEO satellites in June 2022 and another batch of 11 LEO satellites in February 2024. By 2025, their constellation should consist of 72 LEO satellites and is designed to support autonomous vehicles.

Such a design process often consists of evaluating simulations with different configurations of models whose target scenario is the communication between LEO satellites and vehicles such that the vehicles receive all the information necessary for safe cooperative and autonomous driving. Ensuring safe cooperative and autonomous driving is a challenging task as it must consider a wide variety of different scenarios and locations, e.g., remote/rural areas or urban environments with severe obstacle shadowing. Additionally, the integration of LEO satellite constellations adds more complexity in terms of coverage as it depends on the LEO satellites' mobility and the ground scene.

While related works consider a wide variety of isolated parameters like building geometry, ground mobility, satellite mobility, or different numbers of satellites, each of them focuses on, at best, a subset of aspects and scenarios. Consequently, there is a research gap in understanding the interplay of all these parameters.

To fill this gap, this paper's contribution is an extensive simulation study that considers three different locations on Earth, three distinct LEO satellite constellations, and varying building heights to show the influence of location, street layout, building heights, and satellite mobility on the coverage of Vehicle-to-Satellite (V2S) communication.

This paper is structured as follows: Section II discusses related research on LEO satellite coverage prediction, channel modeling in general, and of modeling the impact of obstacle shadowing in particular. Section III introduces background on the high-level impact of different LEO satellite constellations. Section IV presents the details of the simulation study design, including the selected scenario geometry on the ground, the investigated LEO satellite constellations, and the computed metrics. Section V presents and discusses the results of the simulation study. Finally, Section VI puts the results into broader perspective and discusses future work.

15th IEEE Vehicular Networking Conference (VNC 2024) Digital library entry → http://dx.doi.org/10.1109/VNC61989.2024.10575991

II. Related Work

LEO satellite coverage and obstacle shadowing have been studied for a long time, often with the goal of creating models that can be used for simulations. The methodology for developing these models can be divided into three categories: measurement based, geometry based, and stochastic geometry based.

Scalise et al. [6] performed a measurement campaign whose results are the foundation of a three-state channel model and a simplified two-state model. In their measurement campaign, they used a vehicle to drive in different areas of Munich while communicating with the geostationary satellite Astra 19.2E, which has a fixed elevation of 34 degrees in Munich. Although these models cannot be directly applied to LEO satellite constellations due to the use of a geostationary satellite, the authors indicate that the street orientation had a significant impact on the visibility of the satellite.

The work of Seyedi et al. [7] and Hornillo-Mellado et al. [8] focuses on the geometry of the environment, i.e., the building heights and street widths. Based on these values the authors develop models that predict the shadowing moments and the outage probability [7] or calculate the projected shadowing area on the street [8]. Both approaches are validated with measurement campaigns that either use a single geostationary satellite in an urban area of Barcelona [8] or a helicopter flying parallel to a ground vehicle to maintain different elevation angles [7]. Consequently, only a limited number of scenarios are evaluated in these studies.

To compensate this limitation, other works rely on stochastic geometry. It is used to calculate Line of Sight (LOS) probability [9], [10], coverage probability [11], or outage probability [12], [13]. To incorporate the influence of buildings, components like shadowed-Rician Fading or Rayleigh Fading are used. Such models are either validated with measurements [9], [10] or with Monte Carlo simulations [11]–[13]. The work of Momani and Nabeel [14] shows that the parameterization of these models is crucial to obtain valid predictions. Since developing models out of measurement campaigns is time consuming, complex, and might include side effects, simulations [15] are also used to compute realistic parameters for stochastic models.

But still, due to the stochastic approach, relevant aspects like the LEO satellite constellation characteristics, ground station locations (especially the latitude, see Section III) are represented in an abstract fashion only. To gain more specific insights, discrete event simulations are a reasonable tool that enables researchers to evaluate a wider variety of scenarios in less time than real-world measurements would. At the same time, simulations do not require as many simplifications as stochastic geometry based models.

Simulators that support precise ground vehicle mobility as well as detailed LEO satellite mobility already exist. So do obstacle shadowing models that support their simulation engines, yet the many publications either do not provide any details if they are used [16], [17] or model the impact of building heights by a static threshold elevation angle between a ground vehicle and a LEO satellite that has to be exceeded for successful communication [18].

