

Article

Jamming Analysis of a Full-Duplex UAV-Driven C-V2X Platform Employing Millimeter Waveband Communication: A Stochastic Approach

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Abstract

Jamming introduces unintentional disruptions in the system to exploit the legitimate communicating equipment. Clustered jamming considers jammers that are present in multiple groups to disrupt the intended communication. Vehicle-to-everything (V2X) transmissions are critical for smart transportation. This research considers full-duplex environment, featuring unmanned aerial vehicles (UAVs) and cellular-base-station-aided V2X (C-V2X) systems exploiting clustered jamming using 3-dimensional (3-D) beam-forming millimeter-wave antennas. UAVs are modeled as a 3-D Poisson point process (PPP), and macro-based tower-mounted base-stations (MBSs) are modeled as a 2-D PPP. Roads are modeled as a Poisson line process. The vehicular nodes (V-Ns) are modeled on each road as a 1-D PPP. The deviations of the UAV's millimeter-wave band antenna beam follow a Normal distribution. In this paper, for a full-duplex setting, the probabilities of coverage and equipment-association, along with the efficiency of the spectrum associated with various UAV and tower-based connections, are explored in the presence of clustered jamming. The probability of coverage and association of multiple links is derived with respect to the jamming clusters, V-Ns, MBSs, UAVs, jammers' power, and antenna beams. The results demonstrated that jamming degrades system's efficiency. This efficiency is further degraded whenever higher 3-D beam-width deviations of the millimeter waveband antenna and jammers are present. Therefore, robust counter-scenarios should be designed for the cases where jamming signals and varying beams disrupt the network.

Keywords: jamming; Poisson line process; V2X systems; UAV networks; Poisson point process; full-duplex systems

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1. Introduction

Jamming is the technique of introducing random signals into wireless communication systems in order to undermine connectivity between legitimate users. Clustered jamming considers jammers that are present in multiple groups to disrupt the intended communication components. The severity of jamming is determined conventionally by the strength

or quantity of the disrupting equipment as well as by its distribution. Clustering utilizes the clustered distribution of the equipment [1]. Traditionally clustered jamming involves numerous clusters, with their placement outlined via the Matern cluster process (MCP) consisting parents (hubs) and nodes that are children (jammers) [2,3]. The jammers spread themselves uniformly throughout a disc-shaped cluster. Jamming clusters, as well as jammers inside the clusters, follow a Poisson-based distribution.

Jammers disrupt vehicle-to-everything (V2X) connectivity in regard to the vehicle's spectral efficiency (SE), energy efficiency and coverage [3–5]. Vehicular links are essential for intelligent transportation systems, which is why it has garnered substantial attention from businesses and academics in the past few decades [6]. V2X systems define numerous wireless connections exploiting vehicle-to-vehicle (V2V) connections, vehicle-to-road-side unit (RSU) connections, vehicle-to-tower-based connections, and vehicle-to-unmanned aerial vehicles (UAVs) connections [7]. Cellular-V2X (C-V2X) connectivity for beyond 5G and 6G aims to improve road safety and vehicle connectivity by using two main radio interfaces [8,9]. These interfaces include the PC5-based channel for V2V transmission and the LTE-Uu interface, which uses wireless transmission for UAVs or terrestrial base-stations for network-based V2X communication. By tampering wirelessly, interception efforts by jammers can significantly affect such crucial communications, increasing the risk of accidents, prolonging delays or missing messages, and decreasing the efficiency of automotive systems. In UAV-driven C-V2X platforms, examining the effects of jamming is therefore crucial.

To comply with the stringent criteria of autonomous vehicles, millimeter-wave connectivity is important for UAV-driven V2X communications. While utilizing the millimeter-wave spectrum, beam orientation is essential to avoiding delayed transmissions and preserving operational continuity. Tracing the beam-width involves the ongoing tracking of a moving user device [10]. As a result, recognizing the vehicle's beam moving at different speeds is more difficult than identifying stationary devices. Tracing the three-dimensional (3-D) antenna beam variations (because of atmospheric pressure, wind, or noise generated by controlling gears) is a challenging task. The tracking of the beam orientation gets more critical when jamming is present, and it significantly weakens the networks' efficiency. Consequently, it has become vital to determine the changes or fluctuations in the UAVs' 3-D wireless beam, particularly in the case of clustered jammers for the UAV-driven C-V2X transmissions.

In a half-duplex C-V2X communication [11], the up-link associated with a V-N can support transmission of information to MBSs using V2M connections, line-of-sight (LOS) low-altitude platforms (LAPs) using V2L connections, and non-line-of-sight (NLOS) LAPs using V2N connections, all using different frequency bands. Additionally, the downlink from MBS, LOS, and NLOS-LAP to V-N works over different frequency bands. The V-N's access is based on sharing spectrum with MBSs, LOS-LAPs, and NLOS-LAPs via the Uu connection. Direct transfer, on the other hand, allows the transmitting typical V-Ns as well as the receiving V-Ns to communicate across a side-link framework [12]. Jamming can have a major influence on the effective operation of links in UAV-assisted C-V2X systems, whether operated over the shared or direct platforms. Hence, it is critical to analyze the jamming in UAV-driven C-V2X platforms to evaluate the reliability of vehicular transmissions.

A framework of C-V2X full-duplex network has been investigated in the research in [13,14] using stochastic geometry, where simultaneous communication between MBSs and vehicular nodes (V-Ns) enhances spectral efficiency. However, this improvement comes at the cost of residual self-interference, which negatively impacts network coverage. Notably, the above-mentioned research does not account for the integration of UAV-assisted V2X networks,

which have the potential to further enhance vehicular communication by leveraging UAVs and cellular base-stations. Moreover, jammers in a system considering fluctuating beams, further degrade communication reliability and network performance. Therefore, it is essential to conduct a comprehensive performance evaluation of a full-duplex UAV-driven C-V2X platform while considering the impact of jamming and varying 3-D beams.

1.1. Related Work

Jammers reduce the accuracy of UAV-assisted infrastructure with respect to user outage. Haroon et al. in [15] implemented a UAV-driven system to optimize the outage efficacy of the typical user-equipment. The work used stochastic analysis to describe the base-stations and treated the MBS positions as a 2-D Poisson point process (PPP), while unmanned platforms are treated as a 3-D PPP. The research work additionally looked at the influence of airborne jamming devices on link reliability and determined that airborne jamming interference degrades system functionality with regard to the typical user's coverage. Furthermore, the user's coverage by considering jammers and cellular stations as a 2-D PPP was analyzed in [16] where the equipment's jamming activity prompted a decrease in clients' coverage. However, the research has not considered C-V2X systems exploiting clustered jamming. The above-mentioned works rely on a simple 2-D PPP for jammer placement rather than a clustered distribution and do not consider vehicular link structures or the combined effect of UAV assistance and jamming on C-V2X performance.

Dhillon et al. in [17,18] evaluated vehicle systems through employing V-Ns as a Poisson line process (PLP). The process assumes that highways possess a population intensity of λ_R and the V-Ns positioned next to highways comprise a 1-D PPP with a population intensity of λ_V . The authors derived the efficiency of a V-N connection with reference to the system outage. Similarly, [5] represented a C-V2X vehicular network with roads and V-Ns as a Cox process employing a PLP. The work modeled the MBSs as a 2-D PPP and vehicular equipment as a 1-D PPP. The authors evaluated the V-Ns' performance in terms of user load per node. However, the aforementioned studies fail to take into account the combination of UAVs in V2X systems in order to maximize the potential advantages of UAVs in automobiles. The above works do not consider UAV-assisted communication in V2X systems and therefore cannot capture the performance implications of airborne base-stations in vehicular networks.

Peng et al. in [19] presented UAVs and MBSs as a PPP, providing a stochastic analysis for examining the system's coverage efficiency. Additionally, the mathematical equations of coverage for a conventional vehicle linked to MBS (V2M link), LOS UAV (V2L link), or NLOS UAV (V2N link) are obtained. Xu et al. in [20,21] worked on vehicular edge networks by considering digital twin and blockchain technology and analyzed the security aspects of the network. The authors also analyzed task offloading, communication bandwidth, computing frequency, task deadline and heterogeneous task scheduling. However, the impact of clustered jamming in V2X network is not evaluated. Dabiri et al. in [22] investigated UAV-driven systems by exploiting millimeter-waves. The authors focused on the coverage of a conventional user device linked to UAVs in [23,24]. The authors used a stochastic technique to assess changes in beam-width orientations due to controlling motors' built-in mechanical noise, air pressures, or high wind speeds. The investigation revealed that increasing changes in the beam-width reduce the efficiency of networks. Consequently, it is vital to describe the 3-D beam-width fluctuations in a UAV-assisted system. However, the aforementioned studies did not take into account the advantages of combining UAVs with V2X systems. However, the aforementioned studies do not extend their analysis to V2X systems and therefore do

not address the interaction between UAV beam-width fluctuations and vehicular link performance under jamming conditions.

Khabbaz et al. in [25] presented a stochastic approach for investigating UAV-assisted C-V2X systems. The authors considered a half-duplex environment for vehicular communications by exploiting only LOS UAV links. The research focuses on the investigation of the transmission of information delay for UAV-assisted C-V2X systems. However, the research is limited to LOS UAV links, and NLOS links are not considered. Furthermore, the research does not exploit multiple roads in a full-duplex paradigm where roads are distributed using a PLP. The analysis is limited to a half-duplex setting with LOS UAV links only, and does not consider NLOS links, clustered jamming, or the impact of millimeter-wave antenna beam-width variations on vehicular network performance.

In [13,16], a stochastic approach is taken into account when analyzing a full-duplex setting for C-V2X networks. The research treated BSs according to a 2-D PPP, highways according to a PLP, and V-Ns distributed around highways according to a 1-D PPP. The researchers proposed coverage and rate expressions for V-N connections. The model still fails to take into account the impact of clustered jammers for a full-duplex scenario involving LOS UAVs (for V2L connections), NLOS UAVs (for V2N connections), MBSs (for V2M connections), and V-Ns (for V2V connections). Likewise, the model did not take into account the influence of fluctuations of the millimeter-wave antenna. Moreover, these works do not integrate UAVs into the full-duplex C-V2X framework, do not model clustered jamming, and do not examine 3-D millimeter beam-width fluctuations, leaving a significant gap in understanding full-duplex UAV-driven C-V2X performance under realistic adversarial and propagation conditions.

1.2. Motivation and Objectives

Several limitations in the existing literature collectively motivate this work. Research studies such as [4,5,11,12] investigate half-duplex C-V2X systems without UAV integration or jamming and hence cannot capture the performance implications of full-duplex operation or adversarial interference on vehicular networks. Refs. [15,16] consider jammers in UAV-enabled cellular networks but rely on a simple 2-D PPP for jammer placement, ignoring clustered jamming distributions and vehicular links. Refs. [25–27] incorporate UAVs in C-V2X systems but are limited to half-duplex operation, and either exclude jamming or consider only LOS UAV links, leaving NLOS propagation unaddressed. Refs. [13,14] analyze full-duplex C-V2X systems but do not integrate UAVs, do not model clustered jamming, and do not examine the effect of millimeter-wave antenna beam-width variations. Previously, no work jointly analyzed full-duplex operation, UAV assistance with both LOS and NLOS links, clustered jamming via the MCP, and 3-D millimeter-wave beam fluctuations in a unified stochastic geometry framework for C-V2X networks, and this paper addresses this gap directly.

To address this research gap and improve the reliability of the vehicle communication networks, a full-duplex design that takes advantage of the UAVs and cellular-BSs for V2X communications by exploiting clustered jammers and beam-width variations needs to be investigated. To achieve this objective, a UAV-driven architecture with C-V2X full-duplex system exploiting clustered jammers and beam-width variations is proposed. The contributions of the manuscript are as follows:

- Modeling clustered jamming in a UAV-driven C-V2X full-duplex platform by exploiting millimeter-wave varying 3-D beams.
- Analyzing the association of vehicular link probability, coverage of the vehicular equipment probability, and spectrum of the vehicular equipment in a full-duplex environment that is disrupted by clustered jamming and beam-variations.

- Deriving analytical expressions for probabilities of vehicular links' association and coverage of the vehicular links as a function of clustered jammers and varying antenna 3-D beam-width.
- The outcomes depicted higher coverage and SE of C-V2X full-duplex platform driven by UAVs relative to a half-duplex platform, but the efficiency of the system degrades by increasing clustered jammers and antenna beam variations in the system.

This work is different than the state-of-the-art works as follows:

- In [13,14], full-duplex C-V2X systems without UAVs is investigated. However, this paper differs in three ways. First, UAVs are integrated as a 3-D PPP, introducing LOS and NLOS UAV links, requiring the V-N to select among four competing link types rather than two. Second, clustered jamming modeled via the MCP introduces spatially correlated interference requiring a fundamentally different Laplace transform analysis as derived in Section 5.5 and Appendix B, which is absent in [13,14]. Third, 3-D beam-width deviations of UAV millimeter-wave antennas are modeled using a Normal distribution, capturing the impact of wind, atmospheric pressure, and mechanical motor noise, introducing a beam-width dependent LOS probability and antenna gain into the coverage and SE expressions, which are not considered in [13,14].
- In [22,23,28], beam-width variations in UAV-assisted cellular networks are investigated. However, this paper differs in three aspects. First, 3-D beam-width deviations are modeled within a C-V2X framework where the V-N selects among V2V, V2M, V2L, and V2N links, and beam-width deviation selectively degrades only UAV-assisted links. Second, the combined effect of beam-width variations and clustered jamming is jointly analyzed, showing that their combined impact on V2L and V2N links is more severe than either impairment in isolation. Third, the analysis is extended to a full-duplex setting where RSI compounds with beam misalignment and clustered jamming, which is not considered in the aforementioned works.

The remaining manuscript is outlined in the following. Section 2 addresses how to configure the network's design for C-V2X full-duplex systems driven by UAVs. Section 3 provides distance distributions for LOS unmanned stations, NLOS unmanned stations, cellular stations, and vehicular stations, while Section 4 provides the likelihood of V-N connection. Section 5 discusses the interference characterization for V-Ns, MBS, LOS UAVs, and NLOS UAVs. Section 6 provides the statistical approach for evaluating performance metrics. Section 7 presents the main outcomes of the research, and Section 8 presents the conclusion.

Table 1 shows current research works, frameworks for vehicular systems, major conclusions, and the limitations of the study and Table 2 shows the nomenclature used in the manuscript.

Table 1. Recent works and their deficiencies.

Research	Framework Architecture	Outcomes	Deficiencies
[4,5], 2018–2020	C-V2X system.	Investigation of user load and V-N distance distributions. The deduction of analytical formulas for the connection.	Analysis of UAV-driven C-V2X System.
[12], 2016	C-V2X system.	The deduction of connection and coverage probability for the V-N.	Analysis of a full-duplex UAV-driven C-V2X system.

Table 1. Cont.

Research	Framework Architecture	Outcomes	Deficiencies
[11], 2019	C-V2X system.	The deduction of V-N's association probability, coverage probability, and rate. Analytical expressions for the V-N connection.	Full-duplex UAV-driven C-V2X analysis.
[1], 2024	C-V2X system considering jammers.	Deduction of coverage and SE expressions for C-V2X system.	UAV-driven C-V2X analysis.
[29], 2022	UAV-driven C-V2X employing meta-surfaces.	Deduction of data-rate and bit-error-rate for multiple applications.	Analysis of the clustered jammers in UAV-driven C-V2X full-duplex system.
[22,28,30], 2022–2023	UAV-driven cellular framework.	Analysis of beam variations.	UAV-driven C-V2X analysis.
[10], 2022	UAV-driven V2X network.	Assessing imperfections by monitoring the antenna beam of a V-N employing millimeter-waves.	UAV-assisted C-V2X analysis.
[25], 2019	UAV-driven C-V2X network.	Investigating delay for V-N connection	Analysis of a full-duplex UAV-driven C-V2X system employing highways as a Cox process.
[19], 2022	UAV-driven cellular network.	Coverage of various links.	UAV-driven C-V2X analysis.
[26], 2023	UAV-driven C-V2X network with millimeter-waves.	Spectrum analysis.	Analysis of the jamming in a full-duplex UAV-driven C-V2X system employing millimeter-wave communications considering 3-D beam-width variations.
[27], 2023	UAV-driven C-V2X half-duplex system.	Investigated network spectrum.	Analysis of jammers in a full-duplex UAV-driven C-V2X system.
[13,14], 2024	C-V2X-based full-duplex system.	Computation of full-duplex platform's coverage and rate in the C-V2X environment.	Analysis of clustered jammers in UAV-driven C-V2X full-duplex system enabled by millimeter-wave antenna considering 3-D beam-width variations.
This work	Clustered jamming in UAV-driven C-V2X full-duplex system.	Investigated association, coverage, and bandwidth efficiency of the links for a full-duplex network by considering clustered jamming and varying 3-D beams. Derived association and coverage expressions by exploiting jamming in a full-duplex scenario.	–

Table 2. List of key parameters and symbols.

Symbol	Definition
λ_R	Density of roads (km^{-2})
λ_V	Density of (V-Ns) (km^{-1})
λ_M	Density of macro base-stations (km^{-2})
λ_U	Density of UAVs (km^{-2})
λ_J	Clustered jammer density per system (km^{-2})
r_J	Radius of jamming cluster (m)
P_J	Jammer transmit power (dBm)
J	Number of jammers per cluster
α_J	Path-loss exponent of jammers
P_V, P_M, P_U	Transmit power of V-Ns, MBSs, UAVs
α_V, α_M	Path-loss exponents of V-Ns and MBSs
α_L, α_N	Path-loss exponents of LOS and NLOS UAVs

Table 2. Cont.

