

Design and Evaluation of Adaptive Handover Algorithm Based on Non-Line-of-Sight Detection for Low-Earth Orbit Satellite-Vehicle Communications

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Abstract—In recent years, the widespread adoption of connected vehicles has led to low-Earth orbit (LEO) satellite communications gaining increasing attention as a wide-area communication solution to complement terrestrial vehicular radio networks. However, frequent handover is required because LEO satellites move at high speeds, and conventional methods based on received signal strength can cause unnecessary handovers and communication interruptions because of blockage and power fluctuations in urban areas. Therefore, this paper proposes an adaptive handover algorithm that selects a target satellite based on satellite elevation angle information while monitoring visibility on the vehicle side and excluding blocked satellites from the candidate list. In addition, an integrated satellite-to-vehicle simulation environment at the granularity of a single vehicle is constructed for performance evaluation. Integrated simulation results indicate that, in a non-line-of-sight environment simulating building blockage in urban areas, the proposed method suppresses throughput degradation and communication interruption compared with the conventional method, improving communication stability.

Keywords—connected vehicles, elevation angle, handover, low-Earth orbit satellite communication, non-line-of-sight

I. INTRODUCTION

Recently, the demand for connected vehicles has increased in the automotive industry. A vehicle is connected to the cloud and expected to support a wide range of services such as in-vehicle infotainment using augmented reality and virtual reality (AR/VR), predictive emergency calls, and various driving assistance functions. Providing these services requires wide-area coverage and seamless communication connectivity regardless of the driving environment [1]. Currently, terrestrial cellular networks such as long-term evolution (LTE) and fifth generation (5G) are used for cloud connectivity in vehicles. However, guaranteeing complete connectivity is difficult because these networks are significantly affected by signal blockages in urban areas, and they suffer from coverage holes in mountainous areas and during disasters.

Therefore, satellite communication technology is considered a promising approach to achieve wide-area coverage without being constrained by terrestrial limitations. Conventionally, geostationary orbit satellites have been used for wide-area communications. However, they suffer from propagation delays of several hundred milliseconds or more,

which makes them unsuitable for applications requiring real-time communication [2]. In recent years, technological development has advanced toward the practical implementation of low-latency communications using low-Earth orbit (LEO) satellites, which orbit at relatively low altitudes such as ~550 km [3, 4].

Several technical challenges remain in communications between LEO satellites and connected vehicles. LEO satellites move at high speeds relative to the surface of the Earth, and therefore, the communication time between a single satellite and a vehicle, or that between a single satellite and mission control center (MCC), which serves as a ground station connected to the Internet, is extremely short, on the order of several minutes. Therefore, operations based on satellite constellations are essential. Wireless links can experience successive degradation because of blockage based on the driving environment, and this degradation becomes significant in dense urban areas with many buildings. Designing handover (HO) that appropriately switches the serving satellites is important to maintain stable communication and preserve communication quality under such conditions. In conventional mobile communications over terrestrial cellular networks, HO control is performed based on the received signal strength. In contrast, in LEO satellite communications, the received power fluctuates significantly because of blockage effects and changes in propagation distance. Therefore, applying received-signal-strength-based HO control can result in frequent unnecessary HOs [5].

The effectiveness of HO control based on geometric metrics such as elevation angle and distance, which is a conventional LEO satellite HO technique, has been reported [6, 7]. However, studies explicitly incorporating non-line-of-sight (NLOS) conditions caused by building blockages and other obstructions into HO decision making remain limited. Thus far, several methods for determining the NLOS state of satellites have been proposed, including methods that apply machine learning to features extracted from global navigation satellite system (GNSS) observations [8], methods using in-vehicle light detection and ranging (LiDAR) to measure surrounding obstacles based on laser reflection [9], and methods that match three-dimensional (3D) maps with GNSS observations [10]. However, their application to HO control

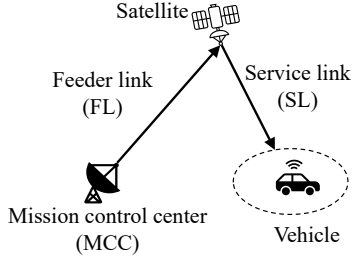


Fig. 1. System model.

in satellite communications has not been sufficiently investigated.

In this study, we propose an HO algorithm that considers blockage environments in urban areas and selects the serving satellite using satellite elevation angle information. The proposed method can achieve more stable control using geometric relationships without relying on received signal strength, which fluctuates significantly.

