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Modelling and Statistical Analysis of Geometry- Based Vehicle-to-Vehicle Communication Channels in Tunnel Environments

By

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Project submitted as part of the requirements for
the award of MSc Software Engineering and
Artificial Intelligence

9 July 2024

I. DECLARATION OF ORIGINALITY

I am Wenhao Zhong, I declare that I am the sole author of this Project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits. This work has not previously been accepted as part of any other degree submission.

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II. FORM OF CONSENT

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III. ACKNOWLEDGEMENTS

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IV. ABSTRACT

With the development of sixth generation (6G) wireless network technology and the advancement of Internet of Things (IoT) technology, people's attention to vehicle-to-vehicle (V2V) communication in tunnel scenes is increasing. It means that accurate mathematical models need to be established to characterise the channel characteristics of tunnels. Unlike the method of characterising tunnel channel characteristics through a large amount of measured data, establishing geometry-based stochastic model (GBSM) and scattering cluster models simulates the channel characteristics of actual environments by establishing abstract and concise geometric models and changing the parameters of the models. This study mainly introduces the basic theory and analysis methods of GBSM and scattering clusters, establishes a non-stationary three-dimensional (3D) channel model combining GBSM and scattering clusters in tunnel scenes, and provides calculation methods as well as corresponding closed form expressions for channel impulse response and spatial-temporal cross-correlation function. On this basis, corresponding statistical characteristics were investigated through MATLAB software simulation, including channel impulse response (CIR) temporal auto-correlation function (ACF), spatial cross-correlation function (CCF) and doppler power spectral density (PSD).

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1. INTRODUCTION

The first chapter serves as an introduction, outlining the background of research on GBSM and scattering clusters in the context of vehicle-to-vehicle wireless communication, as well as the goals, objectives, and significance of this field's study. Additionally, this report's structure is described in this section.

1.1 BACKGROUND

In recent years, the increasing use of motor vehicles has sparked great interest and investment in improving vehicle-to-vehicle (V2V) wireless communication technology under the sixth generation (6G) communication framework [1]. These developments are crucial for achieving smooth data exchange and control between vehicles, supporting various applications such as autonomous driving, intelligent transportation systems, and emergency response [2]. The core of V2V communication system improvement is the use of complex modelling techniques that can accurately capture the inherent complex propagation characteristics in vehicle-to-vehicle communication channels [3], [4].

Among various modelling methods, the Geometry-Based Stochastic Model (GBSM) has become a particularly useful tool. GBSM provides a method for simplifying complex physical environments encountered in V2V communication scenarios into geometric representations, while still including fundamental factors such as line of sight (LoS) and non-line of sight (NLoS) conditions, multipath propagation phenomena, and the influence of variable environmental factors [5]. By using GBSM, researchers and engineers can gain valuable insights into the behavior of wireless channels in different operating environments, enabling them to design and optimise communication protocols and signal processing algorithms based on the specific requirements and limitations of V2V communication systems.

However, although the traditional GBSM framework is useful in many scenarios [6], its applicability is limited in certain environments, especially those where geometric structures and propagation conditions undergo dynamic changes [7]. One challenging scenario is the communication between vehicles in a tunnel environment. Tunnels pose unique propagation

challenges due to their limited space, irregular shape, and the presence of reflective surfaces that may cause multipath interference and signal attenuation [8], [9], [10]. In addition, the movement of vehicles within tunnels introduces additional complexity, resulting in non-stationary channel conditions that traditional stationary channel models can not fully capture [11].

To address these challenges, there is an urgent need to develop a new channel modelling framework specifically designed for vehicle-to-vehicle communication in tunnel environments. This study aims to supplement the existing literature on V2V communication systems in tunnel environments, and contribute to building a more robust and reliable V2V communication system that can support a wide range of applications in tunnel environments.

1.2 AIM

This research activity aims to develop and optimise novel geometry-based channel models specifically suited for V2V communication within tunnel environments in order to address issues like limited line-of-sight opportunities and multipath propagation to enhance communication reliability and efficiency.

1.3 OBJECTIVES

The objectives of this study are showed as follows.

Examine and evaluate the current literature: Perform a thorough analysis of the body of research on geometry-based channel modelling methods and how they are used in tunnel contexts for V2V communication systems. Determine the main obstacles and variables affecting the effectiveness and dependability of communication in tunnel contexts.

Model development: Create innovative geometry-based channel models that are especially suited for V2V communication in tunnel contexts, taking into account characteristics related to the environment, multipath propagation, and restricted opportunities for loss of service.

Analysis and appraisal of performance: Evaluate the suggested channel models' performance in terms of throughput, latency, and communication dependability by

contrasting it with the models and standards that are currently in use. Determine methods and approaches for reducing the impact of multipath propagation and restricted LoS in tunnel situations in order to improve the dependability and effectiveness of V2V communication systems.

1.4 STRUCTURE OF THE REPORT

This report is divided into six chapters to establish and simulate the model of GBSM combined with scattering clusters. The structure of the entire report is arranged as follows.

Chapter 1 is the introduction section, which mainly introduces the research background of GBSM and scattering clusters in the wireless communication environment of vehicle-to-vehicle, the research aims, objectives, significance of research of GBSM and scattering clusters. Moreover, the structure of this report is stated.

Chapter 2 is the section of the review of literature, which introduces the current research status of automobiles, the research status of wireless communication of vehicle-to-vehicle, and the research status of GBSM and scattering clusters.

Chapter 3 introduces the research methodology of this report, which includes the research methods, paradigms and so on determined based on the Research Onion framework, the research results and innovative points to be achieved in this report, the Gantt chart of project management in this study, and an introduction to GBSM and scattering cluster methods.

Chapter 4 presents the design of a model using GBSM combined with scattering cluster methods for V2V wireless communication in tunnel environments, including the introduction of various parameters in the model, derivation and calculation of channel impulse response formulas, introduction of distribution functions, and relevant knowledge of wireless communication used. Moreover, CIRs are simulated and analysed.