Symbol	Definition
$\mathcal{L}_M, \mathcal{L}_L, \mathcal{L}_N$	Extra attenuation for MBS, LOS, NLOS links
g_V, g_M, g_L, g_N	Small-scale fading coefficients
m_L, m_N	Nakagami- m fading parameters
H_U	UAV deployment altitude (m)
σ_x, σ_y	Beam-width deviation standard deviations
σ	Overall beam-width deviation (°)
$\mathcal{L}$	Bias factor ($0 \leq \mathcal{L} \leq 1$)
C_N	RSI magnitude after interference cancellation (dB)
p_N^{RSI}	Residual self-interference power
τ	SIR threshold
p_L, p_N	LOS and NLOS UAV link probabilities
A_V, A_M, A_L, A_N	Association probabilities for V2V, V2M, V2L, V2N
C_J^{FD}	Full-duplex coverage probability with jammers
SE_J^{FD}	Full-duplex spectral efficiency with jammers
I_J	Aggregate jamming interference
I_V, I_M, I_L, I_N	Interference from V-Ns, MBSs, LOS UAVs, NLOS UAVs
Y_S	Overall antenna gain
f_c	Carrier frequency (GHz)
W	Bandwidth (MHz)

2. System Model

Consider a UAV-driven C-V2X system operating in a full-duplex environment exploiting clustered jammers and millimeter-wave antenna 3-D beam-width, as shown in Figure 1. The clustered jammers are modeled according to an MCP. The parents or cluster-centers are distributed in a 2-D space and are given by Poisson-distributed variables, and the density of clusters is given as λ_J . The children inside a cluster are also a Poisson-distributed variable, and the density of children or jammers inside a cluster is given as J . The jammers are distributed in a 2-D space with a circular radius given as r_J . The transmission power considered for jammers is given as P_J , and the pathloss associated with the clustered jamming devices is given as α_J . In this work, the locations of UAVs, MBSs, and clustered jammers are modeled using independent spatial point processes. Specifically, the UAVs and MBSs are modeled as independent homogeneous PPPs, while the clustered jammers follow an MCP. The independence assumption is adopted to maintain analytical tractability and is widely used in stochastic geometry-based investigations. Since the deployment of communication infrastructure and the spatial distribution of malicious jammers are generally determined by different mechanisms, modeling them as independent processes provides a reasonable approximation while enabling closed-form performance analysis [31,32].

The V-Ns are considered as a Cox process exploiting a PLP, where vehicles are distributed along all roads generated by the PLP. Consequently, the aggregate interference is contributed by vehicles located not only on the typical road but also on neighboring roads. This allows the proposed framework to capture the cumulative interference from the entire PLP-based road network while maintaining analytical tractability. The roads, represented by R , are distributed via a PLP, Φ_R , and comprise V-Ns, such as cars, pedestrians, and RSUs. The V-Ns have a density of λ_V and correspond to a 1-D PPP, Φ_V . $\lambda_V = \lambda_v + \lambda_r + \lambda_p$ where λ_v , λ_r , λ_p indicate vehicle density, RSU density, and pedestrian density. UAVs conform to a 3-D PPP, Φ_U , whereas MBSs conform to a 2-D PPP, Φ_M . UAVs are deployed at an elevation of H_U . The average cellular-MBSs and unmanned stations density is λ_M and λ_U , correspondingly.

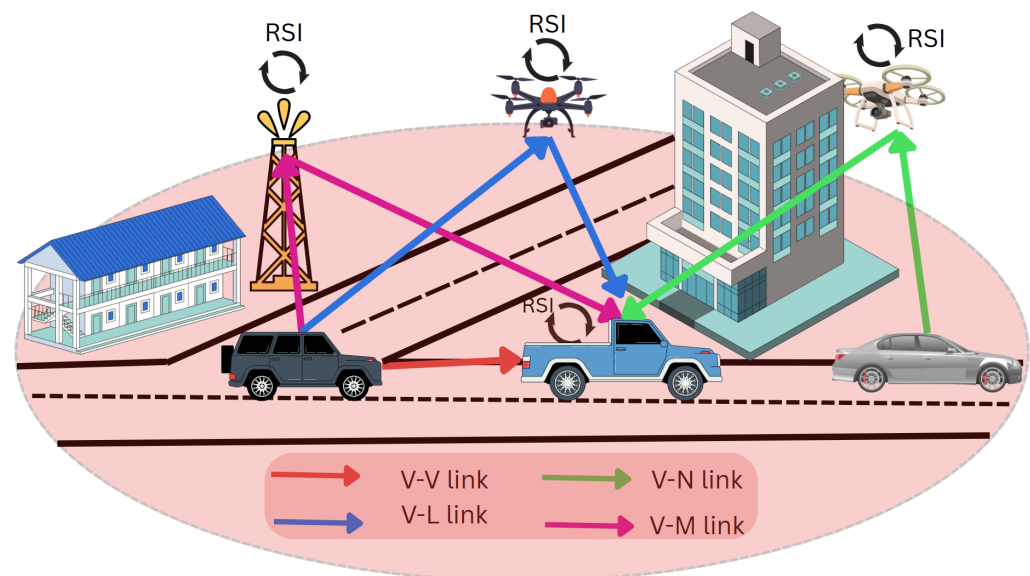


Figure 1. Full-duplex UAV-driven C-V2X system disrupting clustered jammers.

P_V and P_M indicate the V-Ns' and cellular-MBSs' transmission power, respectively. The amount of data transmitted via the link is influenced by these power characteristics. The pathlosses, α_V and α_M , correspond to V-N and MBS, respectively, which show how the strength of signals decreases with range. The MBSs follow a standard path-loss; however, an extra attenuation component, $\mathcal{L}_M$, accounts for ambient factors that affect the propagation of signals. Furthermore, the link's quality of signal is significantly impacted by small-scale fading. The variables g_V and g_M represent the small-scale exponentially distributed Rayleigh fading impact for V-Ns and MBSs, respectively.

The UAV's power is indicated by P_U , and the path-losses for LOS and NLOS unmanned stations linkages are specified by α_L and α_N , correspondingly. $\mathcal{L}_L$ and $\mathcal{L}_N$ represent the extra path-loss which LOS and NLOS unmanned stations experience, respectively. $\mathcal{L}$, an influential variable, fluctuates between 0 and 1, where $\mathcal{L} = 1$ denotes communication from one V-N to another V-N, whereas $\mathcal{L} = 0$ denotes communication from one V-N to another non-V-N. g_L represents the small-scale fading co-efficient for LOS UAVs, while g_N represents the NLOS UAVs' fading co-efficient. The power received by the UAV exhibits a Gamma-distributed amplitude provided the link follows a Nakagami- m distributed fading. $g_U(t) = \frac{m_U^{m_U} t^{m_U-1} \exp(-m_U t)}{\Gamma(.)}$ is the equation for the channel-dependent fading for the UAV, considering the shape parameter m_U which refers to the Nakagami- m distributed function such that $U \in \{L, N\}$, and $\Gamma(.)$ is the equation for the Gamma function that is equivalent to the Gamma distribution [33]. The Normal-distributed variances can be utilized for varying antenna beam-widths in the x- and y-planes and are given by σ_x and σ_y , respectively. According to the current research, a number of variables, such as winds, atmospheric pressure, or malfunctions in the UAVs' electrical motors, affect how well millimeter-wave beams variate in the x-y planes. The probability of the unmanned station receiving a direct transmission for a V-N-based link depends on the unmanned stations height, the traditional environment (for instance, suburban, rural, or urban), and the link distances. It is given as

$$p_L = \left(1 + a \cdot e^{-\frac{180}{\pi} \mathbf{b} \cdot \theta + a \cdot \mathbf{b}} \right)^{-1}, \quad (1)$$

where $\theta = \tan^{-1}(\sqrt{\tan(\sigma_x)^2 + \tan(\sigma_y)^2})$. An outdoor, indoor, etc. setting is depicted by parameters a and b . The corresponding complementary value of (1) can be used to determine the probability of an NLOS UAV link, $\mathbf{p}_N$. Additionally, the phase associated with the 3-D beam is indicated by $\phi = \arctan\left(\frac{\tan(\sigma_y)}{\tan(\sigma_x)}\right)$.

$\mathbf{N}_t$ denotes the antenna of a sending device and $\mathbf{N}_r$ denotes the antenna of a receiving device, wherein $\{t, r\} \in \{L, N, M, V\}$. The overall antenna gain, Y_S , for $\mathbf{N}_t \times \mathbf{N}_r$ collection of antennas, can be presented as a collection of several gains, which include the efficiency of the primary lobe, Y_S^o , the efficiency of just one of the element of antennas Y_S^E , and the efficiency of the antenna with consistent 3-D amplitude, Y_S^A , resulting in $S \in \{t, r\}$. It can be represented as $Y_S = Y_S^A \times Y_S^E \times Y_S^o$.

The Y_S^A antenna gain is given as [34]

$$Y_S^A = \left(\frac{\sin\left(\frac{\mathbf{N}_S(\kappa_x + \chi_x)}{2}\right) \sin\left(\frac{\mathbf{N}_S(\kappa_y + \chi_y)}{2}\right)}{\mathbf{N}_S \sin\left(\frac{(\kappa_x + \chi_x)}{2}\right) \mathbf{N}_S \sin\left(\frac{(\kappa_y + \chi_y)}{2}\right)} \right)^2, \quad (2)$$

where $\kappa_x = \rho_x \omega_x \delta_x$, and $\kappa_y = \rho_y \omega_y \delta_y$ such that $\delta_x = \delta_y = \sin(\theta) \sin(\phi)$. $\rho_x = \rho_y = 2\pi f_c$ indicates wave-number and f_c indicates frequency. $\omega_x = \omega_y = c/2f_c$ is the plate thickness and $\chi_x = \chi_y = 0^\circ$ indicates phase shift in progressive direction.

The Y_S^E antenna gain is given as [35]

$$Y_S^E = G^{E,\max} - \min\left\{-\left(G^\#(\theta^E) + G^{\#\#}(\theta_x)\right), \Xi\right\}, (\text{dB}) \quad (3)$$

where $G^\# = \min\left\{-12\left(\frac{\theta^E - 90^\circ}{\theta_V}\right)^2, \circ\right\}$ and $G^{\#\#} = \min\left\{-12\left(\frac{\theta^E}{\theta_H}\right)^2, \Xi\right\}$.

$\theta^E = \tan^{-1}\left(\left(\frac{1 + \sin^2(\theta_x)}{\sin(\theta_y)}\right)^{0.5}\right)$ and $G^{E,\max} = 8$ dBi indicates antenna-element highest gain. $\theta_H = 65^\circ$ indicates horizontal beam and $\theta_V = 65^\circ$ indicates vertical beam. $\circ = 30$ dB and $\Xi = 30$ dB indicate limit of side-lobes and front-to-back ratio, correspondingly.

Optimal gain is calculated in order to deliver consistent energy from transmitters in a balanced way using Equation (2.22) of [34] and is given as

$$Y_S^o = \frac{4\pi}{\int_0^{2\pi} \int_0^\pi Y_S^A \sin(\theta) d\theta d\phi}. \quad (4)$$

In an area with cellular towers up to 150 m as well as building levels up to 50 m, the path-loss for millimeter-waves can be defined by the 3GPP as [35]

$$\begin{aligned} \mathcal{Z}(z) = & 20 \log_{10}\left(\frac{40\pi z f_c}{3}\right) + \min\{0.03 H_b^{1.73}, 10\} \times \log_{10}(z) - \min\{0.044 H_b^{1.73}, 14.77\} \\ & + 0.002z \log_{10}(H_b). \end{aligned} \quad (5)$$

Without losing generalization, the recipient V-N lies at point, o . The typical/conventional highway navigates through o . The distribution of nodes does not change if a main highway consisting a recipient V-N passes a point o (according to Slivnyak's Theorem) [36]. The average number of transmissions by the V-Ns in a system is provided as $\lambda_{V_t} = p\lambda_V$. In contrast, $\lambda_{V_r} = 1 - \lambda_{V_t}$ can be used to determine the receiving nodes in the region.

In a full-duplex, excellent SIC setting, the residual-signal is ignored at the receiver. For example, whenever V-Ns communicate, the RSI of the V-Ns is ignored. In a similar manner, whenever MBSs (or UAVs) communicate, the RSI of MBSs (or UAVs) is ignored. However, for a non-perfect full-duplex SIC situation, the RSI for every link needs to be classified. The power delivered by a node, $\mathbb{N}$ assumes residual signal and is stated as

$$P_{\mathbb{N}}^{RSI}(P_{\mathbb{N}}) = P_{\mathbb{N}}|h_c|^2, \quad (6)$$

where $P_{\mathbb{N}}$ is the power of device, and h_c represents the fading link separating the receiving and sending devices. $|h_c|^2$ is calculated as a proportion of a transmitting equipment's power to the residual-interfering power. The residual interference at a device is typically stated (in non-dB) as

$$|h_c|^2 = 10^{C_{\mathbb{N}}/10}, \quad (7)$$

where $C_{\mathbb{N}}$ indicates the fixed magnitude of residual-interfering power. Employing (6), the residual-interfering power from a V-N is determined as $P_V^{RSI}(P_V) = P_V|h_c|^2$, the residual-interfering power of cellular-MBS is determined as $P_M^{RSI}(P_M) = P_M|h_c|^2$, and the residual-interfering power of the unmanned station is determined as $P_U^{RSI}(P_U) = P_U|h_c|^2$. Residual self-interference reduction can be between 50 and 55 dB, according to outcomes of experiments in contemporary millimeter-wave full-duplex setups [37]. Thus, extra computational suppression by digital and analog cancellation is necessary to reduce the interference.

Signals from transmitting nodes (other than the traditional signal) result in characterizing the system interference. Since interfering signals outweigh noise, this research investigates a network focusing on interfering signals while ignoring the impacts of thermal noise on the system. Figure 2 shows the interference encountered by a typical receiver in a UAV-driven C-V2X connectivity exploiting full-duplex connectivity and clustered jamming. Note that the main focus of the paper is to determine the impact of clustered jammers distribution on the intentional communication link. This is because the jammers in real-world situations are traditionally present in clusters and typically distributed according to an MCP. Moreover, the aim of the current work is to consider multiple random jammers placed in random jamming-clusters and investigate the influence of jamming.

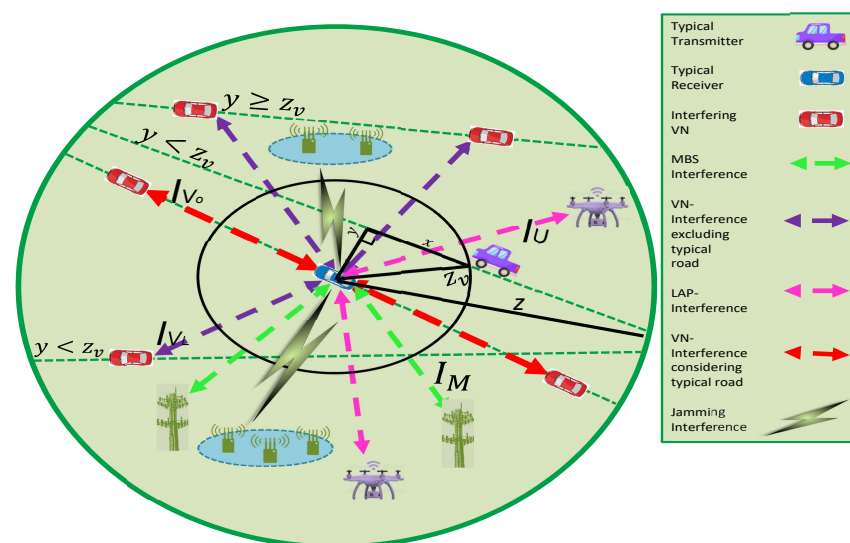


Figure 2. Interference in UAV and cellular-powered V2X system.

For the given system, the signal-to-interference ratio (SIR) in a full-duplex environment is calculated as

$$\text{SIR}_{t2r,J}^{FD} = \frac{P_t \mathcal{L} g_t Y_t Y_r \|z_r - z_t\|^{-\alpha_r}}{I_J + I_N + P_N^{RSI}}, \quad (8)$$

where $N \in \{V, L, N, M\}$, $\|z_r\|$ represents the equipment (that receives the intended signal) to o distance, $\|z_t\|$ represents the sending node to o distance, Y_t represents the V-N transmission gain, and Y_r represents the V-N receiving gain. The jamming interference representing jammers in the specified area is represented by I_J , the nodes' interference is represented by I_N , and the RSI at the destination is represented by P_N^{RSI} . The SIR for the V2N link reflecting clustered jammers in a full-duplex setting is provided as

$$\text{SIR}_{V2N,J}^{FD} = \frac{P_V \mathcal{L} g_V Y_{t,V} Y_{r,N} \|z_N - z_V\|^{-\alpha_N}}{I_J + I_{V_o} + I_V + I_L + I_N + I_M + P_N^{RSI}}, \quad (9)$$

where $\|z_V\|$ indicates o to recipient V-N distance, $\|z_N\|$ indicates o to transmitter (N node) distance, $Y_{V,t}$ indicates the gain of the transmitting V-N, and $Y_{N,r}$ indicates the gain of the receiving node. The V-Ns' interference from the nodes situated on highways that travel through o is represented by I_{V_o} , and the disruption emanating from the highways except highways passing o is represented by I_V . For a full-duplex setting exploited by clustered jammers, the SIR with regard to N2V link is provided as

$$\text{SIR}_{N2V,J}^{FD} = \frac{P_N \mathcal{L} g_N Y_{t,N} Y_{r,V} \|z_N\|^{-\alpha_V}}{I_J + I_{V_o} + I_V + I_L + I_N + I_M + P_V^{RSI}}, \quad (10)$$

where $Y_{r,V}$ is the V-N's receiving-gain and $Y_{t,N}$ is the equipment's transmitting-gain. It is important to note that in the given approach, a perfect SIC acts as an upper limit benchmark. The RSI variable C_N in (7) captures the non-perfect SIC scenario and is configured to the value of 55 dB according to the analysis obtained for a 60 GHz setup [37], in which RSI following both the digital and analog cancellation was observed to fall within 50 dB and 55 dB. The RSI values used in this work are chosen according to recent studies on full-duplex wireless communications [37,38]. These values represent practical self-interference cancellation levels that can be achieved using existing analog and digital cancellation techniques. Although the level of residual self-interference depends on the hardware implementation and operating conditions, the selected values provide a reasonable operating point for evaluating the proposed framework. Different RSI levels would mainly affect the numerical performance, while the analytical model and the conclusions drawn from the performance trends remain unchanged.