Previous studies [11, 12] conducted orbital analyses of satellite constellations and individual evaluations of communication link performance. However, simulation environments that simultaneously consider multiple LEO satellites with spatially dynamic behavior and moving vehicles and comprehensively evaluate communication performance remain limited. Therefore, in this study, we newly construct a simulation environment at the granularity of a single vehicle using open-source simulators for the integrated evaluation of vehicle–satellite communications. In this simulation environment, an NLOS condition is introduced during a specified time, and throughput performance is evaluated using a simplified scenario in which building blockage in an urban area is applied in a controllable manner. Through this evaluation, we clarify the effect of the proposed HO design on communication quality.

The remainder of this paper is organized as follows: Sections II and III describe the system model and proposed HO method, respectively, whereas Section IV introduces the integrated simulation environment. Section V presents the numerical results, and Section VI provides a summary.

II. SYSTEM MODEL

A. Network Architecture

Fig. 1 illustrates the system model. In this study, we assume a bent-pipe satellite communication architecture defined in the 3GPP non-terrestrial network (NTN) standardization [4]. In this architecture, the LEO satellite functions only as a relay, whereas HO control is centrally performed on the MCC side, which has control functions corresponding to those of a 5G base station.

B. Satellite Orbit Calculation Method

The orbital information of satellites in the LEO satellite constellation such as satellite position and velocity is calculated by inputting two-line element (TLE) data [13] into the simplified general perturbations satellite orbit model 4, which is a mathematical orbit propagation model. The TLE is a data format used for representing satellite orbits, wherein mean orbital elements such as orbital inclination and eccentricity are described in a two-line format. In this study, we use orbital information based on the Starlink constellation

TABLE I. CLUTTER LOSS AND SHADOWING IN THE DENSE URBAN MODEL (KA-BAND)

Elevation angle (deg)	LOS	NLOS	
	σ_b (dB)	σ_b (dB)	C_l (dB)
10	2.9	17.1	44.3
20	2.4	17.1	39.9
30	2.7	15.6	37.5
40	2.4	14.6	35.8
50	2.4	14.2	34.6
60	2.7	12.6	33.8
70	2.6	12.1	33.3
80	2.8	12.3	33.0
90	0.6	12.3	32.9

TABLE II. PROPAGATION LOSS PARAMETERS

Parameter	Value
Shadowing L_b	$\mathcal{N}(0, \sigma_b^2)$
σ_b	2.7 dB
Scintillation L_s	$\mathcal{N}(0, \sigma_s^2)$
σ_s	0.6 dB
Atmosphere absorption L_a	0.6 dB

from publicly available TLE data to emulate realistic coverage characteristics.

C. Scenario Model

As shown in Fig. 1, we focus on the forward link in which data are transmitted from the MCC on the backhaul side to a satellite via the feeder link (FL), and then, they are received by moving vehicles through service links (SL). The MCC and vehicle are assumed to be located at the latitude and longitude of Fukuoka City and Yokohama City, respectively.

D. Forward Link Propagation Model

In wireless communications, communication quality is determined by the overall link budget, which includes the transmit power, antenna gain, and various losses in the propagation channel. However, in LEO satellite communications, the transmit power is often evaluated in terms of the effective isotropic radiated power (EIRP). When the EIRP is denoted by P_e dBW and the receive antenna gain is denoted by G_r dBi, the received power P_r dBW is expressed as

$$P_r = P_e + G_r - L, \quad (1)$$

where L represents the total loss that occurs only in the propagation channel, including free-space path loss and fading.

$$L = L_f + L_b + L_s + L_a + L_N, \quad (2)$$

where L_f , L_b , L_s , L_a , and L_N represent the free-space path loss, shadowing, tropospheric scintillation, atmospheric absorption loss, and additional loss caused by NLOS conditions, respectively. This study sets $L_N = 30$ dB as an additional loss value that is close to real-world environments because 3GPP showed that clutter loss caused by building blockages can reach ~ 30 dB.

L_f is expressed as

$$L_f = 20 \log_{10}(f_c) + 20 \log_{10}(d) + 92.45, \quad (3)$$

where d and f_c represent the propagation distance (km) and center frequency (GHz), respectively [3]. In long-distance propagation such as satellite communication, this term becomes dominant.

L_b represents the fluctuations in received power caused by blockage and is modeled as a normal distribution with zero mean and standard deviation σ_b . Average additional loss caused by blockage is referred to as clutter loss, and its value depends on the surrounding environment of the vehicle,

elevation angle, and frequency band. Although [3] does not provide values for the Ku-band assumed in this study (i.e., 12–18 GHz), the blockage loss increases with increasing frequency. Therefore, we use the clutter loss C_L and standard deviation of shadowing σ_b for the dense urban model in the Ka-band (26.5–40 GHz) to avoid underestimating the effect of blockage, as listed in Table I [3].