Chapter 5 analyses and calculates the channel characteristics of the established model, such as spatial-temporal correlation functions and Doppler power spectrum density, as well as MATLAB simulation and analysis of important functions that characterise channel correlation characteristics. Functions simulated and analysed in this report mainly are the

temporal auto-correlation function, spatial cross-correlation function, and Doppler power spectrum density, to verify the correctness of the derived formulas and whether they match the measured data curves in the part of review of literature. Additionally, the properties and reasons for the changes of each function based on the simulation results are compared and analysed.

Chapter 6 is the summary section of the report, which reviews and summarises the research content of this report, then the aim and objectives of this study are recapped on.

Chapter 7 offers reflections based on the lecture learning gains in UWTSD, accomplishments and study findings of the master project.

2. REVIEW OF LITERATURE

The second chapter of this study provides a comprehensive review of the existing literature and presents an overview of the current state of research on vehicles, vehicle-to-vehicle wireless communication, GBSM, and scattering clusters. This chapter aims to contextualise the study within the broader academic and technological landscape, highlighting the significant advancements and identifying the gaps that this research seeks to address.

2.1 INTRODUCTION

The automobile, a vehicle powered by an internal combustion engine or electric motor, has revolutionised personal and commercial transportation since its inception. The concept of automobiles dates back to the late 19th century, with pioneers such as Karl Benz and Henry Ford [12] playing crucial roles in their development and mass production. Over the decades, automobiles have evolved significantly, incorporating advanced technologies to enhance safety, efficiency, and comfort. Modern automobiles are equipped with sophisticated systems, including electronic control units (ECUs), advanced driver-assistance systems (ADAS), and various sensors and communication modules that facilitate semi-autonomous and autonomous driving capabilities [13].

Vehicle to Vehicle (V2V) wireless communication is a critical component of Intelligent Transportation Systems (ITS), enabling vehicles to communicate with each other to improve road safety and traffic efficiency. The concept of V2V communication involves the exchange of information such as speed, location, and direction between vehicles in real-time. This technology aims to reduce accidents, enhance traffic flow, and support autonomous driving. The development of V2V communication has been driven by advancements in wireless communication technologies, including Dedicated Short-Range Communications (DSRC), Cellular Vehicle-to-Everything (C-V2X), and advancements in 5G networks [14], [15], [16]. These technologies provide the necessary infrastructure for reliable and low-latency communication between vehicles.

Geometry-Based Stochastic Model (GBSM) and scattering clusters are advanced channel modelling techniques used to represent the complex propagation environments encountered in wireless communication [17], [18]. GBSM combines deterministic geometric modelling

with stochastic elements to simulate the variability and randomness of wireless channels. This approach is particularly useful in V2V communication scenarios, where the environment is dynamic and unpredictable. The concept of scattering clusters involves grouping scatterers based on their spatial and temporal characteristics, providing a detailed representation of multipath propagation. The development of these models has been essential for understanding and predicting the behavior of wireless channels, enabling the design of robust communication systems.

2.2 RESEARCH OF AUTOMOBILES AT THE PRESENT

In 1886, Karl Benz invented the world's first automobile, marking the official beginning of the development of automobiles. At the beginning of the 20th century, Ford Motor Company introduced assembly line production, significantly reducing the production cost of automobiles and promoting their popularity. By the end of the 20th century, many countries had developed advanced automotive technology, greatly promoting the development of modern transportation [19]. At present, the United States is at the world's leading level in autonomous driving and intelligent vehicle technology, while European countries such as Germany, Japan, and France are also in a rapid development stage in automotive technology. In recent years, the United States has made significant breakthroughs in autonomous driving technology and has begun large-scale commercialisation. Due to its advantages of intelligence and efficiency, smart cars have been widely used in multiple civilian fields.

With regard to the application of automobiles, [20], [21] reviewed the current application fields, future trends and applications of related technologies of autonomous vehicle. Intelligent vehicles are also widely used in fields such as monitoring, agriculture, environmental monitoring, disaster management, infrastructure inspection, and urban planning. Papers point out that intelligent vehicle solutions require interdisciplinary research, integration of different professional knowledge, and interaction of research topics in different fields.

The advancement of automotive technology has led to the development of more complex platforms, which have been enhanced in terms of range, payload capacity, and autonomy. It is worth noting that the integration of artificial intelligence and machine learning algorithms has also played a key role in pushing the performance boundaries of intelligent vehicles [22], [23],

[24].

Despite significant progress in the development of intelligent vehicles, there are still some challenges. These include issues related to the integration of road traffic systems, collision avoidance, communication and navigation in complex environments, network security, and ethical considerations in the use of autonomous vehicle [25]. Cheng-Xiang Wang *et al.* [1] pointed out that specific channel measurements require other equipment/conditions, such as vehicles and large antenna arrays. The measurement of 6G channels related to smart cars is more challenging, especially in high-frequency maneuvering, long-distance, and harsh environments. Addressing these challenges provides opportunities for further innovation and collaboration among academia, industry, and government departments to unleash the full potential of intelligent vehicle technology.

2.3 DEVELOPMENT OF V2V WIRELESS COMMUNICATION

Vehicle-to-Vehicle (V2V) wireless communication has emerged as a pivotal technology in the realm of intelligent transportation systems (ITS), with the potential to significantly enhance road safety [26], traffic efficiency [27], autonomous driving capabilities [28] and so on. The development of V2V communication can be traced back to the late 20th century when the need for real-time information exchange between vehicles became apparent as a means to mitigate traffic accidents and improve driving conditions.

The initial concept of V2V communication was proposed in the 1990s, primarily focusing on short-range communication technologies that could enable vehicles to share information such as speed, position, and direction [29]. Early research efforts were concentrated on understanding the fundamental requirements and challenges associated with inter-vehicular communication. The advent of Dedicated Short-Range Communications (DSRC) marked a significant milestone in the development of V2V communication. DSRC, operating in the 5.9 GHz band, was specifically designed to support low-latency and high-reliability communication between vehicles, making it suitable for safety-critical applications [30].