According to the beam variation analysis, air turbulence, variations in air pressure, and noise from machinery in standard rotary controllers are the causes of UAV disturbances. The Normal distribution is a logical and accepted alternative because these disturbances are spatially homogeneous and have a modest amplitude beneath typical operational setups. Such Gaussian directional error frameworks were theoretically verified in earlier millimeter-wave UAV investigations [22,23]. In this work, beam pointing deviations are modeled using a Gaussian distribution, following the approach adopted in several existing studies on UAV-assisted wireless communications. This model effectively captures beam fluctuations caused by UAV vibrations, wind disturbances, and tracking inaccuracies under normal operating conditions. The Gaussian assumption also enables a tractable analytical framework while preserving the main characteristics of beam misalignment [28,30]. We acknowledge that more challenging environments, such as severe atmospheric conditions or highly unstable UAV motion, may require alternative statistical models. However,

investigating such scenarios is not the focus of this work and will be considered in future research. The mathematical findings show that system effectiveness is sensitive to σ (varying from 0° to 5°), indicating real-world significance of this variable.

3. Distance Distribution

For a typical wireless communication, a conventional V-N placed at the location z is assumed to communicate with a receiving node at the origin by considering that there is no interfering node present between them.

For a vehicular link communicating with a cellular tower-mounted station at z , it is assumed that no other interfering V-N or LOS/NLOS unmanned station is located with a smaller value of distance, z . Hence, according to [39], $F_M(z) = 1 - e^{-\pi\lambda_M z^2}$ is the cumulative distribution function (CDF) of the MBS, and the MBS probability density function (PDF) is computed as

$$f_M(z) = dF_M(z)/dz = 2\pi\lambda_M z e^{(-2\pi\lambda_M z^2)}. \quad (11)$$

The LOS/NLOS unmanned station's CDF (with $\psi \in \{L, N\}$) is given as [40]

$$F_\psi(z) = 1 - e^{-2\pi\lambda_U \int_{H_U}^z t \mathbf{p}_\psi(\sqrt{t^2 - H_U^2}) dt}. \quad (12)$$

The LOS/ NLOS unmanned station's PDF is computed as

$$f_\psi(z) = 2\pi\lambda_U t \mathbf{p}_\psi\left(\sqrt{t^2 - H_U^2}\right) e^{-2\pi\lambda_U \int_{H_U}^z t \mathbf{p}_\psi(\sqrt{t^2 - H_U^2}) dt}. \quad (13)$$

By taking into account the CDF obtained in Appendix A, the PDF distance from sending to receiving V-N is obtained and stated as

$$f_V(z) = \frac{dF_V(z)}{dz} = 2 \exp\left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy\right) \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy\right). \quad (14)$$

4. V-N Association Probability

V-N associates to another equipment right away in UAV-assisted C-V2X systems, or it connects through a LOS UAV, NLOS UAV, or MBS to convey information to the recipient equipment. The equipment's link or affiliation is defined as its association with the LOS unmanned stations, NLOS unmanned stations, macro base-stations, or recipient vehicular device.

4.1. Vehicle-to-Vehicle Link'S Connecting Probability

A conventional vehicular device connects to the vehicular device (directly omitting shared architecture) in a full-duplex regime whenever the power at the receiving vehicular device exceeds that of the MBS, LOS UAV, and NLOS UAV. The likelihood that V-N will be connected with the recipient V-N is provided as

$$\begin{aligned}
A_V &= \Pr \left\{ \frac{Y_{t,V} Y_{r,V} \|z_V\|^{-\alpha_V}}{\mathcal{L}^{-1}} > \frac{Y_{t,V} Y_{r,M} \|z_M\|^{-\alpha_M}}{\mathcal{L}_M^{-1}} \right\} \\
&\times \Pr \left\{ \frac{Y_{t,V} Y_{r,V} \|z_V\|^{-\alpha_V}}{\mathcal{L}^{-1}} > \frac{Y_{t,V} Y_{r,L} \|z_L\|^{-\alpha_L}}{\mathcal{L}_L^{-1}} \right\} \times \Pr \left\{ \frac{Y_{t,V} Y_{r,V} \|z_V\|^{-\alpha_V}}{\mathcal{L}^{-1}} > \frac{Y_{t,V} Y_{r,N} \|z_N\|^{-\alpha_N}}{\mathcal{L}_N^{-1}} \right\} \\
&\stackrel{a}{=} \Pr \left\{ z_M > z^{\frac{\alpha_V}{\alpha_M}} \left(\frac{\mathcal{L}^{-1} Y_{M,O}}{\mathcal{L}_M^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_M}} \right\} \\
&\times \Pr \left\{ z_L > z^{\frac{\alpha_V}{\alpha_L}} \left(\frac{\mathcal{L}^{-1} Y_L}{\mathcal{L}_L^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_L}} \right\} \times \Pr \left\{ z_N > z^{\frac{\alpha_V}{\alpha_N}} \left(\frac{\mathcal{L}^{-1} Y_N}{\mathcal{L}_N^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_N}} \right\} \\
&\stackrel{b}{=} \int_0^\infty (1 - F_{MV}(z)) f_V(z) dz \times \int_{H_u}^\infty (1 - F_{LV}(z)) f_V(z) dz \times \int_{H_u}^\infty (1 - F_{NV}(z)) f_V(z) dz. \quad (15)
\end{aligned}$$

Assuming identical transmission antenna gains, (a) follows, taking into account that the recipient gains of antennas, e.g., $Y_{V,O}$ and $Y_{M,O}$, have the highest gain when compared to the recipient gains of antennas, e.g., Y_L and Y_N . This is true simply because of factors such as high wind, high pressure, and other factors that tend the 3-D millimeter-wave beam of UAVs to vary, which lowers the gain that the UAVs are able to achieve. The formulae can then be simplified with the help of the corresponding CDF and PDF in (b). Equation (16) provides the analytical formula for the V2V connection probability.

$$\begin{aligned}
A_V &= \int_0^\infty \exp \left(-2\pi\lambda_M z^{\frac{\alpha_V}{\alpha_M}} \left(\frac{\mathcal{L}^{-1} Y_{M,O}}{\mathcal{L}_M^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_M}} \right)^2 \exp \left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy \right) \\
&\times \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy \right) dz \times \\
&\int_{H_u}^\infty \exp \left(-2\pi\lambda_U \int_{H_u}^\infty \left(z^{\frac{\alpha_V}{\alpha_L}} \left(\frac{\mathcal{L}^{-1} Y_L}{\mathcal{L}_L^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_L}} \right) \mathbf{p}_L \left(\sqrt{\left(z^{\frac{\alpha_V}{\alpha_L}} \left(\frac{\mathcal{L}^{-1} Y_L}{\mathcal{L}_L^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_L}} \right)^2 - H_U^2} \right) dt \right) \\
&2 \exp \left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy \right) \times \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy \right) dz \\
&\times \int_{H_u}^\infty \exp \left(-2\pi\lambda_U \int_{H_u}^\infty \left(z^{\frac{\alpha_V}{\alpha_N}} \left(\frac{\mathcal{L}^{-1} Y_N}{\mathcal{L}_N^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_N}} \right) \mathbf{p}_N \left(\sqrt{\left(z^{\frac{\alpha_V}{\alpha_N}} \left(\frac{\mathcal{L}^{-1} Y_N}{\mathcal{L}_N^{-1} Y_{V,O}} \right)^{\frac{1}{\alpha_N}} \right)^2 - H_U^2} \right) dt \right) \\
&2 \exp \left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy \right) \times \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy \right) dz. \quad (16)
\end{aligned}$$

4.2. Vehicle-to-Macro Base-Station Link'S Connecting Probability

A vehicular device links to a macro base-station in a full-duplex architecture whenever the power received at the MBSs exceeds that of the UAVs in the LOS/NLOS and the recipient vehicular device. The likelihood that a vehicular device will be connected with the MBS is derived in Equation (17) by following a similar approach to Equation (15) and can be expressed in (18).

$$\begin{aligned}
A_M &= \Pr \left\{ \frac{Y_{t,V} Y_{r,M} \|z_M\|^{-\alpha_M}}{\mathcal{L}_M^{-1}} > \frac{Y_{t,V} Y_{r,L} \|z_L\|^{-\alpha_L}}{\mathcal{L}_L^{-1}} \right\} \\
&\times \Pr \left\{ \frac{Y_{t,V} Y_{r,M} \|z_M\|^{-\alpha_M}}{\mathcal{L}_M^{-1}} > \frac{Y_{t,V} Y_{r,N} \|z_N\|^{-\alpha_N}}{\mathcal{L}_N^{-1}} \right\} \times \Pr \left\{ \frac{Y_{t,V} Y_{r,M} \|z_M\|^{-\alpha_M}}{\mathcal{L}_M^{-1}} > \frac{Y_{t,V} Y_{r,V} \|z_V\|^{-\alpha_V}}{\mathcal{L}^{-1}} \right\} \\
&= \Pr \left\{ z_L > z^{\frac{\alpha_M}{\alpha_L}} \left(\frac{\mathcal{L}_M^{-1} Y_L}{\mathcal{L}_L^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_L}} \right\} \\
&\Pr \left\{ z_N > z^{\alpha_M/\alpha_N} \left(\frac{\mathcal{L}_M^{-1} Y_N}{\mathcal{L}_N^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_N}} \right\} \Pr \left\{ z_V > z^{\alpha_M/\alpha_V} \left(\frac{\mathcal{L}_M^{-1} Y_V}{\mathcal{L}^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_V}} \right\} \\
&= \int_{H_u}^{\infty} (1 - F_{LM}(z)) f_M(z) dz \times \int_{H_u}^{\infty} (1 - F_{NM}(z)) f_M(z) dz \times \int_0^{\infty} (1 - F_{VM}(z)) f_M(z) dz,
\end{aligned} \tag{17}$$

$$\begin{aligned}
A_M &= \int_{H_u}^{\infty} \exp \left(-2\pi\lambda_U \int_{H_u}^{\infty} \left(z^{\frac{\alpha_M}{\alpha_L}} \left(\frac{\mathcal{L}_M^{-1} Y_L}{\mathcal{L}_L^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_L}} \right) \mathbf{p}_L \left(\sqrt{\left(z^{\alpha_M/\alpha_L} \left(\frac{\mathcal{L}_M^{-1} Y_L}{\mathcal{L}_N^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_L}} \right)^2 - H_U^2} \right) dt \right) 2\pi\lambda_M z \\
&\exp(-2\pi\lambda_M z^2) dz \times \int_{H_u}^{\infty} \exp \left(-2\pi\lambda_U \int_{H_u}^{\infty} \left(z^{\frac{\alpha_M}{\alpha_N}} \left(\frac{\mathcal{L}_M^{-1} Y_N}{\mathcal{L}_N^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_N}} \right) \mathbf{p}_N \left(\sqrt{\left(z^{\alpha_M/\alpha_N} \left(\frac{\mathcal{L}_M^{-1} Y_N}{\mathcal{L}_N^{-1} Y_{M,O}} \right)^{\frac{1}{\alpha_N}} \right)^2 - H_U^2} \right) dt \right) \\
&2\pi\lambda_M z \exp(-2\pi\lambda_M z^2) dz \times \int_0^{\infty} \exp \left(-2\pi\lambda_R \int_0^{z^{\alpha_M/\alpha_V} \left(\frac{\mathcal{L}_M^{-1} Y_V}{\mathcal{L}^{-1} Y_{M,O}} \right)^{1/\alpha_V}} \frac{1}{1-e} \sqrt{\left(z^{\alpha_M/\alpha_V} \left(\frac{\mathcal{L}_M^{-1} Y_V}{\mathcal{L}^{-1} Y_{M,O}} \right)^{1/\alpha_V} \right)^2 - y^2} dy \right) \\
&\exp(-2\lambda_V z) 2\pi\lambda_M z \exp(-2\pi\lambda_M z^2) dz.
\end{aligned} \tag{18}$$

4.3. Vehicle-to-LOS Unmanned Station Link's Connecting Probability

A vehicular device connects to the LOS UAV whenever the power received at the recipient LOS UAV exceeds that of the macro base-stations, NLOS UAVs, and the receiving vehicular device. The likelihood that a V-N will be connected with the LOS UAV is derived in Equation (19) by following a similar approach to Equation (15) and is expressed in (20).

$$\begin{aligned}
A_L &= \Pr \left\{ \frac{Y_{t,V} Y_{r,L} \|z_L\|^{-\alpha_L}}{\mathcal{L}_L^{-1}} > \frac{Y_{t,V} Y_{r,M} \|z_M\|^{-\alpha_M}}{\mathcal{L}_M^{-1}} \right\} \\
&\times \Pr \left\{ \frac{Y_{t,V} Y_{r,L} \|z_L\|^{-\alpha_L}}{\mathcal{L}_L^{-1}} > \frac{Y_{t,V} Y_{r,N} \|z_N\|^{-\alpha_N}}{\mathcal{L}_N^{-1}} \right\} \times \Pr \left\{ \frac{Y_{t,V} Y_{r,L} \|z_L\|^{-\alpha_L}}{\mathcal{L}_L^{-1}} > \frac{Y_{t,V} Y_{r,V} \|z_V\|^{-\alpha_V}}{\mathcal{L}^{-1}} \right\} \\
&= \Pr \left\{ z_M > z^{\frac{\alpha_L}{\alpha_M}} \left(\frac{\mathcal{L}_L^{-1} Y_{M,O}}{\mathcal{L}_M^{-1} Y_L} \right)^{\frac{1}{\alpha_M}} \right\} \\
&\times \Pr \left\{ z_N > z^{\frac{\alpha_L}{\alpha_N}} \left(\frac{\mathcal{L}_L^{-1}}{\mathcal{L}_N^{-1}} \right)^{1/\alpha_N} \right\} \times \Pr \left\{ z_V > z^{\frac{\alpha_L}{\alpha_V}} \left(\frac{\mathcal{L}_L^{-1} Y_{V,O}}{\mathcal{L}^{-1} Y_L} \right)^{\frac{1}{\alpha_V}} \right\} \\
&= \int_{H_u}^{\infty} (1 - F_{ML}(z)) f_L(z) dz \times \int_{H_u}^{\infty} (1 - F_{NL}(z)) f_L(z) dz \times \int_0^{\infty} (1 - F_{VL}(z)) f_L(z) dz.
\end{aligned} \tag{19}$$

$$\begin{aligned}
A_L = & \int_{H_U}^{\infty} \exp \left(-2\pi\lambda_M z^{\frac{\alpha_L}{\alpha_M}} \left(\frac{\mathcal{L}_L^{-1} Y_{M,O}}{\mathcal{L}_M^{-1} Y_L} \right)^{\frac{1}{\alpha_M}} \right) 2\pi\lambda_U t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2} \right) \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2} \right) dt \right) \\
& dz \times \int_{H_U}^{\infty} \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} \left(z^{\frac{\alpha_L}{\alpha_N}} \left(\frac{\mathcal{L}_L^{-1}}{\mathcal{L}_N^{-1}} \right)^{\frac{1}{\alpha_N}} \right) \mathbf{p}_N \left(\sqrt{\left(z^{\frac{\alpha_L}{\alpha_N}} \left(\frac{\mathcal{L}_L^{-1}}{\mathcal{L}_N^{-1}} \right)^{\frac{1}{\alpha_N}} \right)^2 - H_U^2} \right) dt \right) \\
& 2\pi\lambda_U t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2} \right) \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2} \right) dt \right) dz \\
& \times \int_0^{\infty} \exp \left(-2\pi\lambda_R \int_0^{z^{\alpha_L/\alpha_V}} \left(\frac{\mathcal{L}_L^{-1} Y_{V,O}}{\mathcal{L}^{-1} Y_L} \right)^{1/\alpha_V} \frac{-2\lambda_V \sqrt{\left(z^{\alpha_L/\alpha_V} \left(\frac{\mathcal{L}_L^{-1} Y_{V,O}}{\mathcal{L}^{-1} Y_L} \right)^{1/\alpha_V} \right)^2 - y^2}}{dy} dy \right) \\
& 2\pi\lambda_U t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2} \right) \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2} \right) dt \right) dz.
\end{aligned} \tag{20}$$

4.4. Vehicle-to-NLOS Unmanned Station Link's Connecting Probability

A vehicular device links with the NLOS UAV in a full-duplex environment whenever the signal-strength at the recipient NLOS unmanned station exceeds that of the UAVs in the LOS, MBSs, and recipient equipment. The likelihood that V-N will be connected with the NLOS UAV is derived in Equation (21) by following a similar approach to Equation (15) and is expressed in (22).

$$\begin{aligned}
A_N = & \Pr \left\{ \frac{Y_{t,V} Y_{r,N} \|z_N\|^{-\alpha_N}}{\mathcal{L}_N^{-1}} > \frac{Y_{t,V} Y_{r,M} \|z_M\|^{-\alpha_M}}{\mathcal{L}_M^{-1}} \right\} \\
& \times \Pr \left\{ \frac{Y_{t,V} Y_{r,N} \|z_N\|^{-\alpha_N}}{\mathcal{L}_N^{-1}} > \frac{Y_{t,V} Y_{r,L} \|z_L\|^{-\alpha_L}}{\mathcal{L}_L^{-1}} \right\} \times \Pr \left\{ \frac{Y_{t,V} Y_{r,N} \|z_N\|^{-\alpha_N}}{\mathcal{L}_N^{-1}} > \frac{Y_{t,V} Y_{r,V} \|z_V\|^{-\alpha_V}}{\mathcal{L}^{-1}} \right\} \\
= & \Pr \left\{ z_M > z^{\frac{\alpha_N}{\alpha_M}} \left(\frac{\mathcal{L}_N^{-1} Y_{M,O}}{\mathcal{L}_M^{-1} Y_N} \right)^{\frac{1}{\alpha_M}} \right\} \\
& \times \Pr \left\{ z_L > z^{\frac{\alpha_N}{\alpha_L}} \left(\frac{\mathcal{L}_N^{-1}}{\mathcal{L}_L^{-1}} \right)^{1/\alpha_N} \right\} \times \Pr \left\{ z_V > z^{\frac{\alpha_N}{\alpha_V}} \left(\frac{\mathcal{L}_N^{-1} Y_{V,O}}{\mathcal{L}^{-1} Y_N} \right)^{1/\alpha_V} \right\} \\
= & \int_{H_U}^{\infty} (1 - F_{MN}(z)) f_N(z) dz \times \int_{H_U}^{\infty} (1 - F_{LN}(z)) f_N(z) dz \times \int_0^{\infty} (1 - F_{VN}(z)) f_N(z) dz.
\end{aligned} \tag{21}$$

$$\begin{aligned}
A_N = & \int_{H_U}^{\infty} \exp \left(-2\pi\lambda_M z^{\frac{\alpha_N}{\alpha_M}} \left(\frac{\mathcal{L}_N^{-1} Y_{M,O}}{\mathcal{L}_M^{-1} Y_N} \right)^{\frac{1}{\alpha_M}} \right) 2\pi\lambda_U t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2} \right) \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2} \right) dt \right) \\
& dz \times \int_{H_U}^{\infty} \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} \left(z^{\frac{\alpha_N}{\alpha_L}} \left(\mathcal{L}_N^{-1} / \mathcal{L}_L^{-1} \right)^{\frac{1}{\alpha_L}} \right) \mathbf{p}_L \left(\sqrt{\left(z^{\frac{\alpha_N}{\alpha_L}} \left(\frac{\mathcal{L}_N^{-1}}{\mathcal{L}_L^{-1}} \right)^{\frac{1}{\alpha_L}} \right)^2 - H_U^2} \right) dt \right) \\
& 2\pi\lambda_U t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2} \right) \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2} \right) dt \right) dz \\
& \times \int_0^{\infty} \exp \left(-2\pi\lambda_R \int_0^{z^{\alpha_N/\alpha_V}} \left(\frac{\mathcal{L}_N^{-1} Y_{V,O}}{\mathcal{L}^{-1} Y_N} \right)^{1/\alpha_V} \frac{-2\lambda_V \sqrt{\left(z^{\alpha_N/\alpha_V} \left(\frac{\mathcal{L}_N^{-1} Y_{V,O}}{\mathcal{L}^{-1} Y_N} \right)^{1/\alpha_V} \right)^2 - y^2}}{dy} dy \right) \\
& 2\pi\lambda_U t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2} \right) \exp \left(-2\pi\lambda_U \int_{H_U}^{\infty} t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2} \right) dt \right) dz.
\end{aligned} \tag{22}$$

5. Interference Analysis

Every connection in a full-duplex platform exploiting UAV-driven C-V2X connectivity will experience interference from the surrounding area whenever a vehicular device communicates to another vehicular device, whether it occurs via a V2V link or through a network employing V2M, V2L, or V2N connections. For example, a V2V link that has been set up and is using a specific band gets interference from nearby V-Ns that are also using that frequency. Additionally, the system's cumulative interference is going to increase due to any remaining self-interfering signals in the system. Typically, UAV-assisted C-V2X networks exploiting full-duplex environment are going to experience residual self-interfering signals as P_N^{RSI} at reception nodes (such as for V2N connections, like V2M, V2L, and V2N connections).

