Multi-Link Connectivity for Vehicle-to-Satellite Communications Under Obstacle Blockage

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***Abstract*—Maintaining reliable Vehicle-to-Satellite (V2S) connectivity for critical mobile services is a significant challenge for Low Earth Orbit (LEO) satellite constellations due to high orbital velocities and frequent radio obstructions in urban environments. Spatial diversity through multi-link connectivity – the use of multiple simultaneous satellite links – can mitigate these shadowing effects, but introduces a potential increase in signaling overhead via frequent Handovers (HOs). This paper investigates this fundamental trade-off by evaluating three HO mechanisms. Leveraging a high-fidelity simulation framework that integrates orbital dynamics, vehicle mobility, and urban geometry, we analyze the impact of using up to three parallel links on the satellite link availability and HO frequency. Our results demonstrate that while multi-connectivity effectively mitigates obstacle blockage, the magnitude of the reliability gains and the associated signaling costs are strictly dependent on the HO logic. These findings establish a baseline for future works, including more detailed channel models and real-world scenarios.**

***Index Terms*—LEO Satellites, Vehicle-to-Satellite Communication, Handover Management, Multi-Link Communication**

I. INTRODUCTION

Satellite communications are rapidly emerging as a critical backbone for next-generation vehicular networks, particularly for mission-critical applications where terrestrial infrastructure is absent or compromised [1]. In scenarios such as the teleoperation of first-responder vehicles, emergency coordination in post-disaster zones, or operations in contested environments, Low Earth Orbit (LEO) satellite constellations offer the promise of ubiquitous connectivity. However, the integration of Non-Terrestrial Networks (NTN) into the vehicular ecosystem faces a significant challenge: terrestrial signal blockage [2].

In environments with ground-level obstacles, such as buildings, the reliability of Vehicle-to-Satellite (V2S) links is severely degraded. These obstacles create intermittent Line-of-Sight (LoS) connectivity that fluctuates as a vehicle moves. This geometric blockage threatens the stringent requirements of low-latency and high-reliability services, as even momentary signal loss can disrupt the control loops required for safety-critical applications.

Recent literature has demonstrated the promise of multi-link connectivity in LEO networks to optimize data allocation and improve transmission efficiency for static ground terminals [3]. However, the application of such strategies to highly mobile vehicular environments remains an open challenge, mainly due to the frequent link disruptions caused by terrestrial obstacles. Moreover, while a multi-link approach can enhance the LoS probability, it introduces a complex trade-off between communication robustness and system overhead. In particular, maintaining multiple active links may lead to frequent Handovers (HOs). These HOs are driven by both the high orbital dynamics of LEO constellations and the rapid changes in visibility caused by the surrounding environment. Minimizing HO frequency is essential to reduce control-plane signaling, prevent packet reordering, and conserve the vehicle's computational resources.

To address this challenge, we investigate the benefits of various spatial diversity strategies that leverage multiple concurrent satellite links. The core intuition is that by maintaining multiple simultaneous sessions with multiple satellites at different orbital positions, the probability of at least one link remaining unobstructed by ground-level obstacles increases substantially.

In this work-in-progress paper, we quantify the impact of terrestrial obstructions on V2S performance using *space_Veins*[1], a realistic simulation environment that couples microscopic ground mobility simulation with 4D orbital mechanics. By employing a geometric channel model focused on LoS availability, we evaluate how multi-link operations enhance connectivity and characterize the associated cost in terms of increased HO frequency. Our findings provide a preliminary perspective on the feasibility of multi-link LEO connectivity as a solution for resilient vehicular networking.

II. MULTI-LINK HANDOVER STRATEGIES

To evaluate multi-link connectivity strategies, we build upon two existing HO mechanisms previously investigated in single-link scenarios [4]: *Interrupted Stream Handover (IHO)* and *Fixed Interval Handover (FHO)*. Our goal is to ensure that the performance gains attributed to spatial diversity and obstacle mitigation are robust and not biased by a specific HO logic.

Though they differ in their triggering conditions, both HO mechanisms employ the same satellite selection criterion. We assume satellites periodically broadcast beacon-like messages that vehicles can receive. Based on these messages, vehicles maintain an updated list of visible satellites, including their elevation angles. We assume that vehicles can compute the elevation angles from the received beacons. When the HO

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[1] Full source code of the simulator is available at https://sat.car2x.org/

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procedure is triggered, the vehicle connects to the satellite with the highest elevation angle among those visible, which is assumed to provide the best link conditions. The key difference between the two mechanisms lies in their triggering conditions for the HO procedure.