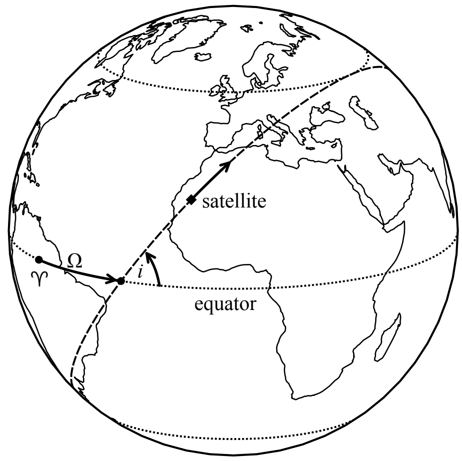


Figure 1. Idealized ground track of a satellite orbit for $\Omega = 30°$, $i = 53°$ and corresponding lines of latitude at ±53°N (Earth drawn assuming −60°E to be currently facing ϒ).

Summing up, we can draw two conclusions from related work. While stochastic models provide a general understanding of the expected performance, they are not suitable for evaluating a specific scenario with its own characteristics. Simulators do either not provide any details about the obstacle shadowing model used or use very abstract representations of the environment.

With this work we aim to close this gap by evaluating the influence of the street layout, building heights, location on Earth, and LEO satellite constellation on the performance of V2S communication in a wide variety of scenarios. We present the details, e.g., scenario geometry and obstacle shadowing model, of the simulation study in Section IV and discuss its results in Section V.

III. LEO Satellite Constellations vs. Coverage

Before we present the details of the simulation study, we explain the general architecture of LEO satellite constellations and its impact on ground connectivity. A LEO satellite constellation consists of multiple planes, each of which contains multiple satellites. Usually, operators distribute the planes such that they evenly cover the Earth's surface. LEO satellites belonging to the same plane are again evenly distributed on it.

As visualized in Figure 1, the orientation of a plane is defined by the right ascension of the ascending node Ω and its inclination angle i. The right ascension of the ascending node is the angle between the First Point of Aries ϒ (the reference direction) and the ascending node, which is the point where a LEO satellite crosses the equator from south to north. It ranges from 0° to 360°. The inclination angle is the angle between the plane and the equator and ranges from 0° to 180°. LEO satellites on planes with an inclination angle which is smaller than 90° move in the same direction as the Earth's rotation: they orbit in a prograde direction. In contrast, planes with an

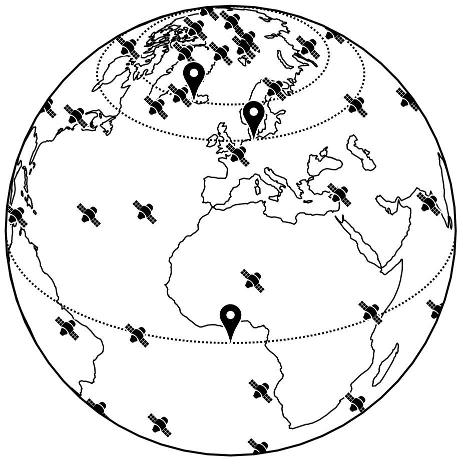


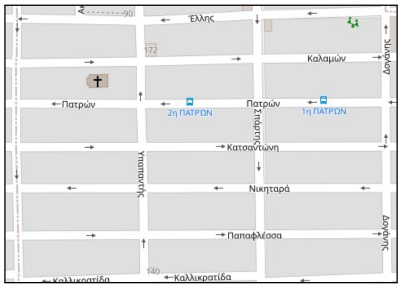
Figure 2. LEO Satellite positions of the Iridium Next constellation as of 4 March 2024 at 21:23:14 UTC, projected onto the surface of Earth. Because of the even arrangement of satellites in orbital planes, overall density of satellites is lower at the equator, higher at the poles.

inclination angle which is greater than 90° are called retrograde because their LEO satellites move against the Earth's rotation. LEO satellites on planes whose inclination angle is 90° orbit from pole to pole, thus, they move in a perfect north-south direction. If the inclination angle is 0°, the LEO satellites orbit from west to east in the equatorial plane.