V-N links (such as V2V, etc.) communicate at a different frequency range than M2V, L2V, or N2V connections in a half-duplex platform; it therefore follows that there can be no self-residual interference within a half-duplex system. On the other hand, it is expected that every sending V-N, with the exception of intended communication, may generate interference in the system for V-N links (such as V2V, etc.). Likewise, it is believed that every MBS, LOS LAP, and NLOS LAP add interfering signals to the infrastructure for the M2V connection, every MBS, LOS LAP, and NLOS LAP add interfering signals to the network for the L2V connection, and every MBS, LOS LAP, and NLOS LAP add interfering signals to the network for the N2V connection.

The nodes' interfering signals are given as $I_{N_t} = \sum_{k \in N_t} P_k g_k \mathcal{L}_k Y_{t,k} Y_{N_r} \|z_{N_r} - z_{t,k}\|^{-\alpha_k}$, where P_k is the k -th device power, g_k is the small scale fading for the k -th connection, $\mathcal{L}_k$ is the supplementary transmission loss of N , $Y_{t,k}$ is the gain of the k th transmitting-device, Y_N is the gain of the recipient device (i.e., N), z_{N_r} is the recipient device's separation with respect to origin, $z_{t,k}$ is the k -th separation of the transmitting device with respect to the origin, and α_r is the exponent loss at the recipient device. The Laplace transform of I_{N_t} is expressed by [39] $L_{I_{N_t}}(s) = \mathbb{E}[e^{-sI_{N_t}}]$, where $s = \tau(P_t g_t \mathcal{L}_k Y_{t,k} Y_{N_r} \|z_{N_r} - z_{t,k}\|^{-\alpha_k})^{-1}$. The interference of N_t devices at the position N_r is characterized as follows by changing the values of N and taking into account the Nakagami- m distribution (i.e., $m = 1$).

$$L_{I_{N_t}}(s) = \mathbb{E} \left[\prod_{k \in N_t} \left(\frac{1}{1 + s P_k \mathcal{L}_k Y_{t,k} Y_{N_r} \|z_{N_r} - z_{t,k}\|^{-\alpha_r}} \right) \right]. \quad (23)$$

5.1. V-Ns Interference

It is possible to determine the interference caused by the V-Ns (e.g., $N_t = V$) at a recipient device, N_r , by supposing that at least two distinct situations induce interference. Whenever the recipient V-N and the disrupting V-Ns causing interference are situated along a similar highway (i.e., first case, such as a conventional highway) or whenever the V-Ns causing interference are situated at different highways.

The V-Ns causing interference will be situated beyond the standard highway defined with (highway of length) $[-z, -z_o]$ and $[z_o, z]$ in the starting or first case, where the receiving apparatus is set up at point o and the emitting V-N resides at z_V (referred to as a standard highway which includes both transmitter and receiver). This is due to the fact that the vehicular instrument only interacts with the recipient V-N as long as there is not another node, N , nearby with a lower Euclidean distance. In the example given by (23), the interference is written as

$$L_{I_V^o}(s) = \mathbb{E} \left[\prod_{k \in N_t} \left(\frac{1}{1 + s P_k \mathcal{L}_k Y_{t,k} Y_{N_{r,o}} \|z_{N_{r,o}} - z_{t,k}\|^{-\alpha_r}} \right) \right]. \quad (24)$$

The V-Ns on a conventional highway are determined utilizing a 1-D PPP, employing polar coordinates and taking into account the probability generating function (PGF) of the V-Ns distance. We get interference as

$$L_{I_V^0}(s) = \exp \left(-2\lambda_V \int_{z_V}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L}Y_{t,v} Y_{N_{V_0}} \|b\|^{-\alpha_r}} \right) db \right). \quad (25)$$

The hyper-geometric function can be used to simplify even more and express the interference. ${}_2F_1(-, -, -; -)$. By taking into account $\alpha_r > 1$, $z_V \approx 0$, and $z_V > 1$ is given as

$$L_{I_V^0}(s) = \exp \left(\frac{-2\lambda_V z \mathcal{L}Y_{t,v} Y_{r,v} {}_2F_1(1, -1 + \alpha_r/\alpha_r; 2 - 1/\alpha_r; -\mathcal{L}Y_{t,v} Y_{r,v} z)}{1 + \alpha_r} \right). \quad (26)$$

For the perpendicular distance given by $y \geq z_V$, the interfering vehicular devices reside on a highway that ranges from $[-\sqrt{z^2 - y^2}, \sqrt{z^2 - y^2}]$ and the PDF of V-Ns is given by $f(c_1) = \frac{1}{2\sqrt{z^2 - y^2}}$. Assuming $y \geq z_V$ and taking into account k V-Ns following a Poisson process, the interference of just one highway with $y \geq z_V$ is written as [12]

$$L_{I_V}^\dagger(s) = \sum_{k \geq 0} \mathbf{P}\{\aleph_V == k\} \left(\int_{-\sqrt{z^2 - y^2}}^{\sqrt{z^2 - y^2}} \frac{f(c_1) dc_1}{1 + sP_V \mathcal{L}Y_{t,V} Y_{r,V} (y^2 + c_1^2)^{\frac{-\alpha_r}{2}}} \right)^k. \quad (27)$$

The likelihood that on a highway, a number of k V-Ns follow PPP distribution, is written as $\mathbf{P}\{\aleph_V == k\} = \frac{e^{(-2\lambda_V \sqrt{z^2 - y^2})} (2\lambda_V \sqrt{z^2 - y^2})^k}{k!}$, where equipments on the roadways can be computed as $2\pi\lambda_V \sqrt{z^2 - y^2}$. Plugging $\mathbf{P}\{\aleph_V == k\}$ and $f(c_1)$, we get

$$L_{I_V}^\dagger(s) = \sum_{k \geq 0} \frac{e^{(-2\lambda_V \sqrt{z^2 - y^2})} (2\lambda_V \sqrt{z^2 - y^2})^k}{k! (2\sqrt{z^2 - y^2})^k} \left(\int_{-\sqrt{z^2 - y^2}}^{\sqrt{z^2 - y^2}} \frac{dc_1}{1 + sP_V \mathcal{L}Y_{t,V} Y_{r,V} (y^2 + c_1^2)^{\frac{-\alpha_r}{2}}} \right)^k. \quad (28)$$

Simplifying the interference expression, we get

$$L_{I_V}^\dagger(s) = \sum_{k \geq 0} \frac{e^{(-2\lambda_V \sqrt{z^2 - y^2})}}{k!} \left(\lambda_V \int_{-\sqrt{z^2 - y^2}}^{\sqrt{z^2 - y^2}} \frac{dc_1}{1 + sP_V \mathcal{L}Y_{t,V} Y_{r,V} (y^2 + c_1^2)^{\frac{-\alpha_r}{2}}} \right)^k. \quad (29)$$

Using $\int_{-a_1}^{a_2} = 2 \int_0^{a_2}$ and $\sum_{k=0}^{\infty} \frac{\mathcal{Y}^k}{k!} = e^{\mathcal{Y}}$, we get

$$L_{I_V}^\dagger(s) = e^{(-2\lambda_V \sqrt{z^2 - y^2})} \exp \left(2\lambda_V \left(\int_0^{\sqrt{z^2 - y^2}} \frac{dc_1}{1 + sP_V \mathcal{L}Y_{t,V} Y_{r,V} (y^2 + c_1^2)^{\frac{-\alpha_r}{2}}} \right) \right).$$

The disruption of a single highway with $y \geq z_V$ is given as

$$L_{I_V}^\dagger(s) = \exp \left(-2\lambda_V \int_0^{\sqrt{z^2 - y^2}} \left(1 - \frac{dc_1}{1 + sP_V \mathcal{L}Y_{t,V} Y_{r,V} (y^2 + c_1^2)^{\frac{-\alpha_r}{2}}} \right) \right). \quad (30)$$

For $\alpha_r > 1$, the V-Ns' interference can be written in a closed-form as

$$L_{I_V}^\dagger(s) = \exp \left(\frac{-2\lambda\pi(sP_V \mathcal{L}Y_{t,V} Y_{r,V})^{-\alpha_r} \csc\left(\frac{\pi}{\alpha_r}\right)}{\alpha_r} \right). \quad (31)$$

For the case, $y < z_V$ interference is going to include the V-Ns whose perpendicular separation is smaller than their distance to the communicating V-N; for instance, the V-Ns located in the region are given as $[-\sqrt{z^2 - y^2}, -\sqrt{z_V^2 - y^2}]$ and $[\sqrt{z_V^2 - y^2}, \sqrt{z^2 - y^2}]$. The V-Ns' interference for one of the highways with $y < z_V$ is expressed via the same procedure of deriving (30) and is given as

$$L_{I_V}^\dagger(s) = \exp \left(-2\lambda_V \int_{\sqrt{z_V^2 - y^2}}^{\sqrt{z^2 - y^2}} \left(1 - \frac{dc_2}{1 + sP_V \mathcal{L}Y_{t,V} Y_{r,V} (y^2 + c_2^2)^{\frac{-\alpha_r}{2}}} \right) \right). \quad (32)$$

V-N interference caused by just one highway is described via Equations (30) and (32). However, the mean number of highways touching a circle placed at the origin having radial distance z_V is determined by a PPP with intensity $2\lambda_R z_V$ and PDF $f(b_1) = 1/2z_V$. This enables the evaluation of the interference across every roadway in the system. Likewise, a PPP of intensity $2\lambda_R \sqrt{z^2 - z_V^2}$ and PDF $f(b_2) = 1/2\sqrt{z^2 - z_V^2}$ gives the mean number of highways crossing a circle located at the origin having radial distance, $\sqrt{z^2 - z_V^2}$. Using the same methodology as (28), the interference is written as

$$L_{I_V}^{\dagger V_r}(s) = \left\{ \sum_{k_1 \geq 0} \frac{\exp(-2\lambda_R \lambda_V z)(2\lambda_R \lambda_V z)^{k_1}}{k_1!} \left(\int_{-z}^z L_{I_V}^\dagger(s) f(b_1) db_1 \right)^{k_1} \right\} \\ \left\{ \sum_{k_2 \geq 0} \frac{\exp(-2\lambda_R \lambda_V (z - z_V))(2\lambda_R \lambda_V (z - z_V))^{k_2}}{k_2!} \left(\int_{-\sqrt{z^2 - z_V^2}}^{\sqrt{z^2 - z_V^2}} L_{I_V}^\dagger(s) f(b_2) db_2 \right)^{k_2} \right\}. \quad (33)$$

Plugging $f(b_1)$ and $f(b_2)$ in (33), we get

$$L_{I_V}^{\dagger V_r}(s) = e^{-2\lambda_R \lambda_V z} \sum_{k_1 \geq 0} \frac{\left(2\lambda_R \lambda_V \int_{-z}^z L_{I_V}^\dagger(s) db_1 \right)^{k_1}}{k_1!} \\ e^{-2\lambda_R \lambda_V (z - z_V)} \sum_{k_2 \geq 0} \frac{\left(2\lambda_R \lambda_V \int_{-\sqrt{z^2 - z_V^2}}^{\sqrt{z^2 - z_V^2}} L_{I_V}^\dagger(s) db_2 \right)^{k_2}}{k_2!}. \quad (34)$$

Assuming $\int_{-a_1}^{a_2} = 2 \int_0^{a_2}$ and $\sum_{k_1=0}^{\infty} \mathcal{Y}_1^k / k_1! = e^{\mathcal{Y}}$, (34) is expressed as

$$L_{I_V}^{\dagger V_r}(s) = e^{-2\lambda_R \lambda_V z} e^{2\lambda_R \lambda_V \int_0^z L_{I_V}^\dagger(s) db_1} e^{-2\lambda_R \lambda_V (z - z_V)} e^{2\lambda_R \lambda_V \int_{z_V}^z L_{I_V}^\dagger(s) db_2}. \quad (35)$$

With the exception of highways that travel through origin, V-N interference is stated as

$$L_{I_V^V}(s) = \exp\left(-2\lambda_R\lambda_V \int_0^z \left(1 - L_{I_V}^\dagger(s)\right) db_1 + \int_{z_V}^z \left(1 - L_{I_V}^\dagger(s)\right) db_2\right). \quad (36)$$

5.2. MBSs Interference

The cellular-MBSs' interfering signals can be computed by following the same procedure of (23) and are given as

$$L_{I_M^{\aleph_r}}(s) = \mathbb{E}\left[\prod_{k \in M} \left(\frac{1}{1 + sP_k\mathcal{L}_k Y_{t,k} Y_{\aleph_r} \|z_{\aleph_r} - z_{t,k}\|^{-\alpha_r}}\right)\right]. \quad (37)$$

Transforming the above equation to polar coordinates and taking into account the interfering signals of vehicular devices, $\aleph_t = M$ at the recipient location, $\aleph_r$, the interference can be simplified as

$$L_{I_M^{\aleph_r}}(s) = \exp\left(-2\pi\lambda_M \int_{z_M}^\infty \left(1 - \left(\frac{1}{1 + sP_M\mathcal{L}_M Y_{t,M} Y_{\aleph_r} \|z_{\aleph_r} - z_t\|^{-\alpha_r}}\right)\right) x dx\right), \quad (38)$$

where $Y_{\aleph_r}$ is recipient gain and $Y_{t,M}$ is MBS gain. To derive Equation (38), assume PGF of the MBSs given in [39] and consider $\mathbb{E}[\prod_{k \in \aleph} \mathbb{G}(x)] = \exp\left(-2\pi\lambda_{\aleph} \int_{z_{\aleph}}^\infty (1 - \mathbb{G}(x)) x dx\right)$.