In the *Interrupted Stream Handover (IHO)* mechanism, an HO is triggered when a predefined number n of consecutive beacons from the serving satellite are not received. The vehicle then scans the list of currently visible satellites and connects to the one with the highest elevation angle. If no satellites are currently visible, the vehicle is considered out of coverage and scheduled packets are dropped until connectivity is restored. As soon as a new satellite becomes visible, the vehicle establishes a connection with it using the same selection criteria.

The *Fixed Interval Handover (FHO)* mechanism relies on the periodic re-evaluation of the serving satellite. Given a time window t_w, the vehicle re-evaluates for new connections at regular intervals. If a visible satellite with a higher elevation angle than the current one is found, a handover is performed. Otherwise, the existing connection is maintained. If connectivity is lost during the time window t_w, the vehicle remains out of coverage until the next re-evaluation instant. Similarly, if no visible satellites are available at the re-evaluation time, the vehicle remains disconnected for the entire duration of the subsequent window t_w. We refer to FHO with different values of t_w as *FHO-*t_w (e.g., FHO-30s).

In this work we build on these algorithms, but allow a vehicle to maintain up to N simultaneous active sessions with different LEO satellites. By leveraging spatial diversity, the probability of at least one link maintaining LoS increases significantly.

The management of these N links depends on the underlying HO mechanism. Under the IHO mechanism, a vehicle initially connects to the N visible satellites with the highest elevation angles. If one of the active links is lost, the vehicle searches among the currently visible satellites and selects the one with the highest elevation angle that is not already connected. Under the FHO mechanism, all N active links are reconsidered at each re-evaluation instant. Depending on the elevation angle of the currently visible satellites, the vehicle may update all connections or only a subset of them. For both mechanisms, if the number of visible satellites is less than N, only the available satellites are used, and the remaining potential links are unused.

Note that, in the present study, HO events are assumed to be instantaneous and always successful; therefore, no HO-related penalties are modeled. Extending the model to include realistic packet delays or losses due to the HO or unsuccessful procedures is part of future work.

III. SIMULATION SCENARIO AND SETUP

A. Simulation Framework and Channel Model

The results presented in this paper were obtained using the openly available *space_Veins* framework (version 0.3). As an extension of the widely used Veins framework, it couples OMNeT++ network simulation with SUMO microscopic traffic simulation. The framework models LEO satellite mobility by incorporating the Simplified General Perturbations 4 (SGP4) model. It processes Two-line Element Set (TLE) files to simulate the orbital parameters of real satellite constellations, updating their orbital positions at 1 s intervals [5].

V2S communications are modeled using a simplified channel model provided by the INET model suite. In particular, when a ground node v_i transmits a unicast message to a satellite s_j, the reception is considered unsuccessful if either (i) the LoS between v_i and s_j is obstructed by buildings, or (ii) v_i is outside of s_j's coverage region (see Section III-B for details on the satellite coverage model). Although the adopted channel model is deliberately simplified, it enables isolating the effects of geometry, satellite motion, and vehicle mobility on the effectiveness of multi-link strategies. More detailed channel modeling, including effects such as carrier frequency, transmission power, and antenna features, is left as future work.

B. Simulation Scenario and Use Case

We simulate an urban scenario consisting of a 5×5 Manhattan Grid layout, where vehicles move along orthogonal north–south and east–west streets. The scenario is 1 km × 1 km in size and it is centered at 0°N, 0°E (Null Island, a fictitious location). To study the impact of urban geometry on V2S communications, buildings are placed along the streets at a distance of 5 m from each traffic lane. The roads consist of two lanes, one per direction, each 3.2 m wide.

The scenario consists of 50 vehicles that are inserted at the beginning of the simulation and remain active throughout its duration. At the application layer, the vehicles periodically transmit packets to satellites at a frequency of 10 Hz, i.e., one message every 100 ms. This traffic pattern ensures the exchange of a sufficient number of packets for reliable performance evaluation and is representative of relevant use cases, such as teleoperated driving. Satellites periodically broadcast beacon-like messages every 100 ms to signal their presence. Vehicles receive these messages and maintain internal data structures that register and update the set of visible satellites. Based on this information, as well as the mechanisms described in Section II, vehicles select the satellite for transmitting packets.