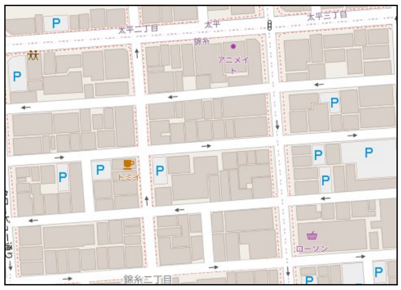
The inclination angle has a significant impact on the coverage provided by the LEO satellite constellation. Figure 1 visualizes a LEO satellite ground track with an inclination angle of 53° that is idealized, i.e., it ignores Earth's rotation. However, it still shows that the plane's inclination angle corresponds with the highest and lowest latitudes a LEO satellite can reach on its trajectory. Consequently, a constellation with such an inclination angle does not cover the poles. The first conclusion is therefore that the higher the inclination angle of the constellation, the higher the latitude the LEO satellite can cover.

Additionally, the satellite density is not uniform over the Earth's surface (cf. Figure 2). Once the deployment of the constellation is completed, the number of LEO satellites is fixed. The average number of satellites that must cover a certain latitude is therefore constant. At the same time the Earth's circumference is largest at the equator and becomes smaller with increasing absolute latitude. The second conclusion is therefore that (within the limits of covered latitudes) the satellite density increases with increasing absolute latitude.

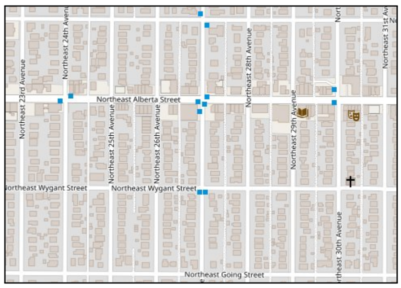
Based on these two conclusions, the selection of the scenario's location on Earth and the inclination angle of the orbital plane has a significant impact on the coverage provided by the LEO satellite constellation. In our simulation study, we account for these aspects by evaluating three different locations on Earth, three different LEO satellite constellations, and multiple building heights.



(a) Athens, 37.962°N 23.630°E



(b) Tokyo, 35.699°N 139.813°E



(c) Portland, 45.559°N −122.638°E

Figure 3. Manhattan grid in various cities. (Map data from OpenStreetMap, openstreetmap.org/copyright)

IV. Simulation Study

The simulation study is conducted with the open source space_Veins (version 0.3) framework.[1] It is an extension for the vehicular network simulator Veins that integrates LEO satellite mobility models which enables to run integrated simulations considering the influence of small ground vehicle movements and LEO satellite mobility on their communication. As shown by a proof-of-concept study of our previous works [18], ground vehicle mobility can have a significant impact on the performance of V2S communication.

As discussed in the preceding section, it is important to evaluate multiple scenarios with different latitudes as it influences the coverage of the LEO satellite constellation. In this study, the investigated locations are: Null Island (0°N 0°E), Hamburg (53.55°N 9.99°E), and Reykjavik (64.13°N −21.89°E). They represent the smallest possible latitude, a latitude in the middle of Europe, and the latitude of the most northern capital of the world, respectively.

[1]Full source code available via https://sat.car2x.org/

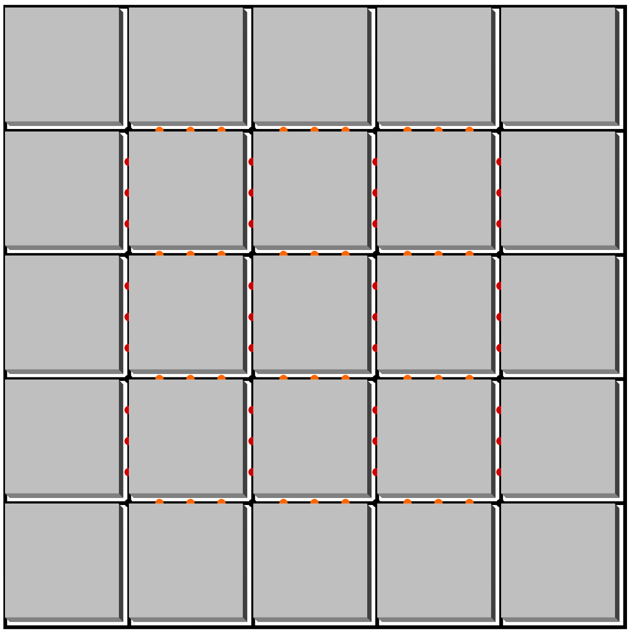


Figure 4. The simulation scenario consists of a five by five Manhattan grid whose side length is 1 km with ground stations placed every 50 m. Ground stations fall in two categories: those on streets running north or south and those on streets running east or west. The height of the buildings in-between streets is varied between 0 m and 45 m.