5.3. LOS-LAPs Interference

The LOS unmanned stations' disrupting interfering signals can be computed by considering that g_L takes into account Nakagami- m fading with $\aleph_t = L$, then simplifying (23); it can be specified as [19]

$$L_{I_L^{\aleph_r}}(s) = \mathbb{E}\left[\prod_{k \in L} \left(1 + \frac{sP_k\mathcal{L}_k Y_{t,k} Y_{\aleph_r} \|z_{\aleph_r} - z_{t,k}\|^{-\alpha_r}}{m_L}\right)^{m_L}\right]. \quad (39)$$

Utilizing the PGF of unmanned stations dispersed as point processes and polar coordinates, interference is expressed as

$$L_{I_L^{\aleph_r}}(s) = \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{p}_L\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L\mathcal{L}_L Y_{t,L} Y_{\aleph_r} \|z_{\aleph_r} - z_t\|^{-\alpha_r}}{m_L}\right)^{m_L}\right) dt\right). \quad (40)$$

5.4. NLOS-LAPs Interference

The unmanned stations located at an NLOS visibility can create disruptive interference at the target apparatus, $\aleph_r$, that can be calculated using an analogous approach to (40) and is represented as

$$L_{I_N^{\aleph_r}}(s) = \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{p}_N\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N\mathcal{L}_N Y_{t,N} Y_{\aleph_r} \|z_{\aleph_r} - z_t\|^{-\alpha_r}}{m_N}\right)^{m_N}\right) dt\right). \quad (41)$$

5.5. Clustered Interference

The clustered interference of the jammers is derived by considering the distribution of jammers as an MCP where parent nodes act as jamming-cluster centers and children act as jamming devices that are placed inside Poisson-distributed clusters. The average power encountered by the receiver from a jammer depends upon the jamming power P_J , distance to the jammer's location $z_{t,J}$, distance to the receiver's location z_r , jamming-gain $Y_{t,J}$ and the pathloss of jammer α_J . It is given as $P_J^r = P_J Y_{t,J} \|z_r - z_{t,J}\|^{-\alpha_J}$. The current work considers jamming by analyzing beam targeting, where jammers additionally direct their interference

toward the intended legitimate receiver rather than transmitting omnidirectionally. This makes the attack significantly more damaging because the jamming energy is concentrated precisely where the legitimate signal is strongest, directly suppressing the beam gain advantage that millimeter-wave directional antennas provide. In Appendix B, the impact caused by the jamming is calculated and represented as

$$L_{I_J} = \exp \left\{ -\frac{2\pi\lambda_J J}{\alpha_J r_J^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_{N_r}^2 - \pi\lambda_J \tau^{2/\alpha_J} z_{N_r}^2 \int_0^{z_{N_r}} \left(1 - \exp\left(\frac{-J}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega \right\}. \quad (42)$$

6. Probability of Coverage and Spectrum Efficiency

6.1. Coverage Probability

For a full-duplex clustered jamming environment considering a UAV-driven C-V2X platform, a conventional user device is in coverage if the SIR of the user equipment is higher than or equivalent to the pre-established limit. This is provided as

$$\begin{aligned} C_J^{FD} &= \int_0^\infty \Pr\{\text{SIR}_{i2r,J}^{FD} \geq \tau\} f_r(z) dz \\ &\stackrel{a}{=} \int_0^\infty \Pr\left\{ \frac{P_t \mathcal{L}g_t Y_t Y_r \|z_r - z_t\|^{-\alpha_r}}{I_J + I_N + P_N^{RSI}} \geq \tau \right\} f_r(z) dz \\ &\stackrel{b}{=} \int_0^\infty \mathbb{E} \left[\frac{\Gamma(m_N, m_N \frac{\tau(I_J + I_N + P_N^{RSI})}{P_t \mathcal{L}Y_t Y_r \|z_r - z_t\|^{-\alpha_r}})}{\Gamma(m_N)} \right] f_r(z) dz \\ &\stackrel{c}{=} \int_0^\infty \mathbb{E} \left[\sum_{k=0}^{m_N-1} \frac{1}{k!} \left(-\frac{m_N \tau(I_J + I_N + P_N^{RSI})}{P_t \mathcal{L}Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right)^k \exp\left(-\frac{m_N \tau(I_J + I_N + P_N^{RSI})}{P_t \mathcal{L}Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right) \right] f_r(z) dz \\ &\stackrel{d}{=} \int_0^\infty \sum_{k=0}^{m_N-1} \frac{1}{k!} \left(-\frac{m_N \tau(I_J + I_N + P_N^{RSI})}{P_t \mathcal{L}Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right)^k \mathbb{E} \left[\exp\left(-\frac{m_N \tau(I_J + I_N + P_N^{RSI})}{P_t \mathcal{L}Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right) \right] f_r(z) dz, \\ &\stackrel{e}{=} \int_0^\infty \sum_{k=0}^{m_N-1} \frac{1}{k!} \left(-\frac{m_N \tau(I_J + I_N + P_N^{RSI})}{P_t \mathcal{L}Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right)^k \frac{d^k}{dz_k} \left[L_{I_J}(s) \times L_{I_N}(s) \times E\left[\exp(-sm_N P_N^{RSI})\right] \right] f_r(z) dz, \end{aligned} \quad (43)$$

where (a) is obtained by plugging $\text{SIR}_{i2r,J}^{FD}$. (b) is obtained by considering g_t as a Nakagami distributed with fading parameter m_N , and its amplitude is given by a Gamma function considering $E[\Pr\{g_t \geq x\}] = \frac{\Gamma(m_N, m_N x)}{\Gamma(m_N)}$ [19]. (c) is obtained by writing (b) in terms of the incomplete Gamma function. (d) is obtained by simplifying the expression, and (e) is obtained by the definition of the Laplace transform. The coverage in a half-duplex jamming network considering $m_N = 1$ can be simplified and expressed as $C^{HD} = \int_0^\infty \exp\{-s(I_J + I_N)\} f_r(z) dz$. In order to prevent residual interfering signals in the given region, a half-duplex system uses different frequency bands, such as $F1$ and $F2$.

The coverage in a full-duplex jamming network exploiting $m_N = 1$ can be computed by considering that whenever the SIR of the V2V connection is larger than or equivalent to the predetermined τ , the given link is considered to be in range. In a full-duplex setting, this is provided as

$$\begin{aligned} C_{V,J}^{FD} &= \int_0^\infty \Pr\{\text{SIR}_{V2V}^{FD} \geq \tau\} f_V(z) dz \\ &\stackrel{a}{=} \int_0^\infty \exp(-sP_V^{RSI}) \times L_{I_J}(s) \times L_{I_{V_0}}(s) \times L_{I_V}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_V(z) dz, \end{aligned} \quad (44)$$

where (a) assumes a similar approach of (43) and considers $\aleph = V$ and $m_V = 1$. Putting values in (44), the coverage of the V2V link can be computed and is given in (45). Likewise, the area covered in an environment exploiting jammers for a half-duplex V2V route is found and stated as $C_{V,J}^{HD} = \int_0^\infty L_{I_J}(s) \times L_{I_{V_0}}(s) \times L_{I_V}(s) f_V(z) dz$.

$$\begin{aligned}
 C_{V,J}^{FD} = & \int_0^\infty \exp(-sP_V^{RSI}) \exp\left\{-\frac{2\pi\Delta\lambda_c j}{\alpha_J r_J^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_V^2 - \pi\Delta\lambda_c \tau^{2/\alpha_J} z_V^2 \int_0^\infty \left(1 - \exp\left(\frac{-j}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega\right\} \\
 & \exp\left(-2\lambda_R \lambda_V \int_0^z (1 - L_{I_V}^\dagger(s)) db_1 + \int_{z_V}^z (1 - L_{I_V}^\dagger(s)) db_2\right) \exp\left(-2\lambda_V \int_{z_V}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L} Y_{t,v} Y_{V_0} b^{-\alpha_V}}\right) db\right) \\
 & \int_0^\infty \exp\left(-2\pi\lambda_M \int_0^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}_M Y_{M,t} Y_{V_0} \|z_{V_0} - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\
 & \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}_L Y_{L,t} Y_{V_0} \|z_{V_0} - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\
 & \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}_N Y_{N,t} Y_{V_0} \|z_{V_0} - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) \\
 & 2 \exp\left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy\right) \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy\right) dz.
 \end{aligned} \tag{45}$$

For a full-duplex jamming environment with a UAV-driven C-V2X platform, whenever the V2M link's SIR is larger than or equivalent to the predetermined τ , the MBS-enabled connection is considered to be in coverage. In a full-duplex setting, the MBS-enabled link's coverage is provided as

$$\begin{aligned}
 C_{M,J}^{FD} = & \int_0^\infty \Pr\{\text{SIR}_{V2M}^{FD} \geq \tau\} f_M(z) dz \times \int_0^\infty \Pr\{\text{SIR}_{M2V}^{FD} \geq \tau\} f_V(z) dz \\
 \stackrel{a}{=} & \int_0^\infty \left(\exp(-sP_M^{RSI})\right) \times L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_M(z) dz \\
 & \times \int_0^\infty \left(\exp(-sP_V^{RSI})\right) \times L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_V(z) dz,
 \end{aligned} \tag{46}$$

where (a) is obtained by considering the approach of (43) and considering $\aleph = M$ and $m_M = 1$. By putting values in (46), the coverage can be computed in (47). For V2M, the coverage is computed as $C_{M,J}^{HD} = \int_0^\infty (L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s)) f_M(z) dz \times \int_0^\infty (L_{I_J}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s)) f_V(z) dz$. Recall that V2 $\aleph$ connections in the half-duplex system interact at frequency band F_1 , while $\aleph$ 2V links interact at frequency band F_2 . It is crucial to remember that devices functioning at F_1 are going to interfere with the devices functioning at F_1 . In a similar manner, devices functioning at F_2 are going to interfere with devices functioning at F_2 frequency band.

$$\begin{aligned}
 C_{M,J}^{FD} = & \int_0^\infty \exp(-sP_M^{RSI}) \exp\left\{-\frac{2\pi\Delta\lambda_c j}{\alpha_J r_J^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_M^2 - \pi\Delta\lambda_c \tau^{2/\alpha_J} z_M^2 \int_0^\infty \left(1 - \exp\left(\frac{-j}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega\right\} \\
 & \int_0^\infty \exp\left(-2\lambda_R \lambda_V \int_0^z (1 - L_{I_V}^\dagger(s)) db_1 + \int_{z_M}^z (1 - L_{I_V}^\dagger(s)) db_2\right) \exp\left(-2\lambda_V \int_{z_M}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L} Y_{M,t} Y_{r,v} b^{-\alpha_M}}\right) db\right) \\
 & \exp\left(-2\pi\lambda_M \int_{z_M}^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}_M Y_{M,t} Y_M \|z_M - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\
 & \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{p}_L \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}_L Y_{L,t} Y_M \|z_M - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\
 & \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{p}_N \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}_N Y_{N,t} Y_M \|z_M - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) 2\pi\lambda_M z \exp(-2\pi\lambda_M z^2) dz \times \\
 & \int_0^\infty \exp\left(-2\lambda_R \lambda_V \int_0^z (1 - L_{I_V}^\dagger(s)) db_1 + \int_0^z (1 - L_{I_V}^\dagger(s)) db_2\right) \exp\left(-2\lambda_V \int_0^z \left(1 - \frac{1}{1 + sP_V \mathcal{L} Y_{M,t} Y_{r,v} b^{-\alpha_M}}\right) db\right)
 \end{aligned}$$

$$\begin{aligned}
& \int_0^\infty \exp\left(-2\pi\lambda_M \int_0^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}_M Y_{M,t} Y_{r,v} \|z_{V_0} - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\
& \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{p}_L\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}_L Y_{L,t} Y_{r,v} \|z_{V_0} - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\
& \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{p}_N\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}_N Y_{N,t} Y_{r,v} \|z_{V_0} - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) \\
& 2 \exp\left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy\right) \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy\right) dz.
\end{aligned} \quad (47)$$

For a full-duplex jamming environment with a UAV-driven C-V2X platform, whenever the SIR of the V2L connection is larger than or equivalent to the predetermined τ , the LOS UAV-enabled connection is considered to be in coverage. In a full-duplex setting, the LOS UAV-enabled link's coverage is provided as

$$\begin{aligned}
C_{L,J}^{FD} &= \int_0^\infty \Pr\{\text{SIR}_{V2L}^{FD} \geq \tau\} f_L(z) dz \times \int_0^\infty \Pr\{\text{SIR}_{L2V}^{FD} \geq \tau\} f_V(z) dz \\
&\stackrel{a}{=} \int_0^\infty \exp(-sP_L^{RSI}) \times L_{I_I}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_L(z) dz \times \\
&\int_0^\infty \exp(-sP_V^{RSI}) \times L_{I_I}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_V(z) dz,
\end{aligned} \quad (48)$$

where (a) exploits (43) by considering $\aleph = L$ and $m_L = 1$. By putting values in (48), the coverage is computed in (49). For V2L link, the coverage is computed as $C_{L,J}^{HD} = \int_0^\infty (L_{I_I}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s)) f_L(z) dz \times \int_0^\infty (L_{I_I}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s)) f_V(z) dz$.

$$\begin{aligned}
C_{L,J}^{FD} &= \int_0^\infty \exp(-sP_L^{RSI}) \int_0^\infty \exp\left\{-\frac{2\pi\Delta\lambda_{cj}}{\alpha_J r_j^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_V^2 - \pi\Delta\lambda_c \tau^{2/\alpha_J} z_V^2 \int_0^\infty \left(1 - \exp\left(\frac{-j}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega\right\} \\
& \exp\left(-2\lambda_R \lambda_V \int_0^z (1 - L_{I_V}^\dagger(s)) db_1 + \int_{z_L}^z (1 - L_{I_V}^\dagger(s)) db_2\right) \exp\left(-2\lambda_V \int_{z_L}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L}_Y Y_{t,v} Y_{r,L} b^{-\alpha_L}}\right) db\right) \\
& \exp\left(-2\pi\lambda_M \int_{z_L}^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}_M Y_{M,t} Y_L \|z_L - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\
& \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{p}_L\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}_L Y_{L,t} Y_L \|z_L - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\
& \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{p}_N\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}_N Y_{N,t} Y_L \|z_L - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) \\
& 2\pi\lambda_U t \mathbf{p}_L\left(\sqrt{t^2 - H_U^2}\right) e^{-2\pi\lambda_U \int_{H_U}^z t \mathbf{p}_L\left(\sqrt{t^2 - H_U^2}\right) dt} dz \times \\
& \int_0^\infty \exp(-sP_V^{RSI}) \exp\left\{-\frac{2\pi\Delta\lambda_{cj}}{\alpha_J r_j^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_V^2 - \pi\Delta\lambda_c \tau^{2/\alpha_J} z_V^2 \int_0^\infty \left(1 - \exp\left(\frac{-j}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega\right\} \\
& \exp\left(-2\lambda_R \lambda_V \int_0^z (1 - L_{I_V}^\dagger(s)) db_1 + \int_{z_L}^z (1 - L_{I_V}^\dagger(s)) db_2\right) \exp\left(-2\lambda_V \int_{z_L}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L}_Y Y_{t,v} Y_{r,L} b^{-\alpha_L}}\right) db\right) \\
& \exp\left(-2\pi\lambda_M \int_0^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}_M Y_{M,t} Y_{r,v} \|z_{V_0} - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\
& \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{p}_L\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}_L Y_{L,t} Y_{r,v} \|z_{V_0} - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\
& \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{p}_N\left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}_N Y_{N,t} Y_{r,v} \|z_{V_0} - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) \\
& 2 \exp\left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy\right) \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy\right) dz.
\end{aligned} \quad (49)$$

If the V2N's SIR is greater compared to the pre-defined τ , the V2N transmission is deemed to be in coverage for an FD scenario that is attacked by jammers. It is given as

$$\begin{aligned} C_{N,J}^{FD} &= \int_0^\infty \Pr\{\text{SIR}_{V2N,J}^{FD} > \tau\} f_N(z) dz \times \int_0^\infty \Pr\{\text{SIR}_{N2V,J}^{FD} > \tau\} f_V(z) dz \\ &\stackrel{a}{=} \int_0^\infty \left(\exp(-sP_N^{RSI}) \right) \times L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_N(z) dz \\ &\quad \times \int_0^\infty \left(\exp(-sP_V^{RSI}) \right) \times L_{I_J}(s) \times L_{I_{V_0}}(s) \times L_{I_V}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_V(z) dz, \end{aligned} \quad (50)$$

For a full-duplex jamming environment, a UAV-driven C-V2X platform, whenever the SIR of the V2N connection is larger than or equivalent to the predetermined τ , the NLOS UAV-enabled connection is considered to be in coverage. In a full-duplex setting, the NLOS UAV-enabled link's coverage is provided as

$$\begin{aligned} C_{N,J}^{FD} &= \int_0^\infty \Pr\{\text{SIR}_{V2N}^{FD} \geq \tau\} f_N(z) dz \times \int_0^\infty \Pr\{\text{SIR}_{N2V}^{FD} \geq \tau\} f_V(z) dz \\ &\stackrel{a}{=} \int_0^\infty \left(\exp(-sP_N^{RSI}) \right) \times L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_N(z) dz \\ &\quad \times \int_0^\infty \left(\exp(-sP_V^{RSI}) \right) \times L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) f_V(z) dz, \end{aligned} \quad (51)$$

where (a) exploits (43) using $N = N$ and $m_N = 1$. By putting values in (51), the coverage is computed as (7). For V2N, the coverage is computed as $C_{N,J}^{HD} = \int_0^\infty \left(L_{I_J}(s) \times L_{I_V}(s) \times L_{I_{V_0}}(s) \right) f_N(z) dz \times \int_0^\infty \left(L_{I_J}(s) \times L_{I_M}(s) \times L_{I_L}(s) \times L_{I_N}(s) \right) f_V(z) dz$.

$$\begin{aligned} C_{N,J}^{FD} &= \int_0^\infty \exp(-sP_N^{RSI}) \int_0^\infty \exp\left\{-\frac{2\pi\Delta\lambda_c j}{\alpha_J r_J^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_V^2 - \pi\Delta\lambda_c \tau^{2/\alpha_J} z_V^2 \int_0^\infty \left(1 - \exp\left(\frac{-j}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega\right\} \\ &\quad \exp\left(-2\lambda_R \lambda_V \int_0^z \left(1 - L_{I_V}^\dagger(s)\right) db_1 + \int_{z_N}^z \left(1 - L_{I_V}^\dagger(s)\right) db_2\right) \exp\left(-2\lambda_V \int_{z_N}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L}Y_{t,v} Y_N b^{-\alpha_L}}\right) db\right) \\ &\quad \exp\left(-2\pi\lambda_M \int_{z_N}^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}M Y_{M,t} Y_N \|z_N - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\ &\quad \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{P}_L \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}L Y_{L,t} Y_N \|z_N - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\ &\quad \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{P}_N \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}N Y_{N,t} Y_N \|z_N - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) \\ &\quad 2\pi\lambda_U t \mathbf{P}_L \left(\sqrt{t^2 - H_U^2}\right) e^{-2\pi\lambda_U \int_{H_U}^z t \mathbf{P}_L \left(\sqrt{t^2 - H_U^2}\right) dt} dz \times \\ &\quad \int_0^\infty \exp(-sP_V^{RSI}) \exp\left\{-\frac{2\pi\Delta\lambda_c j}{\alpha_J r_J^2} \tau^{2/\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right) z_V^2 - \pi\Delta\lambda_c \tau^{2/\alpha_J} z_V^2 \int_0^\infty \left(1 - \exp\left(\frac{-j}{1 + \omega^{\alpha_J/2}}\right)\right) d\omega\right\} \\ &\quad \exp\left(-2\lambda_R \lambda_V \int_0^z \left(1 - L_{I_V}^\dagger(s)\right) db_1 + \int_{z_N}^z \left(1 - L_{I_V}^\dagger(s)\right) db_2\right) \exp\left(-2\lambda_V \int_{z_N}^z \left(1 - \frac{1}{1 + sP_V \mathcal{L}Y_{t,v} Y_N b^{-\alpha_L}}\right) db\right) \\ &\quad \exp\left(-2\pi\lambda_M \int_0^\infty \left(1 - \left(\frac{1}{1 + sP_M \mathcal{L}M Y_{M,t} Y_{r,v} \|z_{V_0} - z_{M,t}\|^{-\alpha_V}}\right)\right) x dx\right) \\ &\quad \exp\left(-2\pi\lambda_L \int_{H_U}^\infty t \mathbf{P}_L \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_L \mathcal{L}L Y_{L,t} Y_{r,v} \|z_{V_0} - z_{L,t}\|^{-\alpha_V}}{m_L}\right)^{m_L}\right) dt\right) \\ &\quad \exp\left(-2\pi\lambda_N \int_{H_U}^\infty t \mathbf{P}_N \left(\sqrt{t^2 - H_U^2}\right) \left(1 - \left(1 + \frac{sP_N \mathcal{L}N Y_{N,t} Y_{r,v} \|z_{V_0} - z_{N,t}\|^{-\alpha_V}}{m_N}\right)^{m_N}\right) dt\right) \\ &\quad 2 \exp\left(-2\lambda_V z + 2\pi\lambda_R \int_0^z 1 - e^{-2\lambda_V \sqrt{z^2 - y^2}} dy\right) \left(\lambda_V + 2\pi\lambda_R \lambda_V \int_0^z \frac{ze^{-2\lambda_V \sqrt{z^2 - y^2}}}{\sqrt{z^2 - y^2}} dy\right) dz. \end{aligned} \quad (52)$$

The coverage of a full-duplex platform exploited by clustered jammers is expressed as

$$C_J^{FD} = A_V C_{V,J}^{FD} + A_M C_{M,J}^{FD} + A_L C_{L,J}^{FD} + A_N C_{N,J}^{FD}. \quad (53)$$

The total coverage probability in the presence of jammers can be found by inserting the values in (53). However, for a half-duplex, the formula for the total coverage is given as $C_J^{HD} = A_V C_{V,J}^{HD} + A_M C_{M,J}^{HD} + A_L C_{L,J}^{HD} + A_N C_{N,J}^{HD}$.