As vehicular technology advanced, so did the need for more sophisticated communication systems. The 2000s saw extensive research and development activities aimed at standardising V2V communication protocols. The IEEE 802.11p standard, an amendment to

the IEEE 802.11 standard specifically tailored for wireless access in vehicular environments, was introduced to address the unique requirements of V2V communication, such as high mobility and dynamic network topology [31].

The technological advancements in V2V communication have been driven by the parallel developments in wireless communication technologies and vehicular electronics. Key technologies that have significantly contributed to the evolution of V2V communication mainly include DSRC, C-V2X and 5G. Dedicated Short-Range Communications (DSRC) provides a reliable platform for V2V communication, enabling applications such as collision avoidance, emergency vehicle warning, and cooperative adaptive cruise control [14]. Its low-latency and high-reliability characteristics are crucial for real-time safety applications. Additionally, Cellular Vehicle-to-Everything (C-V2X) has emerged as a robust alternative to DSRC with the advent of 4G LTE and 5G technologies [15]. C-V2X leverages the existing cellular infrastructure to support not only V2V communication but also Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrian (V2P) communication. The capabilities of C-V2X, particularly in terms of range, scalability, and network management, make it a strong contender for future ITS applications. Moreover, the deployment of 5G networks promises to further revolutionise V2V communication by providing ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) [16]. These capabilities are essential for supporting the high data rate and low-latency requirements of advanced vehicular applications such as autonomous driving and vehicular platooning.

Current research in V2V communication is focused on enhancing the robustness, reliability, and scalability of communication systems to support a wide range of applications. Key areas of research mainly include four parts. The first is channel modelling and propagation studies. Understanding the propagation characteristics of V2V communication channels is crucial for designing reliable communication systems. Research efforts are directed towards developing accurate channel models that can capture the effects of mobility, multipath propagation, and interference in various vehicular environments [32]. The second part is security and privacy. Ensuring the security and privacy of V2V communication is paramount, given the sensitive nature of the data exchanged between vehicles. Research is ongoing to develop robust security protocols and mechanisms to protect against cyber threats and ensure the integrity and confidentiality of vehicular communications [33]. The third section is interoperability and standardisation. Achieving interoperability between

different V2V communication systems and ensuring compliance with international standards is a significant challenge [34]. Research initiatives are focused on harmonising the various standards and protocols to enable seamless communication across different platforms and regions. The last element is network management and resource allocation. Efficient management of network resources and dynamic allocation of communication channels are critical for maintaining the quality of service (QoS) in V2V communication networks [35]. Advanced techniques such as machine learning and artificial intelligence are being explored to optimise network performance and resource utilisation.

Despite the significant progress made in V2V wireless communication, several challenges persist. One of the primary challenges is ensuring robust and reliable communication in highly dynamic and complex environments, such as urban areas and tunnels, where signal obstructions and multipath propagation are prevalent. Security and privacy concerns also pose significant hurdles, as real-time data exchange between vehicles must be protected from cyber threats and unauthorised access. Achieving interoperability and standardisation across different V2V communication technologies and regions remains a complex task, given the diversity of protocols and regulatory frameworks. Efficient network management and resource allocation are critical for maintaining quality of service, yet the dynamic nature of vehicular networks complicates these efforts. Additionally, scaling V2V communication systems to support large numbers of vehicles in diverse environments requires substantial infrastructure investment and coordination among various stakeholders, presenting both technical and logistical challenges. To refer, the challenges associated with V2V wireless communication are well-documented in the literature, particularly in the work Ning Lu *et al.* [36]. The authors highlight several key obstacles that must be overcome to achieve efficient and robust wireless connectivity for vehicles. These challenges include dealing with harsh communication environments both inside and outside the vehicle, implementing multiple radio interfaces (such as DSRC/WAVE, WiFi, and 3G/4G-LTE) which can be costly, and meeting the stringent latency and reliability requirements of in-vehicle systems for control and monitoring purposes. Additionally, the authors note the potential negative impact of providing excessive information to drivers, which can increase their workload and compromise safety. These issues underscore the need for continued research and development to create unified, cost-effective, and reliable solutions for V2V and broader V2X (Vehicle-to-Everything) connectivity.

2.4 CURRENT RESEARCH STATUS OF GBSM AND SCATTERING CLUSTERS

The exploration of GBSM and scattering clusters has become a cornerstone in the field of wireless communication, particularly in the context of V2V communications. These models play a pivotal role in accurately characterising the complex and dynamic propagation environments encountered in V2V scenarios.

GBSM combines deterministic geometric principles with stochastic elements to simulate the variability and randomness inherent in wireless channels. This approach allows for a comprehensive representation of the communication environment, capturing both the predictable and unpredictable aspects of signal propagation. GBSM has been instrumental in modelling the dynamic and mobile nature of V2V communication channels, accounting for factors such as vehicle movement, varying distances, and the presence of obstacles. Recent research has focused on refining GBSM to improve its accuracy and applicability in diverse environments, such as urban areas and tunnels. Studies have investigated various parameters and configurations to enhance the predictive capabilities of GBSM, ensuring that it can accommodate the high mobility and dynamic topology characteristic of vehicular networks. Furthermore, advancements in computational techniques and the availability of high-resolution measurement data have facilitated the development of more sophisticated and reliable models.

Scattering clusters provide a detailed framework for understanding multipath propagation by grouping scatterers based on their spatial and temporal characteristics. This methodology is essential for modelling the interactions of transmitted signals with various objects in the environment, such as buildings, vehicles, and natural obstacles, which cause reflections, diffractions, and scattering. The use of scattering clusters enhances the model's ability to replicate real-world conditions, making it a valuable tool for designing and optimizing V2V communication systems. Research in this area has aimed to identify and categorise the scattering phenomena more precisely, leading to better predictions of signal behavior under various conditions. Advanced techniques for identifying and modelling scattering clusters have been developed, leveraging high-resolution data and sophisticated computational methods to improve the accuracy and reliability of the models.