The satellites considered in our simulation belong to the Starlink constellation. We downloaded a TLE file including 6776 satellites from CelesTrak[2]. To reduce the simulation complexity and avoid modeling satellites that would never provide coverage for the scenario under consideration (centered at 0°N, 0°E), we filtered the constellation, retaining only those satellites that reach a minimum elevation angle of 25° with respect to the scenario center, in accordance with Starlink regulatory requirements [6, III-E-1, para. 42]. This reduces the simulated constellation to 57 satellites.

Our simulations consider satellites equipped with fixed, non-steerable beams. This means that the coverage footprint moves across the Earth's surface in accordance with the satellite's trajectory. This is consistent with the *Earth-moving* service link type defined by 3GPP [7]. The size of each satellite's

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[2] https://celestrak.org/NORAD/elements/gp.php?GROUP=starlink

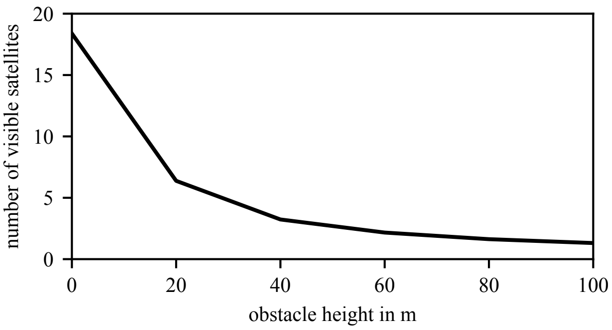


Figure 1. Average number of satellites visible to vehicles as a function of obstacle height.

coverage area depends on the antenna's opening angle. Due to the relatively small geographic scenario being simulated, we adopt a flat-Earth approximation, whereby the footprint radius is $r = h \tan(\beta)$, with h being the satellite altitude and β the half-beam opening angle. Using the parameters of the primary Starlink orbital shell, we set $h = 550\,\mathrm{km}$. With $\beta = 60°$, the footprint radius is approximately 951 km. This value aligns with the operational constraints of early-phase LEO mega-constellations, which frequently utilized a minimum elevation angle of 25° to maximize terrestrial coverage. For the specified altitude, such an elevation angle corresponds to a coverage radius of approximately 940 km [8], confirming that our geometric assumption of $\beta = 60°$ provides a realistic representation of wide-area LEO connectivity.

C. Parameter Selection

Two main performance metrics are studied in this work: *link availability ratio* and *number of handovers*.

- The *link availability ratio* is defined as the probability that a vehicle maintains at least one operational V2S connection at any given 0.1 s simulation step. Effectively, this represents the probability that a message transmitted by a vehicle every 100 ms is successfully received by at least one satellite.
- The *number of handovers* represents the average number of HOs per vehicle over the simulation duration. A HO is registered each time a communication link switches to a different satellite. For example, if a vehicle re-evaluates its connectivity and switches to three new satellites ($N = 3$), three HOs are recorded. Notably, a reconnection following a link outage is only counted as a HO if the newly selected satellite differs from the one utilized prior to the outage.

Simulations are conducted by varying three main parameters:

- the building height, ranging from 0 to 100 m in steps of 20 m;
- the considered HO strategy, namely IHO and FHO (the latter in variants FHO-30s and FHO-60s); and
- the number of simultaneous satellite links N, with $N \in \{1, 2, 3\}$.

We justify the selection of the maximum concurrent links (N) and the re-evaluation window (t_w) based on the physical constraints of the urban environment and orbital dynamics.

As illustrated in Figure 1, building height significantly impacts visibility. The average number of visible satellites decreases from 19 in an unobstructed scenario to 3.22 when building heights reach 40 m, dropping below 2 beyond 80 m. Consequently, $N = 3$ is selected as the upper bound, representing the average maximum availability across the analyzed obstructed urban scenarios.

Regarding the re-evaluation window t_w, given the high orbital velocity of LEO satellites at 550 km altitude, the typical continuous serving time ranges between 20–40 s [9]. Therefore, $t_\mathrm{w}= 30\,\mathrm{s}$ is chosen as a representative baseline (FHO-30s). Additionally, a $t_\mathrm{w}= 60\,\mathrm{s}$ configuration (FHO-60s) is included to evaluate the impact of reduced HO re-evaluation frequency.