As street layout we use a Manhattan grid, which is a grid of streets perfectly oriented in north-south and east-west direction. The reason for this choice is that it is a simple and common street layout that is easy to model and can be found in many cities around the world (cf. Figure 3).

The actual simulated scenario is a five by five Manhattan grid with a side length of 1 km (cf. Figure 4). Streets consist of two lanes, one for each direction. A single lane has a width of 3.2 m. The margin between a street and a building is 5 m. Consequently, the side length of a building is 183.6 m. Its height is varied between 0 m and 45 m in 3 m steps.

To be independent of ground mobility influences, vehicle movement is disabled. A total of 72 static ground stations, separated in two groups of 36 ground stations, are placed in the middle of the streets every 50 m as it is shown in Figure 4. Red dots indicate ground stations on streets running north or south, orange dots indicate ground stations on streets running east or west. Their satellite antennas are placed at a height of 1.895 m.

The communication between ground stations and LEO satellites is modelled based on two constraints. First, the elevation angle between a ground station and a LEO satellite must exceed a constellation-dependent minimum elevation angle θ_{lim}. Second, buildings intersecting the LOS of a ground station and a LEO satellite completely block any communication between them.

The LEO satellite mobility is based on the SGP4 model. Using the Satellite Observer Position (SOP) approach [19], the

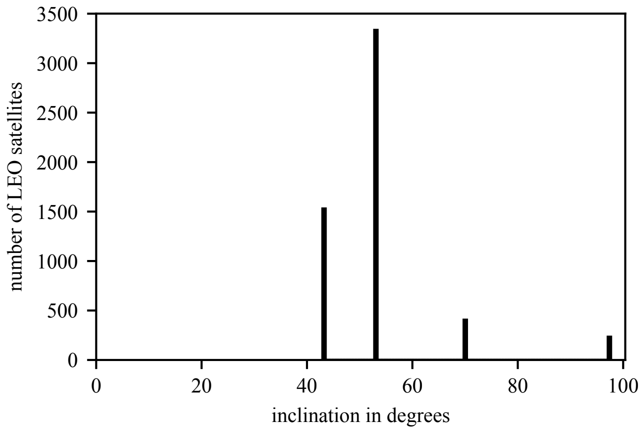


Figure 5. Histogram of the inclination angles of all Starlink satellites based on TLE data valid for 4 March 2024.

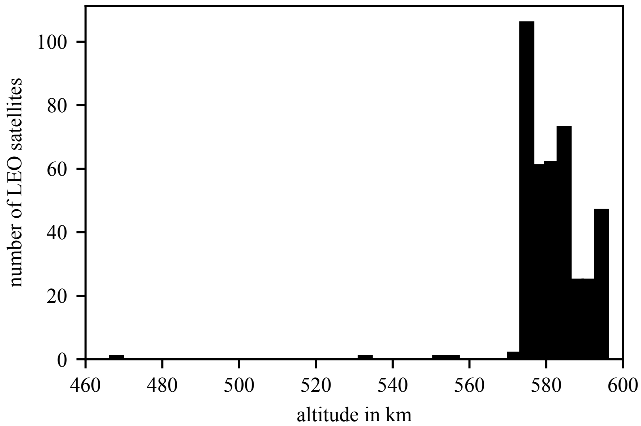


Figure 6. Histogram of the altitude (height above Earth's surface) of the Starlink70 group based on TLE data valid for 4 March 2024.

positions calculated by the SGP4 model are transformed into a ground based coordinate system. In order to propagate the LEO satellite's position, the SGP4 model requires NASA/NORAD Two-line Element Sets (TLEs). They contain relevant parameters like the inclination angle and the right ascension of the ascending node for calculating LEO satellite positions.

We employ publicly available TLEs to derive three artificial, but realistic satellite constellations, one related to *Iridium Next* and two more related to *Starlink*, via filtering. One reason is that publicly available TLEs contain all LEO satellites that technically belong to a constellation even though they might not be active, such as satellites currently in *storage orbit* or being moved into or out of position.