In this part, the specific advancements and current research trends in GBSM and scattering

clusters will be delved into, highlighting the key findings, methodologies, and future directions, aiming to provide a comprehensive understanding of the state-of-the-art in GBSM and scattering clusters, situating this study within the broader context of ongoing research and identifying the gaps that this work seeks to address.

Q. Fu and W. Zhou [37] proposed a reference model for MIMO V2V frequency non-selective channels using a T-shaped scattering model. Their work incorporated both single- and double-bounce multipath components and derived a deterministic simulation model using the Riemann sum method. They analysed correlation properties, including STF-CCF, 2D spatial CCF, temporal ACF, and FCF. The results demonstrated excellent alignment between the simulation and reference models, confirming the model's utility for testing and designing inter-vehicle communication systems under specific propagation conditions. Xiongwen Zhao *et al.* [38] proposed a new GBSSM for wideband MIMO V2V channels, integrating 3D two-cylinder models for stationary scatterers and 2D multirings for moving scatterers. The model included MIMO antenna gain patterns and cross-polarisation. Time-varying channel properties were investigated, showing that moving scatterers significantly impact channel characteristics, such as Doppler spread and system capacity. The model's results aligned well with analytical data, though real-world measurements were recommended for validation. Jie Zhou *et al.* [39] proposed a 3D stochastic channel model for MIMO V2V communications in dense urban environments, accounting for the temporal non-stationarity due to moving transmitters and receivers. They derived time-varying parameters to characterise propagation paths and angles, investigating propagation characteristics relative to road sections and movement dynamics. Numerical results showed the model's theoretical predictions closely matched simulations, demonstrating its suitability for depicting V2V communications in urban scenarios and providing a theoretical reference for accurate urban wireless communication systems. Miguel Gutierrez Gaitán and Ramiro Samano-Robles [40] analysed vehicle-to-vehicle (V2V) communication in tunnel environments using a geometric multi-ray tracing approach. The study extended their previous work by incorporating multiple reflections from tunnel surfaces (ground, walls, and ceiling) into the V2V MIMO model. Their findings revealed that multiple antennas could mitigate destructive interference from these reflections. The study found that Maximum Ratio Combining (MRC) provided better resistance to fades compared to Equal Gain Combining (EGC), although EGC achieved higher signal gains. Full diversity solutions, based on MRC, offered improved resistance to fades and reduced signal fluctuations. Mingming Gan *et al.* [41] introduced a hybrid model

combining ray tracing and propagation graphs to simulate vehicle-to-vehicle (V2V) channels in tunnels with non-stationary fading. This approach partitions the fading process into stationary regions, simplifying the model by linking ray tracing results to a propagation graph. The model effectively handles diffuse reflections and time-variant correlations, reducing computational complexity. The hybrid model demonstrated accurate results in power-delay profiles, Doppler power spectral densities, and delay/Doppler spreads, validated against empirical data. Maotao Li *et al.* [42] introduced a novel three-dimensional (3D) geometry-based stochastic model for massive MIMO vehicle-to-vehicle (V2V) communication in curved tunnel environments. The model uses a geometric semicircle to represent the tunnel and a bicircular arc for the tunnel's curvature, accounting for effective scatterers based on vehicle angle. It investigates how tunnel size, vehicle speed, and curvature affect channel statistics like temporal autocorrelation and spatial cross-correlation functions. The model was validated against theoretical results and can guide future V2V system design in curved tunnels. Nurilla Avazov *et al.* [43] developed a 3-D propagation model for MIMO vehicle-to-vehicle (V2V) communications in rectangular tunnels under nonisotropic scattering conditions. The model captures spatial, temporal, and frequency statistical distributions of multipath signals. They derived a generalised analytical expression for the space–time–frequency correlation function (STF-CF) and examined how parameters like antenna spacing and tunnel width affect V2V channel statistics. The model provides a realistic representation of tunnel environments and aids in analysing the performance of vehicular communication systems. Hao Jiang *et al.* [44] proposed a 3-D wideband geometry-based channel model for MIMO vehicle-to-vehicle (V2V) communications in tunnel environments. The model uses a two-cylinder representation for vehicles and confocal semi-ellipsoid models for tunnel surfaces, incorporating direct line-of-sight and multiple interaction paths. It captures non-stationary characteristics due to vehicle movement. The study reveals that the model accurately characterises V2V channels, with time-varying spatial and frequency correlations influenced by propagation delays and vehicle motion. Validation with measured data confirms its practicality for future V2V systems. Asad Saleem *et al.* [45] proposed a non-stationary 3D-GBSM vehicle-to-vehicle (V2V) channel model for wideband massive MIMO systems in tunnel environments. Unlike traditional models using plane wavefronts, this model employs spherical wavefront assumptions. It derives expressions for the channel impulse response, angle-of-departure and arrival, spatial cross-correlation function, and Doppler power spectrum density, incorporating factors like antenna spacing and velocity. Validated by simulations and measurements, the model accurately reflects V2V channel characteristics in

high-speed train scenarios, proving its effectiveness and adaptability.