We further set the IHO beacon loss threshold to $n = 3$. The simulation length is set to 315 s and simulations repeated 10 times.

IV. RESULT ANALYSIS

A. Link Availability Ratio

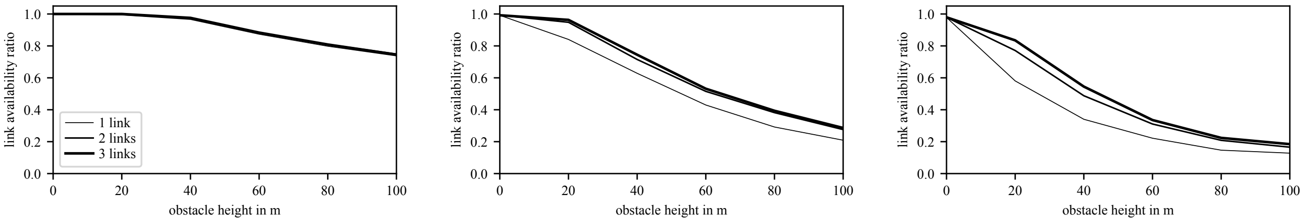
Figure 2 shows the simulation results for the link availability analysis. For the IHO mechanism (Figure 2a), the high reactivity to beacon loss ensures robust communication even for $N = 1$, leaving marginal room for gains via spatial diversity. Indeed, for building heights below 80 m, the gain from $N = 2$ is approximately 1 % though this might still mean an important reduction in communication gaps for mission-critical or teleoperation scenarios. However, $N = 3$ provides no tangible benefit due to limited visibility in dense urban settings.

The behavior is notably different for the FHO mechanism, where spatial diversity ($N > 1$) acts as a critical mitigation strategy against signal loss occurring between re-evaluation intervals. For FHO-30s, maintaining two simultaneous links ($N = 2$) increases the availability ratio by roughly 10 % for building heights of up to 60 m. These benefits are even more pronounced with the larger re-evaluation window of FHO-60s, where $N > 1$ leads to an improvement of up to 25 %.

B. Number of Handovers

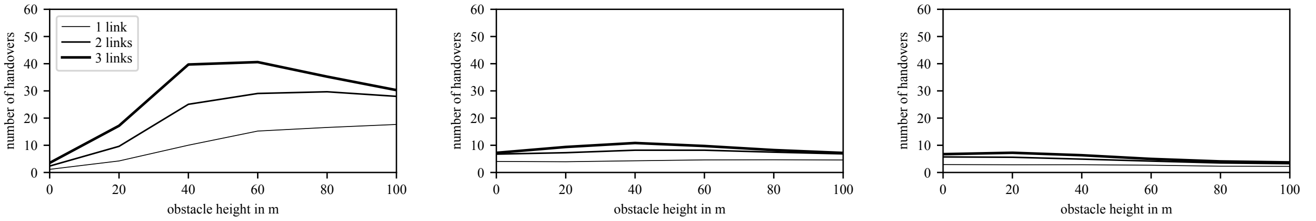
The second metric, illustrated in Figure 3, highlights the inherent cost of increased signaling and potential failure risks associated with multi-connectivity. For IHO (Figure 3a), the signaling cost of $N = 3$ is disproportionately high without offering justifiable performance gains over the $N = 1$ configuration.

A more favorable trade-off is observed for FHO, where HO opportunities are naturally constrained by t_w. With this mechanism, $N = 2$ emerges as the most efficient configuration, offering a substantial boost in connectivity for a moderate increase in handover signaling. For scenarios with reduced re-evaluation frequency (FHO-60s), even $N = 3$ becomes a viable trade-off, as its marginal signaling increase is offset by clear availability gains in low-to-medium obstruction scenarios.



(a) IHO (b) FHO-30s (c) FHO-60s

Figure 2. Link availability ratio versus obstacle height for different Handover (HO) strategies: Interrupted Stream Handover (IHO) and Fixed Interval Handover (FHO). The legend shown in subfigure (a) applies to all subfigures.