For the constellation we call *Iridium86*, we start with all TLEs of the *Iridium Next* constellation. At the time of writing, a total of 80 TLE entries are listed for this constellation, out of which 66 can be presumed to be active as the Iridium Next constellation is built out of 6 orbital planes with 11 LEO satellites each [20], [21]. Based on the altitude and the systematic distribution of LEO satellites, it is possible

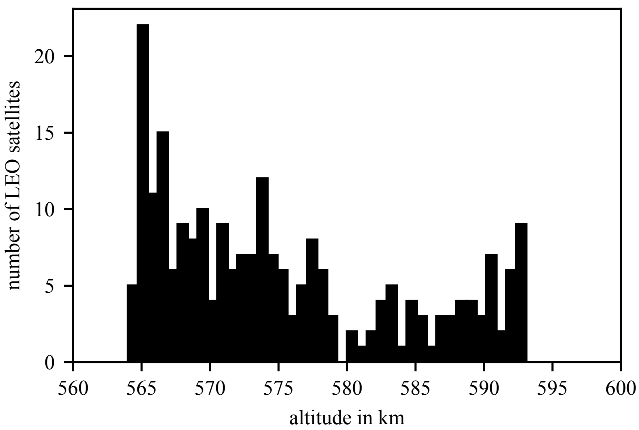


Figure 7. Histogram of the altitude (height above Earth's surface) of the Starlink97 group based on TLE data valid for 4 March 2024.

Table I
CHARACTERISTICS OF THE INVESTIGATED LEO SATELLITE CONSTELLATIONS.

	Starlink70	Iridium86	Starlink97
Number of LEO satellites	401	66	233
Minimum altitude	560 km	775 km	560 km
Number of planes	21	6	5

to identify 66 LEO satellites with an inclination angle of approximately 86.4° that conform with the expected satellite distribution. In line with the constellation, we assume a minimum elevation angle $\theta_{\text{lim}} = 8°$ for V2S communication to these satellites.

For the constellations we call *Starlink70* and *Starlink97*, we start with all TLEs of the *Starlink* constellation. We aim to use these TLEs for constructing realistic satellite constellations that are not fully deployed yet, so are sparsifying the Starlink TLEs further, as follows. We first group TLEs based on the inclination angle. Figure 5 illustrates that four distinct groups can be identified. Their corresponding inclination angles are 43°, 53°, 70°, and 97°. We focus on only satellites in the last two groups because only these cover all three locations that we investigate. Satellites in these groups make up the candidates for inclusion in constellation Starlink70 and Starlink97, respectively. For further filtering, we investigate the altitude (height above Earth's surface) of satellites in both groups in order to exclude LEO satellites that are likely still on their journey to their designated position. Figures 6 and 7 show that four satellites of Starlink70 are on a significantly lower altitude compared to all the other LEO satellite groups while none of Starlink97 are. Thus, we only include LEO satellites whose altitude is higher than 560 km. For V2S communication to these satellites, in line with regulatory requirements of Starlink [22, III-E-1 para. 42], we assume a minimum elevation angle $\theta_{\text{lim}} = 25°$.

To sum up, we investigate three satellite constellations representative of realistic LEO satellite constellations in various stages of deployment. These LEO satellite constellations are: Starlink70 consisting of 401 LEO satellites on 21 orbital planes with a minimum altitude of 560 km, Iridium86 consisting of 66 LEO satellites on 6 orbital planes with a minimum altitude of 775 km, and Starlink97 consisting of 233 LEO satellites on 5 orbital planes with a minimum altitude of 560 km. Table I summarizes the characteristics of the constellations.

We select the Packet Delivery Ratio (PDR) of V2S communication as a metric of LEO satellite performance. To measure the PDR, all ground stations attempt to transmit one data packet to satellites of a given constellation with a frequency of 1 Hz for a full period of 24 h without interfering with each other.

The simulation counts every transmitted packet that is successfully received by any of the LEO satellites in a given constellation (that is, each transmitted packet is counted as received at most once). Based on these values it calculates the PDR for every ground station as the ratio of its packets that were successfully received by the constellation, divided by the number of its transmitted packets. A single data point of the PDR is then computed as the mean of all ground stations in the whole scenario (Figure 8) or of all ground stations in a given group (Figure 9).