Lu Bai *et al.* [46] proposed a novel 3D nonstationary wideband V2V geometry-based stochastic model (GBSM) with uniform planar antenna arrays (UPAs) for massive MIMO systems. The model employed a birth-death process and seed algorithm-based selective cluster evolution to capture space and time nonstationarity. Ground reflections and the impact of vehicular traffic density (VTD) on channel statistics were also considered. The model demonstrated high accuracy and low complexity in calculating channel parameters and mimicked space-time nonstationarity effectively, with simulation results closely matching measurements. Ziwei Huang *et al.* [47] proposed a novel 3D massive MIMO mmWave geometry-based stochastic model (GBSM) for 6G V2V channels. The model divides clusters into static and dynamic types and captures the continuously arbitrary trajectory of transceivers. A new method integrating frequency-dependent factors and selective cluster evolution was developed to model space-time-frequency (ST-F) non-stationarity. Simulation results validated the model's accuracy and highlighted the significant impact of vehicular traffic density (VTD) and vehicular movement trajectory (VMT) on channel statistics. The model's generality and accuracy were confirmed through comparison with measurement data. Ziwei Huang and Xiang Cheng [48] proposed a 3D non-stationary irregular-shaped geometry-based stochastic model (IS-GBSM) for beyond 5G (B5G) and 6G V2V mmWave massive MIMO channels. The IS-GBSM distinguishes between dynamic and static clusters to explore the impact of vehicular traffic density (VTD) on channel statistics. A novel method using an improved K-Means clustering algorithm and a birth-death process was developed to model space-time-frequency non-stationarity. Simulation results showed strong agreement with measurements, confirming the model's accuracy and utility for B5G/6G V2V systems. Hao Jiang *et al.* [49] proposed a general 3D non-stationary wideband twin-cluster channel model for 5G vehicle-to-vehicle (V2V) tunnel communications. The model combines line-of-sight and non-line-of-sight components, incorporating a birth-death algorithm to simulate the dynamic appearance and disappearance of clusters. It analyses the impacts of these non-stationary properties on MIMO channels through spatial cross-correlation functions, temporal autocorrelation functions, and Doppler power spectrum densities. The model's numerical results closely matched simulations and prior measurements, demonstrating its effectiveness for 5G V2V communications in tunnel environments. Mi Yang *et al.* [50] proposed a cluster-based three-dimensional (3D) channel model for vehicle-to-vehicle (V2V) communications, addressing the limitations of existing models by incorporating both horizontal and vertical

dimensions of multipath components (MPCs). The model, validated with 5.9 GHz measurements in urban and suburban environments, utilises clustering and tracking algorithms to distinguish between global and scatterer clusters. It finds that MPC power within clusters follows a truncated-Gaussian distribution, while cluster angles follow a Laplacian distribution. The model's accuracy was confirmed through simulations and measurements, providing a realistic approach for evaluating V2V communication systems.

Yan Li *et al.* [51] proposed a three-dimensional (3-D) cluster-based nonstationary channel model for vehicle-to-vehicle (V2V) communications, addressing the dynamic nature of V2V channels. The model incorporates single- and double-bounced clusters in 3-D space and introduces visibility regions to account for the activity of clusters. It derives the channel impulse response from geometric relationships and analyses space-time-frequency correlation properties. Validation with realistic V2V measurements confirmed the model's accuracy and its ability to represent dynamic scattering environments effectively.

Chen Huang *et al.* [52] proposed a geometry-based stochastic MIMO channel model for vehicle-to-vehicle (V2V) communications in lightly built-up urban environments. The model, parametrised from measurements, includes components such as line-of-sight, reflections from static and mobile scatterers, multiple-bounce reflections, and diffuse scattering. It utilises a high-resolution parameter estimation and joint clustering algorithm to track multipath components. The model was validated against RMS delay spread and angular spreads of arrival/departure, showing good agreement with measurements and suggesting its utility for V2V simulations.

Hao Jiang *et al.* [53] proposed a 3D wideband two-cluster channel model for massive MIMO vehicle-to-vehicle (V2V) communications in semi-ellipsoid environments. The model used confocal semi-ellipsoids to represent cluster distributions and incorporated a birth-death process to simulate cluster dynamics. The study compared spatial cross-correlation functions (CCFs) and temporal auto-correlation functions (ACFs) with and without cluster evolution. Results showed good agreement with theoretical predictions, validating the model's effectiveness in describing real massive MIMO V2V communication environments.

Andreas Theodorakopoulos *et al.* [54] developed a geometry-based stochastic model for MIMO vehicle-to-vehicle (V2V) channels in a cross-junction scenario. The model extends an existing T-junction framework by incorporating four propagation processes: line-of-sight (LOS), single and double bounce reflections from side walls, and single bounce reflections from a building corner. A novel method for scatterer distribution in triangular planes was introduced. The model's time-variant transfer function aligns well with measurement-based path-loss models, making it effective for analysing MIMO V2V fading channels in urban

cross-junctions. Ying Yang *et al.* [55] proposed a general three-dimensional (3D) non-stationary twin-cluster model for vehicle-to-vehicle (V2V) MIMO channels. This model extends existing 3D geometry-based stochastic models to accommodate 3D scattering environments, antenna arrays, and arbitrary trajectories of mobile transmitters and receivers. The model incorporates time-evolving algorithms for path parameters and analyses statistical properties such as spatial cross-correlation, temporal correlation, and Doppler power spectrum density. Results indicated that trajectory variations significantly impact channel statistics, making the model suitable for realistic V2V communication scenarios.

To summarise, research on GBSM and scattering cluster methods has markedly advanced the understanding of V2V communication channels. GBSM has evolved to more accurately simulate complex environments by incorporating dynamic vehicle movements and varying conditions. Scattering cluster methods have been refined to capture multipath effects more precisely by grouping scatterers based on spatial and temporal characteristics. Recent advancements include T-shaped scattering models, twin-cluster models, and hybrid approaches combining ray tracing with propagation graphs. These innovations enhance simulation accuracy by accounting for dynamic scattering and environmental changes, offering valuable tools for optimising V2V communication systems.

3. RESEARCH METHODOLOGY

In the third chapter, the research results and novel points to be accomplished in this report, the Gantt chart of project management in this study, an introduction to GBSM and scattering cluster methods, and the research methods, paradigms, and so forth determined based on the Research Onion framework are all covered.