6.2. Spectrum Efficiency

Shannon's capacity of a UAV-driven full-duplex C-V2X platform determines the frequency utilization efficiency associated with a full-duplex paradigm. The bandwidth efficiency of a system exploited by jammers is defined as follows: $SE_J^{FD} = \int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{t2r,J}^{FD}) f_r(z) dz dt$. Assuming that $\aleph$ -link selected and exhibits an instantaneous SIR equivalent or larger than the threshold, the SE of the connection, $\aleph$, is determined.

$$\begin{aligned} SE_J^{FD} &= \int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{t2r,J}^{FD}) f_r(z) dz dt \\ &\stackrel{a}{=} \int_0^\infty \int_0^\infty (\text{SIR}_{t2r,J}^{FD} \geq e^t - 1) f_r(z) dz dt \\ &\stackrel{b}{=} \int_0^\infty \int_0^\infty \left(\frac{P_t \mathcal{L}_{g_t} Y_t Y_r \|z_r - z_t\|^{-\alpha_r}}{I_J + I_{\aleph} + P_{\aleph}^{RSI}} \geq e^t - 1 \right) f_r(z) dz \\ &\stackrel{c}{=} \int_0^\infty \int_0^\infty \left(g_t \geq \frac{(e^t - 1)(I_J + I_{\aleph} + P_{\aleph}^{RSI})}{P_t \mathcal{L}_{g_t} Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right) f_r(z) dz dt \\ &\stackrel{d}{=} \int_0^\infty \int_0^\infty \sum_{k=0}^{m_{\aleph}-1} \frac{1}{k!} \left(-\frac{m_{\aleph} \tau (I_J + I_{\aleph} + P_{\aleph}^{RSI})}{P_t \mathcal{L}_{g_t} Y_t Y_r \|z_r - z_t\|^{-\alpha_r}} \right)^k \\ &\quad \times \frac{d^k}{dz_k} [L_{I_J}(s) \times L_{I_{\aleph}}(s) \times E[\exp(-sm_{\aleph} P_{\aleph}^{RSI})]] f_r(z) dz dt, \end{aligned} \quad (54)$$

where (a) follows by applying natural log, (b) follows by putting values in $\text{SIR}_{t2r,J}^{RSI}$, (c) follows by re-arranging, and (d) follows by the same procedure of (43) and considering $\bar{s} = (e^t - 1)(P_t \mathcal{L}_{g_t} Y_t Y_r \|z_r - z_t\|^{-\alpha_r})^{-1}$. For a full-duplex V2V link exploiting jamming, the SE is computed as

$$SE_{V,J}^{FD} = \int_0^\infty \int_0^\infty \exp(-\bar{s}(P_V^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt, \quad (55)$$

where $\exp(-I_{\aleph}(\bar{s})) = L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s})$ and $f_r(z) = f_V(z)$. For the half-duplex system, V2V link's SE is computed as $SE_{V,J}^{HD} = 1/2 \int_0^\infty \int_0^\infty (L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s})) f_V(z) dz dt$.

The V2M and M2V links' SE exploiting jammers are integrated together to obtain the SE of the cellular-MBS link exploiting jammers and can be derived as

$$\begin{aligned} SE_{M,J}^{FD} &= \left[\int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{V2M,J}^{FD}) f_L(z) dz dt \times \int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{M2V,J}^{FD}) f_V(z) dz dt \right] \\ &\stackrel{a}{=} \left[\int_0^\infty \int_0^\infty \exp(-\bar{s}(P_M^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_M(z) dz dt \times \right. \\ &\quad \left. \int_0^\infty \int_0^\infty \exp(-\bar{s}(P_V^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt \right], \end{aligned} \quad (56)$$

where (a) considers $\exp(-I_{\aleph}(\bar{s})) = L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s})$ and $f_r(z) = f_M(z)$ for the cellular-MBS link, whereas, for the M2V connection, $\exp(-I_{\aleph}(\bar{s})) = L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s})$

and $f_r(z) = f_V(z)$. The SE of cellular-MBS in a half-duplex setup is computed as $SE_{M,J}^{HD} = 1/2 \int_0^\infty \int_0^\infty L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) f_M(z) dz dt \times \int_0^\infty \int_0^\infty L_{I_J}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt$.

By employing jamming in the system, the V2L connection's SE and L2V connection's SE are combined to produce the LOS unmanned station-aided V2X connection's SE, which is provided as

$$SE_{L,J}^{FD} = \left[\int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{V2L,J}^{FD}) f_L(z) dz dt \times \int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{L2V,J}^{FD}) f_V(z) dz dt \right] \\ \stackrel{a}{=} \left[\int_0^\infty \int_0^\infty \exp(-\bar{s}(P_L^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_L(z) dz dt \times \right. \\ \left. \int_0^\infty \int_0^\infty \exp(-\bar{s}(P_V^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt \right], \quad (57)$$

where (a) considers $\exp(-I_N(\bar{s})) = L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s})$ and $f_r(z) = f_L(z)$, for the V2L connection. Whereas, for the LOS unmanned station link, $\exp(-I_N(\bar{s})) = L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s})$ and $f_r(z) = f_V(z)$. The SE of the LOS unmanned station link in a half-duplex setup is computed as $SE_{L,J}^{HD} = 1/2 \int_0^\infty \int_0^\infty L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) f_L(z) dz dt \times \int_0^\infty \int_0^\infty L_{I_J}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt$.

By exploiting the jamming system, the V2N connection's SE and the N2V connection's SE are combined to produce the NLOS unmanned station-aided V2X connection's SE, which is provided as

$$SE_{N,J}^{FD} = \left[\int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{V2N,J}^{FD}) f_N(z) dz dt \times \int_0^\infty \int_0^\infty \ln(1 + \text{SIR}_{N2V,J}^{FD}) f_V(z) dz dt \right] \\ \stackrel{a}{=} \left[\int_0^\infty \int_0^\infty \exp(-\bar{s}(P_N^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_N(z) dz dt \times \right. \\ \left. \int_0^\infty \int_0^\infty \exp(-\bar{s}(P_V^{RSI})) \times L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt \right], \quad (58)$$

where (a) considers $\exp(-I_N(\bar{s})) = L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s})$ and $f_r(z) = f_N(z)$, for the V2N connection. Whereas, for the N2V connection, $\exp(-I_N(\bar{s})) = L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s})$ and $f_r(z) = f_V(z)$. The SE of the NLOS unmanned station in a half-duplex setup is computed as $SE_{N,J}^{HD} = 1/2 \int_0^\infty \int_0^\infty L_{I_J}(\bar{s}) \times L_{I_V}(\bar{s}) \times L_{I_{V_0}}(\bar{s}) f_N(z) dz dt \times \int_0^\infty \int_0^\infty L_{I_J}(\bar{s}) \times L_{I_M}(\bar{s}) \times L_{I_L}(\bar{s}) \times L_{I_N}(\bar{s}) f_V(z) dz dt$. The SE of a full-duplex jamming environment, considering the C-V2X framework driven by UAVs and MBSs in the presence of jamming, is given as

$$SE_J^{FD} = A_V SE_{V,J}^{FD} + A_M SE_{M,J}^{FD} + A_L SE_{L,J}^{FD} + A_N SE_{N,J}^{FD}. \quad (59)$$

For a full-duplex scenario, the SE exploited by clustered jammers in a UAV-powered C-V2X setup is calculated by inserting the values in (59), while for the half-duplex setup, it is given as $SE_J^{HD} = A_V SE_{V,J}^{HD} + A_M SE_{M,J}^{HD} + A_L SE_{L,J}^{HD} + A_N SE_{N,J}^{HD}$.

7. Results and Discussion

The in-depth physical analysis of a full-duplex system shows that RSI factor adds a coverage degradation to a full-duplex connectivity. The addition of jamming signals in the environment further degrades a full-duplex connectivity. Moreover, SIR and coverage reduce for UAV-enabled connections due to strong environmental influence, whereas V2M and V2V connections are not influenced.

7.1. Simulation Setup and Results

Without compromising generality, the findings are achieved by adhering to Table 3. The variables used in the present work are consistent with the 3GPP report (Table 7.3-1, Table 7.4.1-1 of [35]) [26]. In all the figures, the analytical results are obtained by numerically evaluating the derived expressions, and 100,000 independent simulation runs validate the analysis. For clarity, Figure 3 distinguish analytical results (denoted by -A in the legend) and simulation results (denoted by -S in the legend), and the close agreement between the two validates the accuracy of the derived expressions. The analytical results show a close match with the simulation results over the entire range of the considered parameters. This agreement confirms the accuracy of the derived analytical expressions and validates the proposed analytical framework. The V2V, V2M, V2L, V2N, and U-V2X linkages exploiting jammers are represented by the colors purple, pink, cyan, brown, and black, correspondingly.

Table 3. Simulation parameters and values.

Variables	Value	Variables	Value
Node Densities			
λ_R (Roads)	3/km ²	λ_V (VNs)	3/km
λ_M (MBSs)	3/km ²	λ_U (UAVs)	6/km ²
Path Loss and Fading Parameters			
α_L (LOS)	2.5	α_N (NLOS)	3
α_V (VNs)	3	α_M (MBSs)	4
m_L (Nakagami LOS)	1	m_N (Nakagami NLOS)	1
$\mathcal{L}_L$ (LOS loss)	1 dB	$\mathcal{L}_N$ (NLOS loss)	5 dB
$\mathcal{L}_M$ (MBS loss)	1 dB	$\mathcal{L}$ (Bias Factor)	0.001
Transmission and Antenna Settings			
H_U (UAV height)	80 m	τ (SIR threshold)	−5 dB
N_t (Tx antennas)	20	N_r (Rx antennas)	20
σ_x, σ_y (Beam jitter)	0°	W (Bandwidth)	10 MHz
Jamming Parameters			
λ_J (Jamming clusters)	2/km ²	J (Jammers per cluster)	2
r_J (Cluster radius)	100 m	α_J (Jammer path-loss)	3
P_J (Jammer Tx power)	23 dBm	C (RSI ratio)	62
Environment and Frequency Settings			
a (LOS param)	9.61	b (LOS param)	0.16
f_c (Carrier freq.)	60 GHz	c (Speed of light)	0.3 G m/s

The simulations take into account that highways containing V-Ns (cars, road-side units, and pedestrians living close to highways) are scattered around the specified area employing a PLP, having a road intensity equal to 3/km². With an intensity of V-Ns = 3/km, the V-Ns on each route are evenly split, employing a 1-D PPP. The conventional transmitter is situated on the same highway as the receiver, V-N, or on an entirely separate highway. The vehicular device used for transmitting signals is described as the traditional or typical V-N. The traditional highway or road (with the destination V-N) is set up to guarantee that it crosses the origin for every Monte Carlo experiment run, whereas the recipient vehicular device is positioned at the coordinate center without limiting generality. The jamming clusters are distributed following a Poisson distribution, and their distribution is given by density, $\lambda_J = 2/\text{km}^2$. The intensity of a jamming cluster is given as $J = 2$, and the size of the cluster is given by circular radius, $r_J = 100$ m. $P_J = 23$ dBm and the

jammer's pathloss exponent is given as $\alpha_J = 3$. Assuming a 2-D PPP to represent MBSs, and their corresponding intensity = $3/\text{km}^2$, the UAV intensity is $6/\text{km}^2$, and the UAVs are represented by a 3-D PPP. The probability of a UAV acting as a LOS base-station or NLOS base-station for the V-N depends upon the UAV's elevation ($h_U = 80$ m) and the suburban setting factors ($a = 9.61$ and $b = 0.16$ [27]).

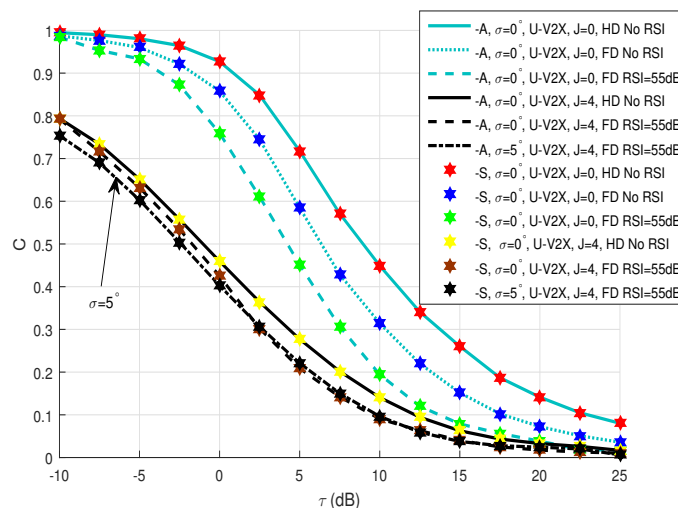


Figure 3. Impact of RSI, varying beam, jammers and SIR thresholds over the typical V-N's coverage.

When choosing the vehicular device for vehicular transmissions, the V-N having the highest average power is called a typical or conventional (transmitting) V-N. The transmitter calculates the mean power acquired at all the stations in order to decide whether to transmit directly to the V-N or through equipment like MBS, LOS UAV, or NLOS UAV. The typical V-N connects itself with the MBS if its highest power acquired at the MBS is above or equivalent to the largest power acquired at the V-N, LOS UAV, and NLOS UAV. In the scenario that the LOS UAV's highest average power surpasses the V-N's, MBS's, or NLOS UAV's highest average power, the typical V-N connects itself with the LOS UAV. Likewise, the transmitter connects itself with the NLOS UAV when its highest power attained at the NLOS UAV is above or equivalent to the highest power attained at the V-N, MBS, and LOS UAV. Otherwise, the conventional V-N connects with the closest V-N, which is located at the origin.

The interfering signals at the target vehicular device from the remaining V-Ns except the typical V-N's signal can be calculated as I_V^V , I_M^V from each of the MBSs at the recipient V-N, I_L^V from all LOS UAVs at the target, and I_N^V from all NLOS UAVs at the target. The interfering signals from all the V-Ns at the closest MBS should also be computed as I_V^M , from all the V-Ns at the closest LOS UAV as I_L^L , and from all the V-Ns at the closest NLOS UAV as I_N^N . A V-N's residual-power is computed by P_V^{RSI} , an MBS's residual-power is computed by P_M^{RSI} , a LOS UAV's residual-power is computed by P_L^{RSI} , and an NLOS UAV's residual-power is computed by P_N^{RSI} using (6).

V2M connection's coverage in a half-duplex operation is calculated by determining the SIR acquired on an MBS (as SIR_{V2M}^{HD}) based on the conventional V-N and MBS link. The power acquired by the MBS divided by the interfering signals (as I_V^M) and jamming signals (as I_J) yields the $\text{SIR}_{V2M,J}^{HD}$. The coverage of a V2M connection in a full-duplex operation is calculated by determining the acquired SIR on the MBS (as SIR_{V2M}^{FD}) dividing by the power acquired on the MBS from the jamming signals (I_J), the interfering signals (as I_V^M), and residual-power from the MBS (as P_M^{RSI}).

M2V connection's coverage for a half-duplex operation exploiting jamming is calculated by measuring the SIR (as $\text{SIR}_{M2V,J}^{HD}$) for the vehicular device related to the MBS.

The power acquired via MBS at the target V-N divided by the jamming signals (I_J) and the interfering signals (as I_M^V) yields the $SIR_{M2V,J}^{HD}$. The SIR given as $SIR_{M2V,J}^{FD}$ is used to calculate the coverage of an M2V connection in a full-duplex configuration, exploiting jamming for the vehicular device linked with the MBS. The ratio of power produced by the MBS at the V-N with the jamming signals (I_J), the interfering signals (i.e., I_M^V), and residual-power of the V-N (i.e., P_V^{RSI}) is used to calculate the $SIR_{M2V,J}^{FD}$.

The SIR via the LOS UAV is calculated as $SIR_{V2L,J}^{HD}$ to determine the extent of the V2L connection using a half-duplex configuration exploited by jamming for the conventional V-N connected with the LOS UAV. The power acquired by the LOS UAV divided by the jamming signals, (I_J) and the interfering signals, I_V^L , yields the $SIR_{V2L,J}^{HD}$. The SIR across the LOS UAV is calculated as $SIR_{V2L,J}^{FD}$ to determine the extent of the V2L connection in the full-duplex operation exploited by jamming for the conventional V-N connected with the LOS UAV. The ratio of the power acquired over the LOS UAV with the jamming signals, (I_J), the interfering signals, I_V^L , and the LOS UAV's residual-power, P_L^{RSI} , is used to calculate the $SIR_{V2L,J}^{FD}$.

The SIR acquired on the V-N generated by the LOS UAV is calculated as $SIR_{L2V,J}^{HD}$ to determine the extent of the L2V connection in the half-duplex fashion exploited by jamming for the conventional V-N connected to the LOS UAV. The power acquired through the LOS UAV over the recipient V-N divided by the jamming signals, (I_J), and the interfering signals, I_L^V , yields the $SIR_{L2V,J}^{HD}$. The SIR acquired through the LOS UAV on the V-N is calculated as $SIR_{L2V,J}^{FD}$ to determine the extent of the L2V connection in the full-duplex configuration exploited by jamming for the conventional V-N connected with the LOS UAV. The ratio of the power generated by the LOS UAV on the V-N with the jamming signals, (I_J), the interfering signals, I_L^V , and V-N's residual-power, P_V^{RSI} , is used to calculate the $SIR_{L2V,J}^{FD}$.