For this study, we report results based on a TLE set that is valid for 4 March 2024, but made sure that their general validity is not time dependent by reproducing the results with a second set of TLEs (valid for 19 February 2024 or 7 June 2023 for the Starlink and Iridium Next constellations, respectively).

In summary, we simulated three locations, three LEO satellite constellations, and 16 building heights, at two different dates. In total, this is 288 simulation runs. As neither the mobility of ground stations and LEO satellites nor packet transmissions depend on randomness, a single simulation run is deterministic and has not to be repeated for statistical validity.

V. RESULTS

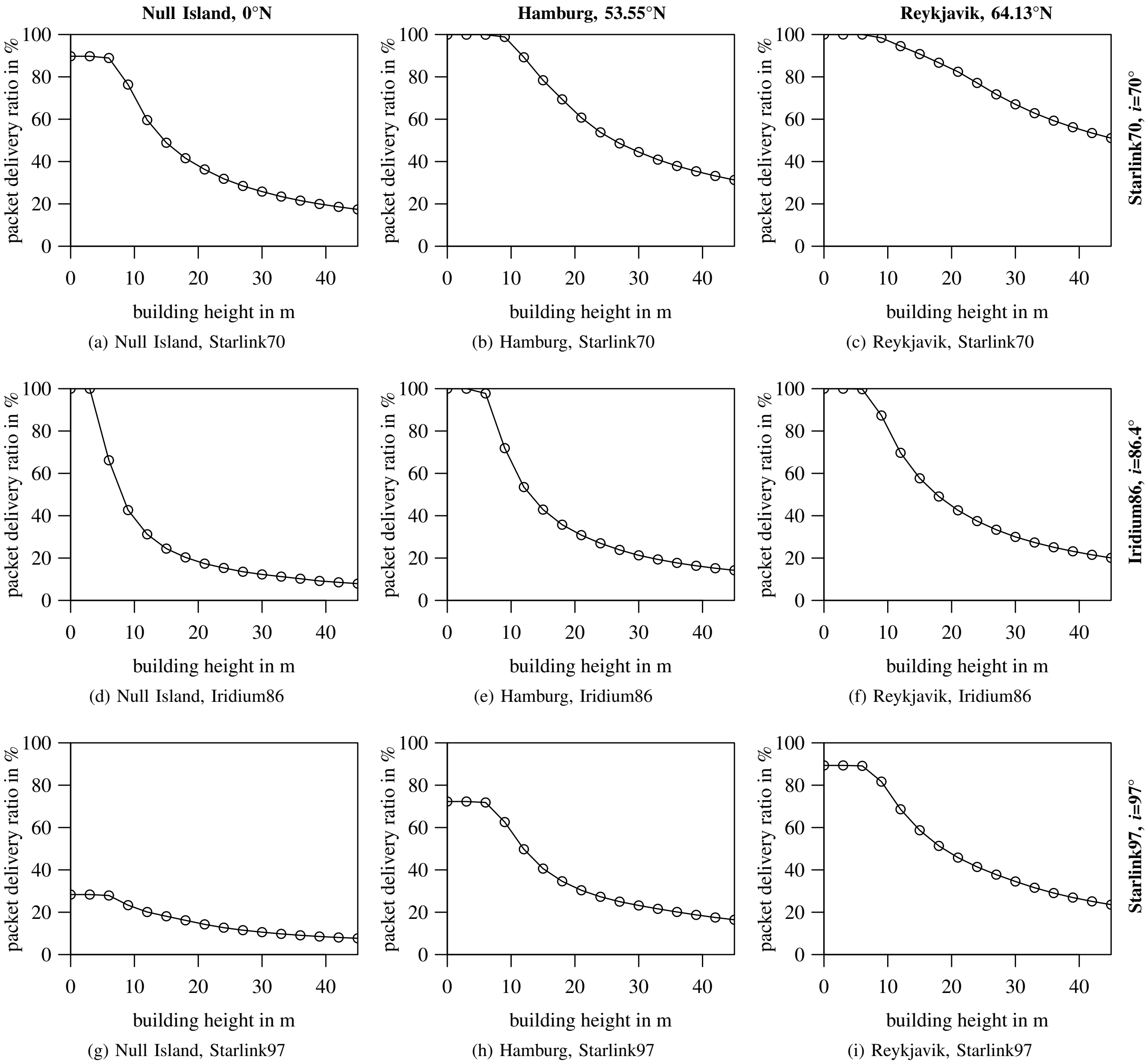
By analyzing the characteristics of the simulation results, we can identify three distinct input parameters which affect the PDR, namely the building height, the LEO satellite density (which, as discussed, also depends on the locations' latitude; cf. Section III), and the street orientation.