3.1 INTRODUCTION

This section will present the research methodology for the study, which includes the activities for the project, the process of conducting the investigation, and the rationale behind the selected model and setting. The goal of the project is to create and assess a 3D MIMO GBSM combined with scattering cluster model for V2V communication in a real tunnel environment. To that end, all work will be done on a laptop utilising programmes like Word, Excel, and MATLAB. Three parts of work were required to be completed: theoretical analysis through literature review; modelling development through the proposal of a GBSM combined with scattering cluster model; and model evaluation through MATLAB simulation using metrics for V2V channel model evaluation, such as the Doppler power spectral density (PSD) and the space-time-frequency correlation function (STFCF). A few scholarly works are included as references to support the models and surroundings used in this investigation. The goal of the GBSM combined with scattering cluster model's establishment is to replicate the real world using regular or irregular geometries while maintaining a low computational cost for programming [56], [57]. One benefit of utilising the GBSM combined with scattering cluster model is the ability to avoid carrying out difficult measurements for local settings. Furthermore, it can reduce multipath components using beamforming [58], [59], and change the direction of NLoS components using IRS [60] without the need for additional devices. Furthermore, although it is significant in both A2G and V2V communication domains, different types of tunnel settings have not yet been thoroughly studied [1], [2]. The statistical features of a channel will be affected differently by tunnels made of varied materials, forms, and lanes [6].

3.2 RESEARCH DESIGN

In this section, the relevant components of the research, including research approaches, research philosophies, and other methodological considerations, will be thoroughly examined using the framework of the Research Onion. This layered model, introduced by Saunders *et al.* [61], provides a structured way to design and explain the research methodology, ensuring a comprehensive and coherent approach to addressing the research questions. The Research Onion consists of several layers, each representing different aspects of the research methodology. These layers include research philosophies, approaches, strategies, choices, time horizons, and techniques and procedures. By systematically peeling back each layer, researchers can develop a well-founded and transparent research design.

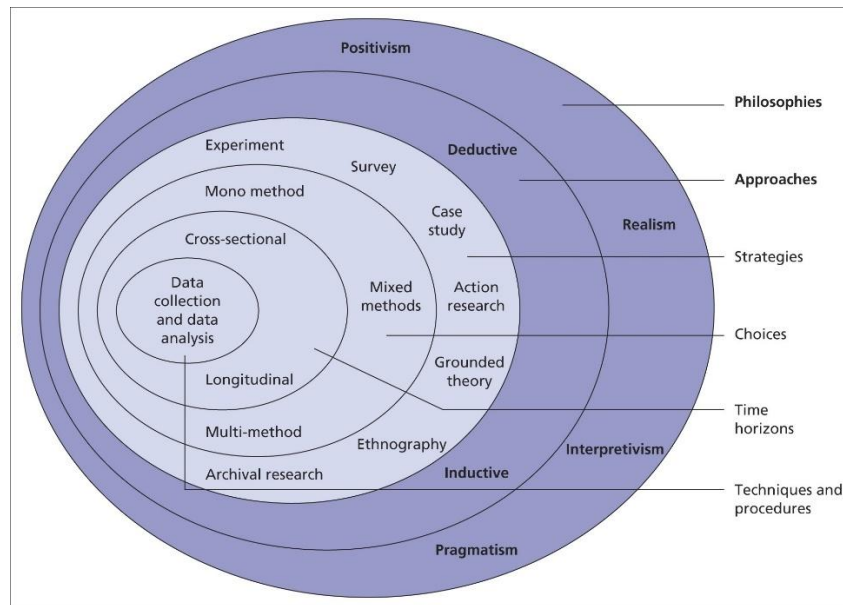


Fig. 1. Research Onion

Experimentation is the chosen research method for this study. Experimentation allows for the controlled manipulation of variables to observe and analyse the effects on the dependent variables. In this context, experimentation is crucial for developing and validating the proposed GBSM combined with scattering cluster channel model. By conducting experiments through simulations, the study can systematically investigate the impact of various factors on V2V communication in tunnel scenarios.

The research approach adopted for this study is deductive. Deductive reasoning involves

starting with a general theory or hypothesis and then conducting specific experiments or observations to test these hypotheses. In this research, existing theories and models of vehicular communication channels form the basis of the hypotheses. These hypotheses are then tested through systematic observation and experimentation. The deductive approach is particularly suitable as it provides a structured framework for investigating how the proposed model performs under different conditions and for verifying the theoretical predictions with empirical data.

The research paradigm guiding this study is pragmatism. Pragmatism focuses on practical outcomes and solutions, emphasising the practical application of research findings to solve real-world problems. This paradigm is chosen because it aligns well with the study's goal of developing a practical and applicable model for V2V communication in tunnel environments. Pragmatism allows for flexibility in research methods, combining both qualitative and quantitative approaches when necessary to achieve the desired outcomes. It prioritises the research questions and the practical implications of the findings over rigid adherence to a single methodological approach.

Quantitative research is the primary research type employed in this study. Quantitative research involves the systematic collection and analysis of numerical data to identify patterns, test hypotheses, and make predictions. This study's focus on developing and validating a mathematical model for V2V communication necessitates a quantitative approach. By collecting numerical data on variables such as automobile velocities, antenna spacing and direction, automobile moving direction, and carrier frequency, the study can quantify the statistical characteristics of the V2V channel in tunnel environments. This data-driven approach ensures objectivity and precision in evaluating the proposed model.

The study identifies several key independent variables, including automobile velocities, antenna spacing and direction, automobile moving direction, and carrier frequency. These variables are manipulated and measured to understand their impact on the dependent variables. The dependent variables in this study are the statistical characteristics of the V2V channel in the tunnel environment, such as Doppler power spectral density (PSD) and space-time-frequency correlation function (STFCF). These characteristics are critical for evaluating the performance and reliability of the proposed channel model.

This study does not lend itself to the use of null and alternative hypotheses, directional tests, or non-directional tests. Instead, the focus is on developing a robust model and validating it through empirical data and simulations. The absence of formal hypothesis testing does not diminish the rigor of the study; rather, it reflects the complexity and exploratory nature of modelling and simulation research.

The boundaries of this study are defined by its approach and environment. The research exclusively focuses on the GBSM and scattering cluster modelling method within tunnel environments. This specificity ensures that the study can provide in-depth insights and detailed analysis of V2V communication in these particular settings. While this focus limits the generalizability of the findings to other environments, it enhances the relevance and applicability of the results to tunnel scenarios, which are currently underrepresented in existing research.