(a) IHO (b) FHO-30s (c) FHO-60s

Figure 3. Average number of Handovers (HOs) versus obstacle height for different HO strategies: Interrupted Stream Handover (IHO) and Fixed Interval Handover (FHO). The legend shown in subfigure (a) applies to all subfigures.

V. CONCLUSION

This paper investigated how multi-link redundancy can mitigate the shadowing effects of obstacle geometry in Vehicle-to-Satellite (V2S) communications. By evaluating three Handover (HO) strategies – the Interrupted Stream Handover (IHO) and the window-based Fixed Interval Handover (FHO) with 30 s and 60 s intervals – we quantified the trade-off between communication reliability and number of HOs. Our analysis leveraged an abstract channel model and a high-fidelity simulator modeling Low Earth Orbit (LEO) orbital dynamics, realistic vehicle mobility, and urban obstructions.

The results show that the effectiveness of multi-connectivity is sensitive to the underlying HO logic. Under the IHO strategy, the transition from a single link to dual links improves communication reliability by approximately 1 %. While this gain is relevant for mission-critical services, it incurs a significant cost, effectively doubling the required HOs. Conversely, for FHO strategies, multi-connectivity ensures a more substantial reliability boost. In the FHO-30s case, $N = 2$ provides the most efficient balance, yielding an absolute gain of 10 % in link availability with a moderate increase of the HOs. For the last strategy considered, FHO-60s, the $N = 3$ configuration emerged as the optimal choice, maximizing robustness against obstructions (with respect to $N = 1, 2$) with only a marginal increase in HOs relative to the $N = 2$ case.

In conclusion, while simultaneous links offer clear performance gains across all evaluated strategies, the magnitude of these gains and their associated signaling costs are intrinsically linked to the HO mechanism. Future work will expand this geometric analysis to include a realistic physical channel model and accounting for HO procedure penalties, such as temporary outages during link re-establishment, and real-world scenarios.

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REFERENCES

[1] X. Luo, H.-H. Chen, and Q. Guo, “LEO/VLEO Satellite Communications in 6G and Beyond Networks – Technologies, Applications, and Challenges,” *IEEE Network*, vol. 38, no. 5, pp. 273–285, Sep. 2024.

[2] M. Franke and C. Sommer, “Obstacle Shadowing in Vehicle-to-Satellite Communication: Impact of Location, Street Layout, Building Height, and LEO Satellite Constellation,” in *IEEE Vehicular Networking Conference (VNC)*, IEEE, May 2024, pp. 305–312.

[3] J. Zheng, T. H. Luan, J. Zhao, G. Li, Y. Zhang, J. Pan, and N. Cheng, “Adaptive Multi-Link Data Allocation for LEO Satellite Networks,” in *IEEE Global Communications Conference (GLOBECOM)*, IEEE, Dec. 2024, pp. 3021–3026.

[4] G. Avino, M. Franke, E. Pardo, C. Sommer, and I. Turcanu, “Impact of Geometry and Satellite Mobility on Handover Strategies for Remote Driving,” in *21st IEEE/IFIP Wireless On-demand Network systems and Services Conference (WONS 2026)*, Crans-Montana, Switzerland: IEEE, Mar. 2026.

[5] M. Franke and C. Sommer, “Toward Space-Air-Ground Integrated Network Simulation with 4D Topologies,” in *19th Wireless On-Demand Network Systems and Services Conference (WONS)*, IEEE, Jan. 2024, pp. 61–68.

[6] “Order and Authorization 22-91,” Federal Communications Commission (FCC), DA/FCC 22-91, Dec. 2022, pp. 1–74.

[7] 3rd Generation Partnership Project (3GPP), “NR; NR and NG-RAN Overall description; Stage-2 (Release 18),” TS 38.300, version 18.5.0, Apr. 2025.

[8] S. Zhang, S. Zhang, W. Yuan, and T. Q. S. Quek, “Rate-Splitting Multiple Access-Based Satellite–Vehicular Communication System: A Noncooperative Game Theoretical Approach,” *IEEE Open Journal of the Communications Society*, vol. 4, pp. 430–441, 2023.

[9] M. A. Massad, A. Y. Alma’aitah, and H. S. Hassanein, “Real-Time Handover in LEO Satellite Networks via Markov Chain-Guided Simulated Annealing,” *Network*, vol. 5, no. 4, p. 49, Nov. 2025.