When calculating the SIR on the NLOS UAV exploiting jamming as $SIR_{V2N,J}^{HD}$, the extent of the V2N connection in the half-duplex configuration is determined for the conventional V-N connected to the NLOS UAV. By dividing the power measured on the NLOS UAV with the jamming signals, (I_J), and the interference, I_V^N , the $SIR_{V2N,J}^{HD}$ is calculated. By calculating the SIR on the NLOS UAV as $SIR_{V2N,J}^{FD}$, the extent of the V2N connection in the full-duplex operation exploited by jamming is determined for the conventional V-N connected to the NLOS UAV. The $SIR_{V2N,J}^{FD}$ is calculated by dividing the power attained on the NLOS UAV with the jamming signals, (I_J), the NLOS UAV's residual-power, P_N^{RSI} , and the interfering signals, I_V^N .

When determining the SIR acquired on the V-N generated by the NLOS UAV exploited by jamming as $SIR_{N2V,J}^{HD}$, the extent of the N2V connection in the half-duplex configuration is determined for the conventional V-N connected with the NLOS UAV. By dividing the power generated by the NLOS UAV on the recipient V-N with the jamming signals (I_J) and the interfering signal, I_N^V , the $SIR_{N2V,J}^{HD}$ is calculated. The SIR acquired on the NLOS UAV via the V-N is calculated as $SIR_{N2V,J}^{FD}$ to determine the extent of the N2V connection in the full-duplex configuration exploited by jamming for the conventional V-N connected with the NLOS UAV. The ratio of the power generated by the NLOS UAV on the V-N with the jamming signals, (I_J), the interfering signals, I_N^V , and the V-N residual-power, P_V^{RSI} , is used to calculate the $SIR_{N2V,J}^{FD}$.

When calculating the acquired SIR on the V-N as $SIR_{V2V,J}^{HD}$, the extent of the V2V connection in half-duplex operation exploited by jamming is determined with regard to the vehicular device connected to the recipient V-N by employing PC5 or side-link interface. When dividing the power on the recipient V-N with the jamming signals, (I_J), and the interfering signals, I_V^V , the $SIR_{V2V,J}^{HD}$ is calculated. When calculating the acquired SIR on the recipient V-N as $SIR_{V2V,J}^{FD}$, the extent of the V2V connection in a full-duplex operation exploited by jamming is determined according to the vehicular device connected to the

target vehicular device directly utilizing PC5/side-link. The $SIR_{V2V,J}^{FD}$ is calculated by dividing the power on the recipient V-N with the jamming signals, (I_J), the interfering signals, I_V^V , and the V-N's residual-power, P_V^{RSI} .

A full-duplex connection exploiting jamming is considered to fall in coverage if its determined SIR is greater than or equivalent to the pre-established SIR limit, τ . This can be derived using (45), (47), (49), and (52) for V2V, V2M, V2L, and V2N links, accordingly. The coverage of the half-duplex connections exploiting clustered jammers can be derived by utilizing a same method and excluding residual interference. Moreover, the coverage of the full-duplex connections, ignoring jammers, can be derived by utilizing a same method and excluding clustered interference. Following Equations (55)–(58), the spectrum effectiveness for a full-duplex connection by exploiting jamming and varying beam is derived. The half-duplex connection's SE exploited by jamming can be calculated by utilizing a same method and avoiding residual-interference. Furthermore, the full-duplex connection's SE ignoring jamming can be calculated by utilizing a same method and avoiding clustered jamming interference.

Figure 3 indicates the impact of clustered jammers, RSIs, variations of antenna 3-D beam-width, and pre-defined SIR threshold values for the UAV-assisted C-V2X overall network in regard to V-N's success in coverage. The V-N's coverage probability of the overall connection decreases by increasing the pre-defined value of the SIR. However, for a network without jammers, coverage is higher in comparison to a network with jammers because of extra jamming interference added at the denominator of the SIR expression, which results in a decrease in the SIR and the corresponding coverage. Moreover, the coverage of a network with a full-duplex environment is less than that of a half-duplex environment due to the addition of residual interference at the denominator of the SIR expression. In addition, the coverage of a full-duplex UAV-assisted C-V2X network exploiting clustered jammers and operating at a millimeter-wave band further decreases if the 3-D beam-width of the antenna varies because of the wind, air pressure, or mechanical UAV-controlling motor faults. This is because the power obtained at the receiver decreases, which decreases the SIR and the coverage. The coverage of the link by excluding jammers and using perfect SIC is roughly 0.92 at $\tau = 0$ dB, whereas the half-duplex link's coverage with jammers and using perfect SIC is roughly 0.47. This difference can be attributed only to jammers. The full-duplex transmission declines to about 0.43 whenever clustered jammers and imperfect RSI ($J = 4$, $RSI = 55$ dB, $\lambda_J = 2/\text{km}^2$) are present in the system. This represents a fractional reduction of about 44% in comparison to the non-jammer full-duplex link with RSI of 55 dB.

Figure 4 indicates the impact of jammers' power on a UAV-assisted C-V2X platform exploiting clustered jammers. The coverage of a UAV-assisted C-V2X network decreases with the increase in the power of jammers. In particular, the full-duplex U-V2X links' coverage excluding RSI along with $\sigma = 0^\circ$ is roughly 0.8 at $P_J = 20$ dBm. Coverage is reduced to about 0.79 when RSI of 55 dB is introduced at a similar power setting. In comparison to the optimal full-duplex analysis, coverage drops to about 0.75 whenever a beam variation of $\sigma = 2.5^\circ$ is added. This is a cumulative reduction of 5.3%. U-V2X coverage excluding RSI decreases to about 0.54 as P_J rises to 30 dBm, a decrease of 38% from previous analysis with $P_J = 20$ dBm, demonstrating the extremely sensitive nature of coverage to jamming transmission power. This is because of the addition of the power of jamming signals in the given region. Moreover, the coverage of a network is further decreased when the antenna 3-D beam-width variations increase in the network. This is because of the reduction of the received power of the intended transmission at the receiver, which reduces the SIR and the coverage of the given link in the network.

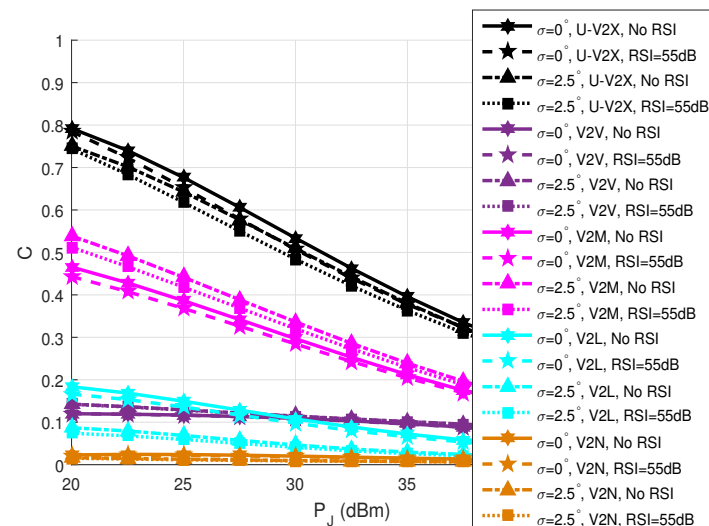


Figure 4. Impact of RSI and jammers' power over the typical V-N's coverage.

Figure 5 indicates the impact of jammers on the V-N's coverage for a clustered jamming network in a UAV-assisted C-V2X system. The coverage of a UAV-assisted C-V2X network decreases with the addition of jamming clusters. In particular, the full-duplex U-V2X coverage excluding RSI along with $\sigma = 0^\circ$ is roughly 0.51 at $\lambda_J = 5/\text{km}^2$. Coverage drops to about 0.50, or two%, when RSI of 55 dB is introduced at a similar intensity. Coverage decreases to about 0.48 whenever a beam variation of $\sigma = 5^\circ$ is added. This is a cumulative deterioration of 6.2% in comparison to the optimal traditional full-duplex. This is because of the addition of jamming signals in the given region. Moreover, the coverage of a network is further decreased when the antenna 3-D beam-width variations increase in the network.

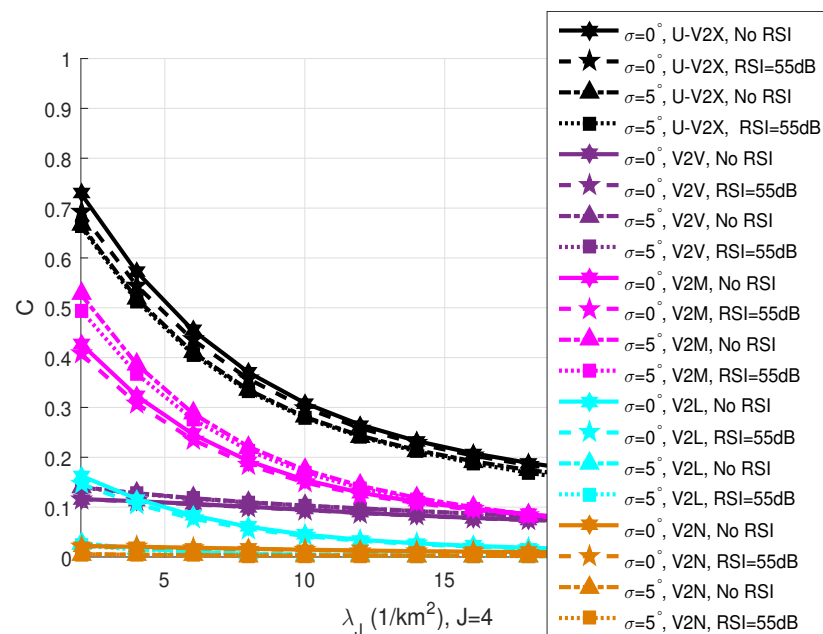


Figure 5. Impact of RSI and jammers on the typical V-N's coverage.

Figure 6 indicates the impact of jammers on the V-N's spectrum effectiveness for a full-duplex UAV-assisted C-V2X system. The efficiency of the UAV-assisted C-V2X system in terms of spectrum for a full-duplex network with perfect interference cancellation in ($J = 0$, U-V2X, No RSI curve) and with residual interference ($J = 0$, U-V2X, RSI = 55 dBm curve) is higher without clustered jammers, as compared to the UAV-assisted C-V2X

system with jammers. The effectiveness of the spectrum of a UAV-assisted C-V2X network decreases with the addition of jamming clusters. This is because of the addition of jamming interference in the given region that reduces the SIR and the bandwidth efficiency. Moreover, the effectiveness of the spectrum of a network is further decreased when the antenna 3-D beam-width variations, along with the clustered jammers, increase in the network. Hence, enhanced counter-jamming strategies should be designed whenever jammers, as well as 3-D beam-width variations, interrupt the communication system. The SE approaches to 1.2 nats/s/Hz at $\lambda_J = 2$ assuming the full-duplex setup with jamming devices; the SE, by eliminating jammers and employing perfect SIC, is around 2.4 nats/s/Hz. Whenever clustered jamming equipment is increased to $\lambda_J = 3$, the full-duplex communication with perfect RSI additionally reduces to around 0.9 nats/s/Hz.

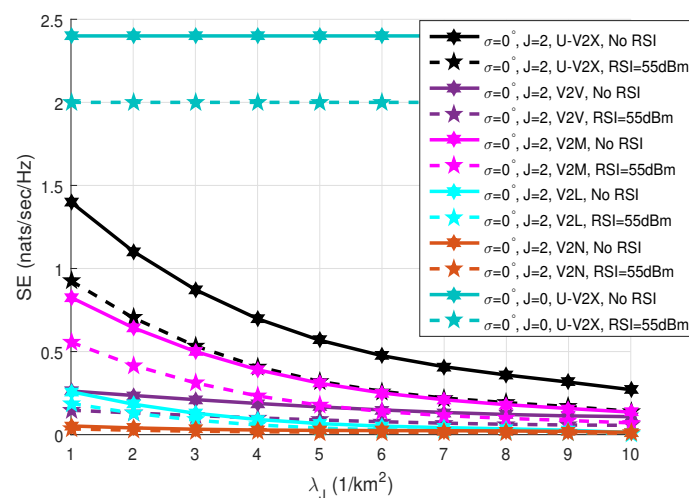


Figure 6. Impact of RSI and jammers on the typical V-N's spectrum.

Figure 7 indicates the impact of jammers' power on the V-N's spectrum for a clustered jamming network in a UAV-assisted C-V2X system. The effectiveness of the spectrum of a UAV-assisted C-V2X network decreases with the addition of the power of jammers. In particular, the SE for the full-duplex U-V2X connection excluding RSI with no beam dispersion ($\sigma = 0^\circ$) equals roughly 1.07 nats/s/Hz at $P_J = 20$ dBm. Whenever RSI of 55 dB is introduced at the identical power value, SE is reduced to about 0.725 nats/s/Hz, a decrease of about 39% that can only be attributed to RSI. The SE of the full-duplex U-V2X connection lacking RSI decreases to about 0.45 nats/s/Hz when P_J rises to 30 dBm, a significant decrease compared to the analysis with $P_J = 20$ dBm. The SE further drops to about 0.25 nats/s/Hz whenever RSI as well as beam variation ($\sigma = 2.5^\circ$) exist at $P_J = 30$ dBm. This is because of the addition of the power of jamming interference in the given region, which decreases the SIR and the spectrum effectiveness. Moreover, the effectiveness of the spectrum of a network is further decreased when the antenna 3-D beam-width variations increase in the network.

Figure 8 shows the effect of the V-Ns on the extent of coverage of the target V-N. The coverage of the UAV-assisted C-V2X connection degrades due to a jamming cluster when the clustered jammers are increased in the network. However, when the percentage of V-Ns in the system is increased, the pathloss across the examined V-Ns minimizes while the obtained SIR associated with the V2V connection grows, which enhances the extent of coverage of the V2V connection compared to the remaining connections. The inclusion of residual-interference in the UAV-assisted C-V2X system reduces its coverage (as indicated by $\sigma=2.5$). In particular, the U-V2X full-duplex coverage excluding RSI with a $\sigma = 0^\circ$ is roughly 0.72 at $\lambda_V = 5/\text{km}$. Coverage is reduced to about 0.68 when RSI of 55 dB is

introduced at the identical density. The coverage reduces even more to about 0.65 when beam variation ($\sigma = 2.5^\circ$) is added. This represents an overall deterioration of 10 (%) in comparison to the optimal full-duplex benchmark. The reason is that when the RSI is added to the system, the interruption in the denominator of the recipient SIR rises, which lowers the obtained SIR and coverage of the evaluated connection. Additionally, whenever the deviations of the LoS or NLoS UAV's antennae beam-width changes grow (that is, from $\sigma = 0^\circ$ to $\sigma = 2.5^\circ$ or $\sigma = 5^\circ$), the coverage of the V2L link and V2N connection reduces (in contrast to the V2M connection and V2V connection). This happens since high-speed winds, air challenges, or the vibration impacts of regulating controllers can trigger the UAV's alignment to oscillate. Hence, enhanced counter-jamming strategies must be designed whenever jammers, as well as 3-D beam-width variations, interrupt the communication system.

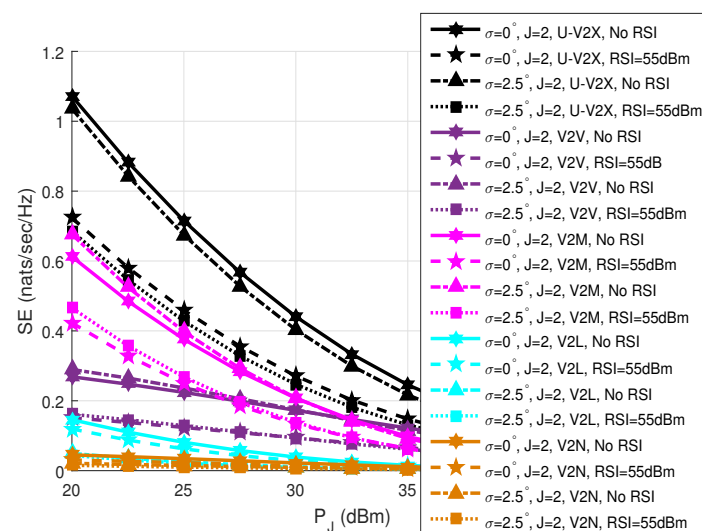


Figure 7. Impact of RSI, beam variations and jammers' power over the typical V-N's spectrum.

Figure 9 demonstrates the way RSIs, beam-width shifts, and UAVs affect the V-N's coverage. It can be observed that the coverage of the U-V2X connection without RSI, clustered jammers, $J = 2$, and beam-width variations of $\sigma = 0^\circ$ has lower performance in comparison to coverage of the U-V2X connection without RSI and $\sigma = 0^\circ$. In particular, at $\lambda_U = 4/\text{km}^2$, the U-V2X full-duplex coverage lacking RSI with $\sigma = 0^\circ$ in the midst of jamming devices is roughly 0.65, as opposed to roughly 0.93 for the jammer-less case at the identical density. This indicates that jamming phenomenon by itself has caused an impairment of almost 43%. When jamming devices at $\lambda_U = 4/\text{km}^2$ are added with RSI of 55 dB, coverage decreases even more to about 0.62 making a fractional decrease of 50%. This is because of the addition of extra jamming interference in the system, which reduces the SIR and the system's performance. Due to the presence of additional interference (i.e., self-interfering signals) in the SIR expression, which lowers the acquired SIR, the coverage of a full-duplex UAV-assisted C-V2X system with RSI for different connections, including V2V, V2M, V2L, or V2N connections, falls short compared to the particular connections lacking RSI. Since the path loss across V-Ns and UAVs reduces as the mean number of UAVs in the system rises, the coverage of V2L or V2N connections enhances (in comparison to V2V and V2M connections).