3.3 EXPECTED RESEARCH RESULTS AND INNOVATIVE POINTS

Expected research outcomes in this study include two parts. The primary expected outcome of this research is to propose a GBSM combined with scattering cluster channel model based on vehicle-to-vehicle communication in tunnel scenarios. Tunnel scenarios present unique challenges for wireless communication due to their confined spaces and reflective surfaces. By focusing on these specific environments, the proposed model will address the propagation characteristics unique to tunnels, including multipath fading and signal attenuation. The development of this model is anticipated to significantly enhance the accuracy and reliability of V2V communication systems in such challenging environments. The second anticipated outcome of the study is to complete a high-quality master's dissertation that encapsulates the methodology, findings, and implications of the study. The thesis will provide a detailed account of the research process, from the initial review of literature and problem statement to the development and validation of the GBSM combined with scattering cluster channel model. A high-quality dissertation will serve as a valuable academic resource for future research in the field and as a proof to the researcher's expertise and contribution to the field of V2V communication.

The innovation points in this report contain two aspects. The first innovative aspect is proposing a novel vehicle-to-vehicle communication channel model. Existing models are not

enough to represent the unique propagation conditions found in specific tunnel environments. By introducing a new model that takes into account the specific characteristics of V2V communication in such scenarios, this research aims to fill the gap in the current literature. This new model will provide predictions of signal behavior, which can be used to improve the design and performance of V2V communication systems. Another critical innovation of this research is the introduction of time-varying non-stationary processes into the channel model. Traditional models often assume stationary conditions, which do not adequately capture the dynamic nature of vehicular communication channels. By incorporating non-stationary processes, this research will better reflect the real-world conditions where vehicles are constantly moving, and channel characteristics are continuously changing. Additionally, the study will examine how various channel parameters, such as vehicle speed, tunnel geometry, and environmental factors, affect the channel model. This comprehensive analysis will provide deeper insights into the factors influencing V2V communication and inform the development of more robust and adaptive communication technologies.

3.4 GANTT CHART FOR PROJECT PLAN

The project timeline is structured to ensure a systematic and organised approach to the research activities, aligning with key deadlines. The due date for the final submission for the master's project is scheduled on the 28th of August in 2024. This schedule allows for adequate time to conduct thorough research, analyse findings, and prepare the necessary documentation and presentations.

The Gantt Chart for the project is shown in Fig. 2. It visually represents the project timeline, highlighting the start and end dates for each phase of the research [62]. This chart serves as a roadmap, ensuring that each task is completed within its designated timeframe, and providing a clear overview of the project's progress. Key milestones such as the final thesis submission are marked prominently, helping to keep the project on track and ensuring timely completion.

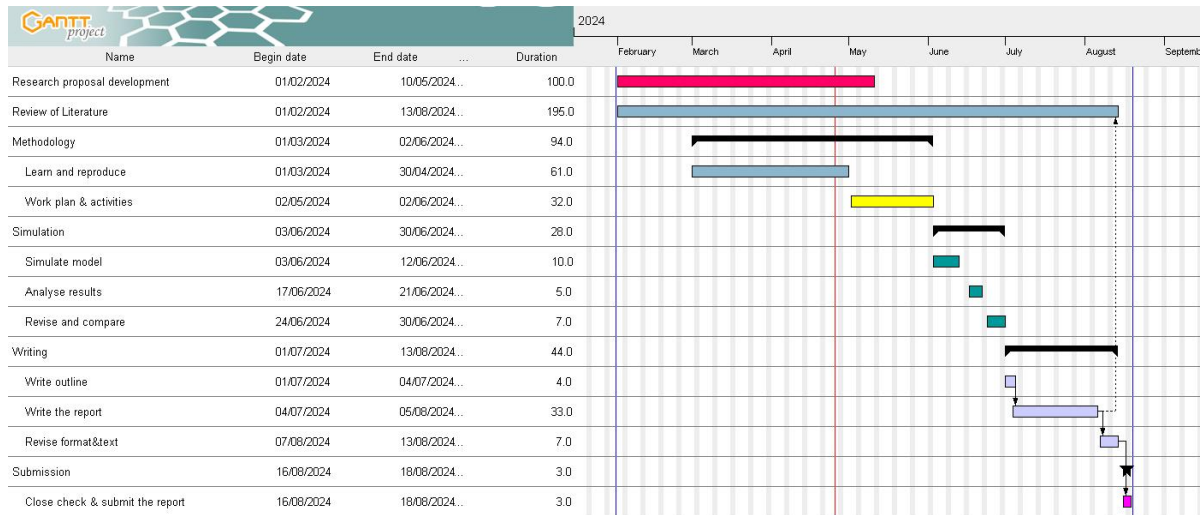


Fig. 2. Gantt Chart for the study

3.5 GBSM AND SCATTERING CLUSTER MODEL IN V2V TUNNEL ENVIRONMENTS

In this section, Geometry-Based Stochastic Model and scattering cluster model will be introduced and analysed in the context of V2V tunnel scenarios in wireless communication area.

3.5.1 GEOMETRY-BASED STOCHASTIC MODEL (GBSM)

The Geometry-Based Stochastic Model (GBSM) is a sophisticated approach to channel modelling that incorporates the geometric layout of the propagation environment along with stochastic elements to accurately represent the variability and unpredictability of wireless channels. In the context of Vehicle-to-Vehicle (V2V) communication, especially in tunnel environments, GBSM plays a crucial role due to the unique and complex propagation characteristics encountered. A typical 3D GBSM geometric model in a vehicle-to-vehicle communication environment [63] is shown in Fig. 3.