For σ_b , we adopt 2.7 dB at an elevation angle of 60° as a representative value for high-elevation conditions among the elevation-dependent clutter loss characteristics shown in Table I. The large attenuation under NLOS conditions is modeled by adding L_N to this baseline L_b .

Finally, L_s represents fluctuations caused by variations in the refractive index of the atmosphere, which have become significant in frequency bands above 10 GHz. In addition, L_a represents the loss caused by radiowave absorption by atmospheric gases. These values are listed in Table II [3].

III. PROPOSED HANDOVER ALGORITHM

A. Definition of Handover

In LEO satellite communications, HO control based on received signal strength is susceptible to large instantaneous fluctuations in the received signal. These fluctuations are caused by blockages, Doppler shift attributed to the high-speed movement of satellites, and instantaneous signal degradation caused by urban obstructions. Consequently, the ping-pong phenomenon is likely to occur, wherein the serving satellite is switched frequently. To prevent these issues, time-to-trigger and hysteresis are commonly introduced [14]. However, these mechanisms may increase propagation delay and adversely affect communication quality.

In recent years, several HO control criteria besides the received signal strength have been proposed such as the minimum communication load, minimum propagation delay, and maximum visibility time criteria [15]. Based on these criteria, HO control based on the elevation angle and NLOS conditions is employed in the proposed method. LEO satellites follow orbits that are close to circular motion, and therefore, the elevation angle has a monotonic relationship with propagation delay. In addition, 3GPP has shown that the LOS probability depends on the elevation angle [3].

We define the method that selects the satellite with the maximum elevation angle as the serving satellite as the elevation-based HO (EHO), and we position it as the baseline method. The method that aims to stabilize the throughput by excluding satellites in NLOS conditions from the candidate serving satellites in the EHO is referred to as the proposed HO (PHO).

B. Proposed Handover Algorithm

In EHO, the candidate satellite with the maximum elevation angle is selected as the serving satellite. Therefore, HO control can be performed with a relatively small number of processing steps using vehicle position information obtained from GNSS and satellite orbital information. However, as indicated in Table I, clutter loss caused by building blockage can reach ~ 30 dB. Therefore, communication quality can degrade or be interrupted when EHO is applied for connected vehicles.

To address this issue, in PHO, the vehicle side monitors the LOS/NLOS states of candidate satellites and excludes

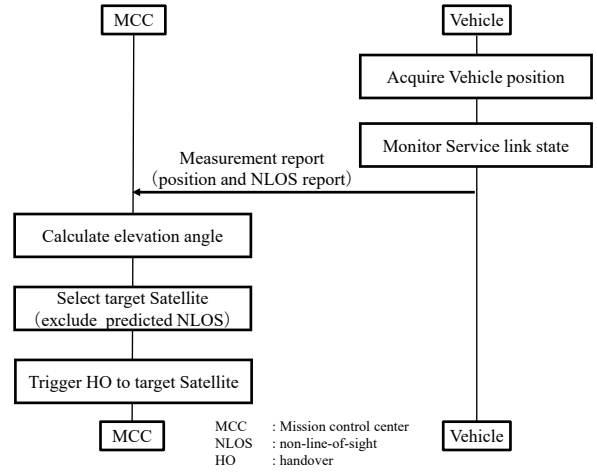


Fig. 2. Flowchart of the proposed handover algorithm.

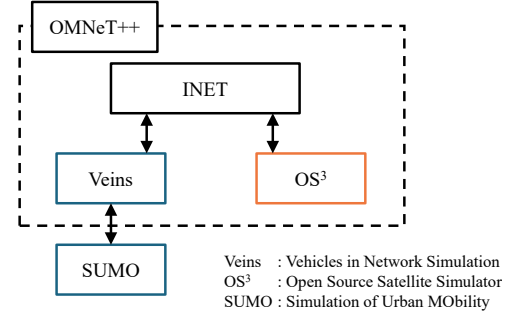


Fig. 3. Module configuration of the simulation environment.

satellites determined to be in NLOS conditions from the candidate set. The processing flow is illustrated in Fig. 2. The vehicle obtains its current position information using GNSS and sends measurement data to the MCC, together with the LOS/NLOS state of the monitored SL. The MCC calculates the elevation angle to each satellite based on the received vehicle information and satellite orbital information.

Subsequently, satellites determined to be in the NLOS condition are excluded from the list of candidate satellites, and the satellite with the maximum elevation angle is selected. If the target satellite needs to be changed, communication is switched to the selected satellite.