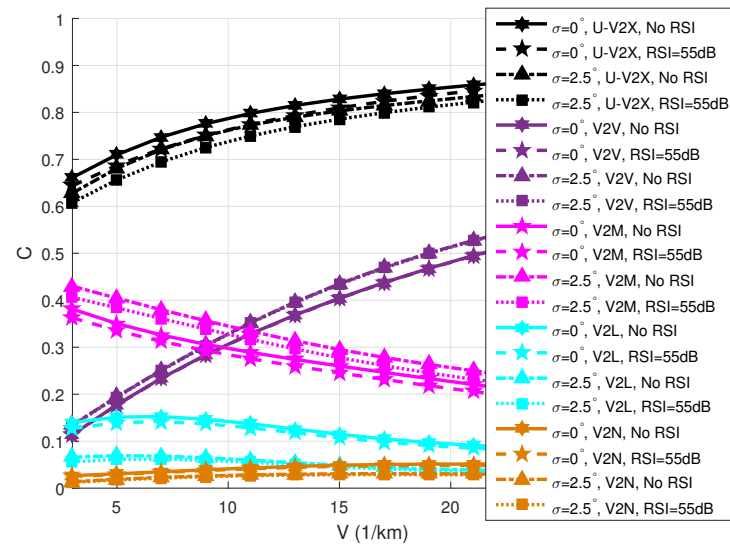


Figure 8. Impact of RSI, varying beams, and V-Ns over the typical V-N's coverage. $\lambda_J = 2, J = 2$.

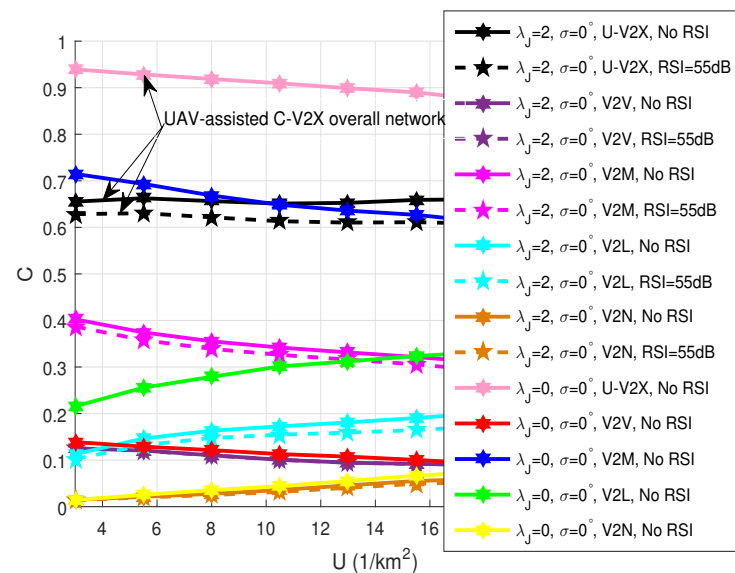


Figure 9. Impact of RSI, jammers and LAPs over the typical V-N's coverage.

Figure 10 illustrates the way UAVs and beam-width fluctuations affect a clustered jamming framework in a full-duplex UAV-assisted C-V2X setup across the V-N's coverage. In contrast to V2V and V2M connections, the extent of coverage of V2L and V2N connections diminishes whenever the beam-width alignment of the UAV changes and oscillates (such as $\sigma = 2.5^\circ$). This happens due to the contrast to non-aerial base-stations; the 3-D radiation of a UAV is susceptible to oscillations having an acceptable dispersion (variance) depending on the velocity of the wind, air challenges, and the noise-disturbance of the regulating motor. Hence, enhanced counter-jamming strategies should be designed whenever jammers, as well as 3-D beam-width variations, interrupt the communication system. The results reveal several non-trivial trade-offs for the full-duplex system with $\lambda_J = 2$ and $J = 2$. The V2V link outperforms the V2L connection when UAV density $< 4/\text{km}^2$ because at low UAV densities the expected V-N to LOS UAV distance is large, resulting in higher path loss on the V2L link than the V2V link. Moreover, a non-monotonic behavior is observed for the V2L connection, where coverage increases with UAV density up to a threshold of approximately $25/\text{km}^2$, beyond which V2L coverage decreases because the aggregate LOS

UAV interference growth dominates the path loss reduction. In contrast, V2N coverage increases monotonically with UAVs since NLOS UAVs experience higher path loss and additional attenuation $\mathcal{L}_N$, making them inherently weaker interferers than LOS UAVs, and the benefit of reduced V-N to UAV distance consistently outweighs the additional interference. This asymmetry between V2L and V2N behaviors with respect to UAVs is a non-trivial result that requires the derived analytical expressions to characterize precisely.

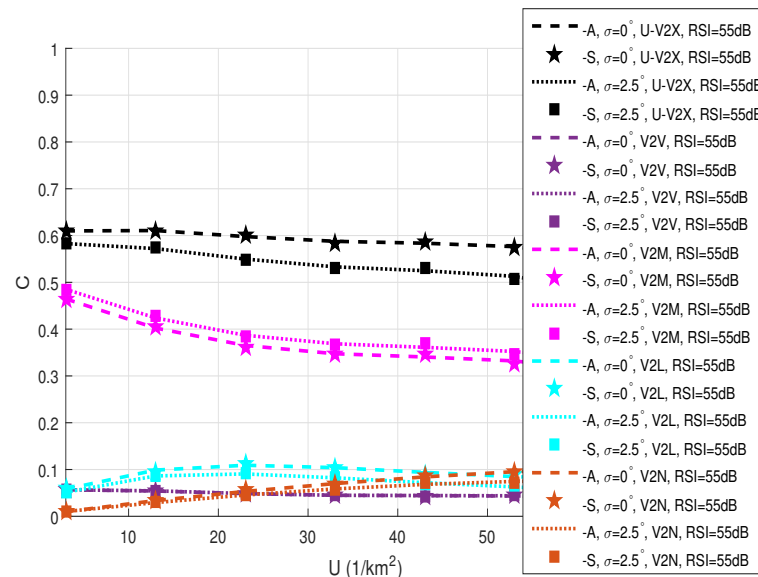


Figure 10. Impact of varying beams and LAPs over the typical V-N's coverage. $\lambda_J = 2$.

Figure 11 shows how MBSs, beam-width fluctuations, RSIs, and clustered jammers affect the V-N's coverage. The coverage of the UAV-assisted C-V2X system with clustered jammers is lower than that without a clustered cellular network because of the addition of extra interference from the clustered jammers. In particular, the U-V2X full-duplex coverage without RSI and having $\sigma = 0^\circ$ is roughly 0.7 at $\lambda_M = 5/\text{km}^2$. Coverage drops to about 0.69 when RSI of 55 dB is introduced at identical intensity. This 1.4% decrease is caused by RSI within the SIR equation. Coverage decreases to about 0.68 whenever a beam variation of $\sigma = 2.5^\circ$ is included. This is a cumulative reduction of 2.8% in comparison to the optimal traditional full-duplex with the identical MBS intensity. In comparison to V2V and V2M connections, the coverage of V2L and V2N connections diminishes as the UAV's beam-width orientation varies, up to $\sigma = 2.5^\circ$. This is due to the fact that the 3-D beam of the UAV is susceptible to variations that are represented by a standard deviation (variance) that is influenced by wind speeds, atmospheric pressures, and the noise produced by mechanically controlled motors. When the mean number of MBSs in an infrastructure grows, the path loss across V-N and MBS reduces, boosting the acquired SIR and extent of coverage of the V2M connection (in comparison to V2V, V2L, and V2N connections). Since additional disruption (for instance, residual-interference) is included in the acquired SIR, a full-duplex UAV-assisted C-V2X system exploiting clustered jammers with RSI (and $\sigma = 2.5^\circ$) for different connections, including V2V, V2M, V2L, and V2N connections, is lower than the coverage of the specified connections lacking RSI.

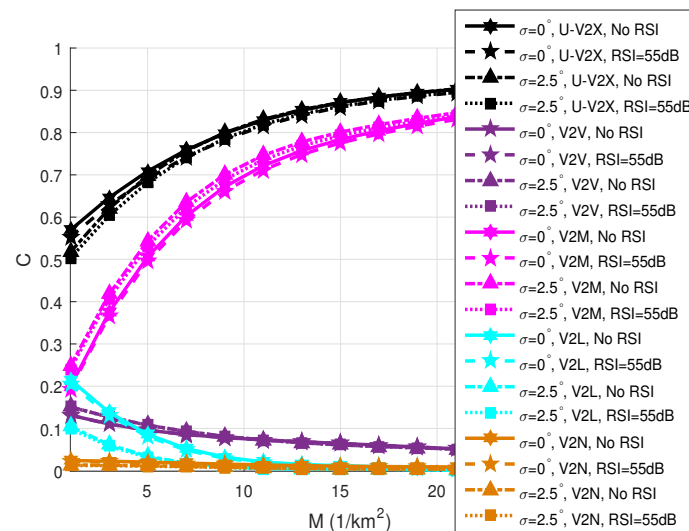


Figure 11. Impact of RSI, varying beams and MBSs over the typical V-N's coverage. $\lambda_J = 2$.

7.2. Anti-Jamming Techniques

To mitigate the negative effects of jamming transmissions and ensure the safe operation of full-duplex configurations, a number of strategies might be used. Slot-centered V2X equipment [41] is one potential strategy that reduces deliberate side-link surveillance and operations that interfere with V2X exchanges by changing the pace of data delivery. It is also possible to employ a randomized station-hopping technique [42], in which the effect of jammy interruption is lessened by channel surfing. According to [43], a sudden change in conventional RF frequencies lessens the negative impacts of jamming equipment by repeating communications on an unhindered path. In [44], a behavioral-based architecture enables vehicular devices to cooperate and exchange identification in order to thwart jamming assaults. Service results in interrupted jamming scenarios might also be evaluated using the MIMO-powered approach in [45]. Additionally, the detrimental effects of various jamming instances are capable of being lessened in real-world situations by modifying information rates and power management techniques [46,47]. The derived coverage and SE expressions in this paper provide analytical benchmarks against which these countermeasures can be evaluated in future work.

7.3. Limitations and Future Research Directions

The analytical characterization of the UAV-enabled C-V2X full-duplex infrastructure under clustered jamming conditions is covered in this research; it is worthwhile addressing a few underlying considerations. First, the approach neglects shadowing that can take place in congested urban settings where adjacent automobiles exhibit identical obstacles since it implies geographically independent fading over connections. Second, organized urban grid geometries like Manhattan-shaped roadway frameworks can be considered to model roads. Third, time-varying impacts like Doppler shift are not included. Lastly, the evaluation is limited to millimeter wavebands (60 GHz) and excludes the terahertz frequency (THz) spectrum, that is becoming more and more popular for vehicle systems.

The current work can be extended by: (i) applying the design to THz band transmissions to assess system behavior according to severe beam sensitiveness and molecular absorption for higher-speed automobile situations [48]; (ii) adding shadow-based modeling and organized road configurations to more accurately simulate complex urbanized configurations; (iii) creating mobility-conscious channel-specific modeling that specifically take into consideration handover parameters and Doppler effects; (iv) implementing counter-jamming approaches like flexible beam-forming, and intelligent reflection-based

surface-aided jamming [49,50]; and (v) examining joint UAV high-altitude optimization techniques along with jamming to increase system capacity within real-world settings [51].

8. Conclusions

This paper examines a full-duplex millimeter waveband UAV-driven C-V2X system exploited by clustered jamming and beam-width variations of the antenna. Clustered jamming uses devices in groups and interrupts the desired or intended transmissions. The paper models UAVs as a 3-D PPP and MBSs as a 2-D PPP, while roads are characterized by a PLP and the V-Ns on each road are characterized by a 1-D PPP. The deviations of the UAV's antenna 3-D beam are characterized by a Normal distribution. From a theoretical standpoint, the association, coverage, and spectrum of a typical connection are investigated by considering a full-duplex infrastructure as a function of jamming clusters, V-Ns, MBSs, UAVs, jammer's power, and beam-width deviations. From a practical engineering prospective, the results revealed that clustered jamming signals reduce the efficiency of a full-duplex UAV-driven C-V2X millimeter-wave connectivity when compared with a network without jamming signals, and that the efficiency of a network further reduces when there are larger 3-D beam-width variations of the antenna along with the clustered jammers. Hence, enhanced counter-jamming strategies must be designed whenever jammers, as well as 3-D beam-width variations, interrupt the communication system.

Future research will focus on producing robust beam correction using deterministic beam monitoring and reinforcement learning-driven beam synchronization, setting up anti-jamming techniques like jamming-sensitive energy management and intelligent reflective surface-supported interfering suppression, expanding the design to THz band transmission for rapid vehicular environments in advanced networks, and adding shadowing and precise mobility models to make the architecture more realistic for dense urban configurations.

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Appendix A. Derivation of (14)

V-N's communication with the closest receiving device is based on the assumption of the absence of additional devices that are located closer than the recipient device. Two important probabilities can be taken into consideration to obtain the desired distance-distributions. Primarily, for the first probability, the devices between V-N and the recipient device are assumed to be zero, and in the subsequent probability, the V-Ns on the highway that runs through $-z_V$ to $+z_V$ but passes the center point, o , are assumed to be zero. A typical method for describing the CDF of distance is computed as [12]

$$F_V(z) = 1 - [\Pr\{z_V > z\}]$$

$$= 1 - \left[\overbrace{\Pr\{\mathbf{N}(\mathbf{D}(o, z_V)) = 0\}}^{\beta_1} \overbrace{\Pr\{\mathbf{N}(\mathbf{D}_o(-z_V, +z_V)) = 0\}}^{\beta_2} \right],$$

where $\overbrace{\Pr\{\mathbf{N}(\mathbf{D}(o, z_V)) = 0\}}^{\beta_1}$ is the probability that the number of V-Ns is null for a disc, $\mathbf{D}(o, z_V)$, placed at origin with radius z_V , and $\overbrace{\Pr\{\mathbf{N}(\mathbf{D}_o(-z_V, +z_V)) = 0\}}^{\beta_2}$ is the probability that the number of V-Ns is null between points $-z_V$ and z_V for a typical road passing origin. β_1 can be simplified by considering that there are l roads in a disc, $\mathbf{D}(o, z_V)$, and can be expressed as

$$\beta_1 = \sum_{l=0}^{\infty} \Pr\{\mathbf{N}_{\text{Roads}}(\mathbf{D}(o, z_V)) = l\} \times \prod_{q=1}^l \Pr\{N(\text{Road}_q) = 0\},$$

where $\mathbf{D}(o, z_V)$ corresponds to l , $\Pr\{\mathbf{N}_{\text{Roads}}(\mathbf{D}(o, z_V)) = l\}$ represents the probability of the entire number of roads within a circle-shaped region, while $\Pr\{N(\text{Road}_q) = 0\}$ represents the probability of the number of equipment on each segment of the q -th motorway. Each highway's V-N is supposed to conform with a 1-D PPP, although highways in the framework under evaluation are assumed to follow a PLP. Thus, the average number of roads in a circular radius is $l_1 = 2\pi\lambda_R z_V$, and the average number of devices on each motorway is $l_2 = 2\lambda_V \sqrt{z_V^2 - y^2}$. The representation of β_1 is

$$\beta_1 = \sum_{l=0}^{\infty} \frac{\exp\left(-\overbrace{2\pi\lambda_R z_V}^{l_1}\right) (2\pi\lambda_R z_V)^l}{l!} \left(\int_{-z_V}^{z_V} \frac{e^{-2\lambda_V \sqrt{z_V^2 - y^2}}}{2z_V} dy \right)^l.$$

β_1 can be simplified by using $\int_{b_1}^{b_2} dz = 2z$ and given as

$$\beta_1 = \exp(-2\pi\lambda_R z_V) \sum_{l=0}^{\infty} \frac{\left(\pi\lambda_R \int_{-z_V}^{z_V} e^{-2\lambda_V \sqrt{z_V^2 - y^2}} dy \right)^l}{l!}.$$

Using $\sum_{l=0}^{\infty} \frac{\mathcal{Y}^l}{l!} = \exp(\mathcal{Y})$, β_1 can be computed as

$$\beta_1 = \exp\left(-2\pi\lambda_R \int_0^{z_V} \left(1 - e^{-2\lambda_V \sqrt{z_V^2 - y^2}}\right) dy\right).$$

Similar steps can lead to get β_2 and can be computed as $\beta_2 = \exp(-2\lambda_V z_V)$. Inserting the values of β_1 and β_2 in $F_V(z)$, the CDF is given as

$$F_V(z) = 1 - \exp\left(-2\pi\lambda_R \int_0^{z_V} \left(1 - e^{-2\lambda_V \sqrt{z_V^2 - y^2}}\right) dy\right) \exp(-2\lambda_V z_V).$$

Appendix B. Derivation of (42)

Given a cluster of jamming equipments, the disruption caused by jammers could possibly be calculated as [52,53]

$$L_{I_j} = \overbrace{\exp\{-\lambda_J \int_0^\infty (1 - \exp\{-J \nabla(t, y)\}) dy\}}^{\mathbb{U}} \times \overbrace{\int_0^\infty \exp\{-J \nabla(t, y)\} f(y) dy}^{\Omega},$$

where $\nabla(t, y) = \int_0^\infty \frac{g(x_1 - x_2 - t)}{g(x_1 - x_2 - t) + g(t)/\tau} f(x_1) dx_1$. For clustering devices, PGF is $\mathbb{U}$, and is computed as

$$\begin{aligned} \mathbb{U} &= \exp\left\{-\lambda_J \int_0^\infty \left(1 - \exp\left\{-J \int_0^\infty \frac{g(x_1 - x_2 - t)}{g(x_1 - x_2 - t) + g(t)/\tau} f(x_1) dx_1\right\}\right) dy\right\} \\ &\stackrel{a}{=} \exp\left\{-\lambda_J \int_0^\infty \left(1 - \exp\left\{\int_0^\infty -\frac{Jg(y)f(x_1)dx_1}{g(y) + g(t)/\tau}\right\}\right) dy\right\} \\ &\stackrel{b}{=} \exp\left\{-\lambda_J \pi \tau^{2/\alpha_J} z_{N_r}^2 \int_0^\infty \left(1 - \exp\left\{\frac{-J}{1 + \Omega^{\alpha_J/2}}\right\}\right) d\Omega\right\}. \end{aligned}$$

Ω can be found using simple math as $\Omega = \exp\left\{-\mathbb{J} z_{N_r}^2 \tau^{2/\alpha_J} \frac{2\pi^2}{\alpha_J} \csc\left(\frac{2\pi}{\alpha_J}\right)\right\}$ [52], where $\mathbb{J} = \lambda_J (\pi r_f^2)^{-1}$. An equation for jammed disruption of clustered equipments is obtained by putting $\mathbb{U}$ and Ω in L_{I_j} .

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