A. Building Heights

Focusing on the building heights, Figure 8 visualizes very different behavior for each of the nine scenarios.

First, the minimum height for a building to markedly impact communications varies substantially by location and constellation. While the average PDR of ground stations in Null Island for Iridium86 is already impacted substantially at 6 m (cf. Figure 8d), at a different location (Hamburg, cf. Figure 8e) buildings need to be 9 m tall or taller, or even 12 m tall for a different constellation (Starlink70, cf. Figure 8b).

Second, the overall impact of building height varies by location and constellation as well. While the PDR of ground stations in Null Island communicating with Iridium86 drops from 100.00 % to 7.91 % (cf. Figure 8d), it only drops from 100.00 % to 51.06 % for ground stations in Reykjavik communicating with Starlink70 (cf. Figure 8c). Similar effects can be observed for the other scenarios.



(a) Null Island, Starlink70 (b) Hamburg, Starlink70 (c) Reykjavik, Starlink70

(d) Null Island, Iridium86 (e) Hamburg, Iridium86 (f) Reykjavik, Iridium86

(g) Null Island, Starlink97 (h) Hamburg, Starlink97 (i) Reykjavik, Starlink97

Figure 8. Dependence of the Packet Delivery Ratio (PDR) of Vehicle-to-Satellite (V2S) communication on location, constellation, and building height.