However, if all candidate satellites are under NLOS conditions, an exception process is applied in which HO is performed based only on the elevation angle. Although NLOS determination can be performed using methods such as those reported in [8]–[10], this study assumes perfect NLOS detection for simplicity. As described in these studies, approaches such as those using LiDAR or 3D building maps are practically feasible. Because 3D building maps also enable the prediction of NLOS, we plan to explore its integration with predictive PHO in future.

IV. INTEGRATED SIMULATION ENVIRONMENT

In this study, we adopt OMNeT++, which is an open-source framework that features a hierarchical module design, high compatibility with external frameworks, and is widely used as a simulation environment for vehicular communication. To evaluate vehicular and satellite

TABLE III. SATELLITE ORBITAL PARAMETERS

Parameter	Value
Orbit altitude	550 km
Orbital inclination angle	53.2 deg
Orbital period	95.4 min
Eccentricity	0.00021

TABLE IV. SIMULATION PARAMETERS

Wireless link	Feeder link	Service link
Frequency (GHz)	28.5	10.825
Bandwidth (MHz)	500	250
EIRP (dBW)	89.5	45.8
Modulation	256QAM	16QAM
Number of satellites	2	
Number of MCC	1	
Number of vehicles	1	
NLOS period	60–75 s	
Extra loss in NLOS (SL, satellite[0])	30 dB	
Simulation time	100 s	
Traffic model	UDPBasicApp	
Send interval	1 ms	

communications in an integrated manner, we construct an integrated simulation environment based on the module configuration shown in Fig. 3, which is based on [11], and we evaluate communication performance. For terrestrial communications, multiple vehicles are deployed on a map by integrating OMNeT++ and the simulation of urban mobility (SUMO) through vehicles in network simulation (Veins), and wireless transmission simulations are performed at each time step.

OMNeT++ is a discrete-event simulation platform based on the C++ language [16], and the INET framework is used for implementing network functions [17]. INET provides physical-layer models, which includes wireless communication models, communication protocol stacks, and application models. SUMO is a simulator that models traffic flows including vehicle movement and traffic patterns [18].

The Veins framework is used to conduct vehicular network simulations based on OMNeT++ and SUMO [19]. For satellite communications, we use an open-source satellite simulator (OS3), which models satellite constellation configurations, satellite behavior, and TLE data [20]. We realize an integrated simulation of terrestrial and satellite communications by combining these open-source frameworks.

V. SIMULATION RESULTS

A. Configuration of Satellite Orbital Parameters

Table III lists the orbital parameters of the satellite. We use a satellite orbit at an altitude of ~550 km based on TLE data for Starlink. The orbit can be assumed to be nearly circular because the eccentricity of this orbit is very small. Orbital inclination is a parameter that defines the latitude range reached by the satellite, with 0° corresponding to the case where the satellite orbital plane coincides with the equatorial plane. An orbital inclination of 53.2° is an important parameter determining satellite visibility in mid-latitude regions, including Japan [21].

B. Wireless link and Traffic Conditions

The simulation parameters are presented in Table IV. The frequency band and modulation scheme are set separately for each link because the communication environments of FL and SL are different. The SL parameters are configured

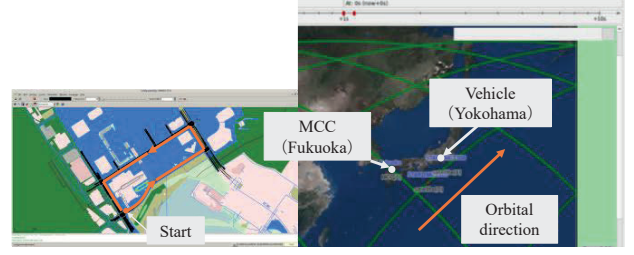


Fig. 4. Snapshot of the integrated simulation screen: SUMO on left and OMNeT++ on right.

considering blockage effects and the use of an in-vehicle antenna. In this study, NLOS conditions are modeled by applying a fixed additional loss to the SL during a specific period; this is intended to clarify the causal relationship between HO algorithms and their performance characteristics. In practice, NLOS conditions are uncontrollable parameters, and detection methods such as those described in Section III-B are required.

In addition, calibration is performed based on the consistency between the time variation of the satellite elevation angles and timing of HO occurrences to confirm that the above parameters and blockage model are reflected in the simulation as intended. We confirm that the time at which the relative order of the elevation angles reverses coincides with the HO timing in the EHO, and that the satellite selection behavior changes appropriately when NLOS loss is applied.

C. Evaluation Results

Simulation comparisons were conducted between EHO and PHO, wherein the vehicle detects NLOS conditions. The time period from 60–75 s is set as the NLOS period to emulate a blockage in an urban environment. The additional loss is set to $L_N = 30$ dB. A snapshot of the simulation screen is shown in Fig. 4. The vehicle route in the urban area of Yokohama is visualized on the left side of the figure, whereas the OMNeT++ screen on the right side shows the positional relationship between the MCC, vehicle, and satellite orbits.

Fig. 5 shows the time variation of the satellite elevation angles and transition of connected satellites selected by each HO method. The dotted lines show the elevation-angle characteristics of the two satellites, which confirms that HO occurs at ~47 s, where the relationship between the two elevation angles is reversed. EHO maintains the connection to the satellite[0] even after 60 s because it uses only the

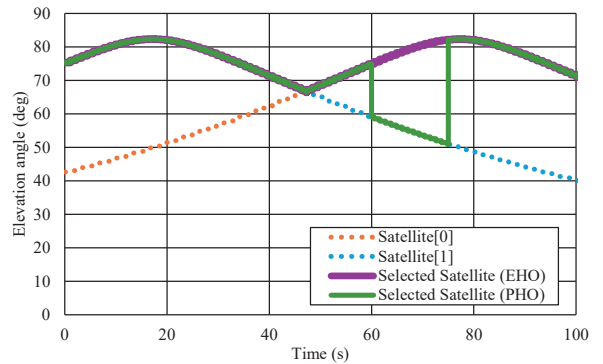


Fig. 5. Time variation in elevation angles of each satellite and selected serving satellite.

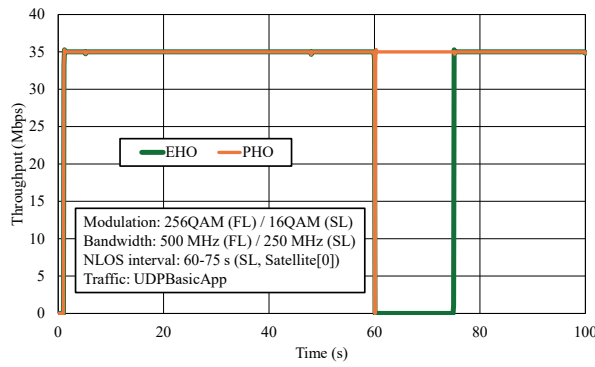


Fig. 6. Forward link throughput characteristics for each HO method.

TABLE V. TOTAL RECEIVED DATA VOLUME FOR EACH HO METHOD

HO method	Total received data (Gbit)
EHO	2.940
PHO	3.461

elevation angle as the HO criterion when the NLOS period starts. In contrast, PHO switches to a satellite[1], which is in the LOS condition when NLOS occurs. These results indicate that the elevation-angle transition based on the satellite orbit model and HO decision logic operates as intended.

Fig. 6 shows the time variation of the forward link throughput on the vehicle side. In EHO, the throughput becomes almost zero during the blockage period with $L_N = 30$ dB. This results in communication interruption, which can be attributed to the link margin becoming insufficient because of the additional loss, and the received signal-to-interference-plus-noise ratio (SINR) falling below the threshold of 4 dB set in this simulation. Therefore, communication interruptions may occur in urban environments where direct waves are likely to be blocked by buildings. In this simulation, the throughput is evaluated as the application-layer received throughput under constant-bit-rate UDP traffic. Therefore, when the received SINR is above the threshold, the throughput is limited by the offered traffic load of approximately 35 Mbps.

However, in PHO, the vehicle monitors the LOS/NLOS condition and excludes satellites evaluated to be NLOS from the connection candidates. Consequently, the connection is immediately switched to an LOS satellite when NLOS occurs. This confirms that the sudden drop in throughput is suppressed even under severe blockage conditions. As shown in Table V, the total received data of the PHO increases by ~17.7% compared to that of the EHO. Therefore, the proposed algorithm stabilizes the received throughput.

VI. CONCLUSION

This paper proposed an adaptive HO algorithm considering urban blockage environments for LEO satellite-to-vehicle communications. In addition, an integrated simulation environment that handles both LEO satellites and moving vehicles at the granularity of a single vehicle was constructed to evaluate the proposed method. The evaluation results confirmed that PHO suppressed communication interruption and stabilized the received throughput compared to that with EHO.

Future work will include introducing actual building models to conduct simulation evaluations under more realistic environments and evaluating the impact of imperfect NLOS prediction and detection, including detection errors and detection latency, on PHO.

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