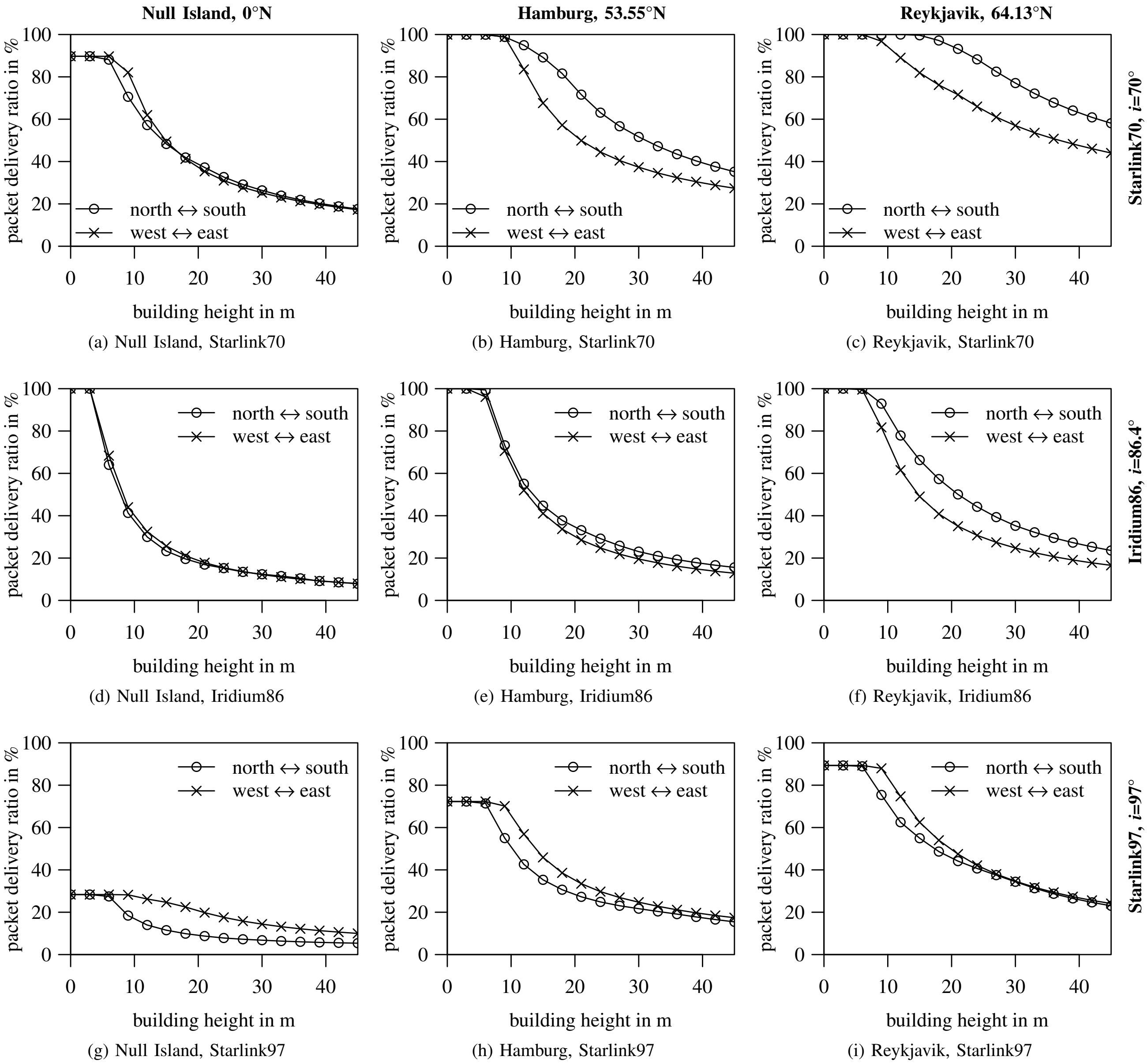
B. LEO Satellite Density

As described in Section IV, the three LEO satellite constellations differ in all of total number of LEO satellites, inclination angle, and number of planes. Further, we showed that the LEO satellite density is dependent on Earth's latitudes in Section III.

All these characteristics have an influence on the coverage of a LEO satellite constellation. The PDRs for building heights equal to 0 m visualized in Figures 8b to 8f are 100 %. This means that all ground stations in these scenarios experienced an uninterrupted connection to the LEO satellite constellation. In contrast to these five scenarios, Figures 8a and 8g to 8i show that the maximum PDR never reaches 100 %. These ground stations do not experience an uninterrupted coverage even if no buildings block the LOS. Consequently, the LEO satellite constellations are too sparse in these locations to be able to provide coverage at all times.

C. Street Orientation

For Figure 9, the PDR is now calculated separately for ground stations located on a north-south street or on a west-east street, respectively. Here, systematic differences can also be observed between the two groups of ground stations within a single scenario. Figure 9b (Hamburg, Starlink70), Figure 9c (Reykjavik, Starlink70), and Figure 9f (Reykjavik, Iridium86) indicate that ground stations located on north-south streets clearly outperform the ground stations on west-east streets. At the same time, Figures 9g to 9i (all locations, Starlink97) show the exact opposite: Here, the PDR of ground stations located



(a) Null Island, Starlink70
(b) Hamburg, Starlink70
(c) Reykjavik, Starlink70
(d) Null Island, Iridium86
(e) Hamburg, Iridium86
(f) Reykjavik, Iridium86
(g) Null Island, Starlink97
(h) Hamburg, Starlink97
(i) Reykjavik, Starlink97

Figure 9. Like Figure 8, but separating ground stations into two groups depending on the orientation of the street they are in.

on west-east streets is higher compared to the ones located on north-south streets. There is only one scenario, Null Island communicating with Iridium86 (cf. Figure 9d), in which the PDR difference is marginal.

VI. Conclusion and Future Work

In this paper, we presented an extensive simulation study investigating the interplay of a multitude of parameters on the performance of Vehicle-to-Satellite (V2S) communication. We studied coarse ground station location on Earth, small-scale ground station position in the overall city layout (regarding both neighboring building locations and heights), and properties of Low Earth Orbit (LEO) satellite constellations (in terms of both density and inclination).

We found that each of these many parameters substantially impacts the performance of V2S communication. This means that the results of any study of system performance conducted for one combination of parameters cannot be taken as indicative of the results for another.

At the same time we could confirm that street and building geometry in the overall city layout give rise to systematic patterns in V2S connectivity on the ground.

Future work will revolve around moving from the synthetic scenarios employed in this study to cities with heterogeneous street layouts and building heights as well as system designs that are aware of – and can exploit – the described systematic interdependence of small changes in vehicle position and overall system performance.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the help of the Luxembourg Institute of Science and Technology (LIST) with debugging and testing efforts in the context of the joint call project LEONE (Low-Latency Command and Control via LEO Satellites), supported by the Luxembourg National Research Fund (FNR) under grant IS/17800623.

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