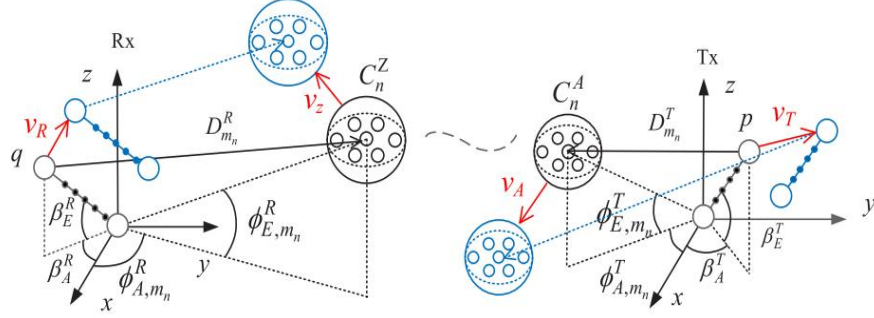


Fig. 4. A 3D broadband twin-cluster channel model

Each cluster represents a group of scatterers that contribute collectively to a specific multipath component. The model accounts for the following aspects: 1. Cluster formation: Clusters are formed based on the spatial correlation and physical proximity of scatterers. For instance, reflections from a tunnel wall might form a distinct cluster. 2. Cluster characteristics: Each cluster has its own statistical properties, such as delay spread, angular spread, and power distribution, which affect the overall channel characteristics. 3. Time-variant behavior: The model captures the dynamic nature of the V2V channel by allowing the clusters to evolve over time as vehicles move and environmental conditions change.

In the context of V2V communication in tunnel environments, the integration of GBSM with the scattering cluster model provides a comprehensive framework for channel modelling. This combined approach offers several advantages: 1. Enhanced realism: By incorporating the physical geometry of the tunnel and the stochastic nature of scatterers, the model can more accurately reflect real-world conditions. 2. Dynamic adaptability: The model adapts to the time-variant nature of V2V channels, accounting for the movement of vehicles and changes in the propagation environment. 3. Detailed multipath representation: The scattering cluster model captures the multipath components in detail, providing insights into the delay and angular spreads that are critical for designing robust V2V communication systems.

To implement the GBSM combined with the scattering cluster model for V2V channels in tunnel environments, the following steps are typically undertaken: 1. Environmental characterisation: Detailed measurements or simulations of the tunnel geometry and material properties are conducted to identify potential scatterers and reflectors. 2. Model initialisation: Parameters such as the positions and velocities of vehicles, antenna configurations, and initial cluster characteristics are defined based on the specific scenario. 3. Simulation execution: Using tools like MATLAB, the model is simulated to generate channel realisations. The

simulation incorporates the relative motion of vehicles, interactions with scatterers, and the evolution of clusters over time. 4. Data analysis: The resulting channel data is analysed to extract key metrics such as Doppler power spectral density (PSD) and space-time-frequency correlation function (STFCF). These metrics are used to evaluate the performance of the V2V communication system under various conditions.

By combining the deterministic structure of GBSM with the stochastic flexibility of the scattering cluster model, highly accurate and practical channel models for V2V communication in tunnels can be developed. This integrated approach facilitates the design and optimisation of communication systems that can reliably operate in the challenging tunnel environments encountered in real-world vehicular networks.

4. MODEL DEVELOPMENT AND CHANNEL CHARACTERISITICS

In the fourth chapter, a model for V2V wireless communication in tunnel environments is designed using GBSM in conjunction with scattering cluster methods. The model's parameters are introduced, channel impulse response formulas are derived and calculated, distribution functions are introduced, and pertinent wireless communication knowledge is utilised.

4.1 INTRODUCTION

This section will present the design and implementation of GBSM combined with scattering cluster methods for V2V communication within tunnel environments. This model aims to accurately simulate the unique propagation characteristics of tunnels by incorporating key parameters, deriving channel impulse responses, and using advanced distribution and algorithmic techniques.

The proposed model integrates the deterministic aspects of GBSMs with the stochastic nature of scattering clusters to capture the complex multipath propagation in tunnels. Key parameters such as vehicle positions, velocities, antenna configurations, and environmental characteristics will be defined to ensure the model's relevance to real-world tunnel environments. The author will derive and demonstrate the channel impulse response (CIR) for both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions by calculating the contributions of different multipath components and considering the effects of various azimuth and elevation angles. Using the von Mises distribution, the author will simulate the distribution of azimuth and elevation angles to capture their variability accurately, providing a more realistic representation of the angular spread in tunnel environments. To model the dynamic nature of the V2V channel, the author will employ birth-death algorithms, which help simulate the appearance and disappearance of scatterers over time, reflecting the non-stationary characteristics of the channel.

The later part of this section will provide detailed insights into the spatial-temporal characteristics of the channel. Key aspects include the channel impulse response (CIR), which describes the channel properties of the output, temporal auto-correlation function (ACF), which analyses how the channel's properties change over time due to the relative

motion of vehicles. The spatial cross-correlation function (CCF) evaluates the spatial correlation between different points in the tunnel, impacted by the tunnel's geometry and scatterer distribution. The Doppler power spectral density (PSD) assesses the frequency shifts due to the relative motion of vehicles, essential for understanding the Doppler effects in V2V communication. By combining the deterministic geometry of GBSMs with the dynamic clustering of scatterers, the author aims to develop a comprehensive model that accurately reflects the real-world conditions of V2V communication in tunnels. This integrated approach not only enhances the realism of the simulations but also provides valuable insights for designing robust and efficient V2V communication systems.

In the following sections, the author will detail the specific methods used for parameter setting, CIR calculations, angle simulations, and the application of birth-death algorithms, followed by an analysis of the resulting channel characteristics through MATLAB simulations in next chapter.

4.2 DEVELOPED 3D V2V CHANNEL MODEL USING GBSM AND SCATTERING CLUSTER METHODS

The complex channel impulse response (CIR) of the channel model is the first topic covered in this section. Next, in order to describe the non-stationary features of the channel, the birth-death process is introduced. A detailed explanation of the geometrical propagation model in this section for a V2V channel in a two-lane, rectangular tunnel.

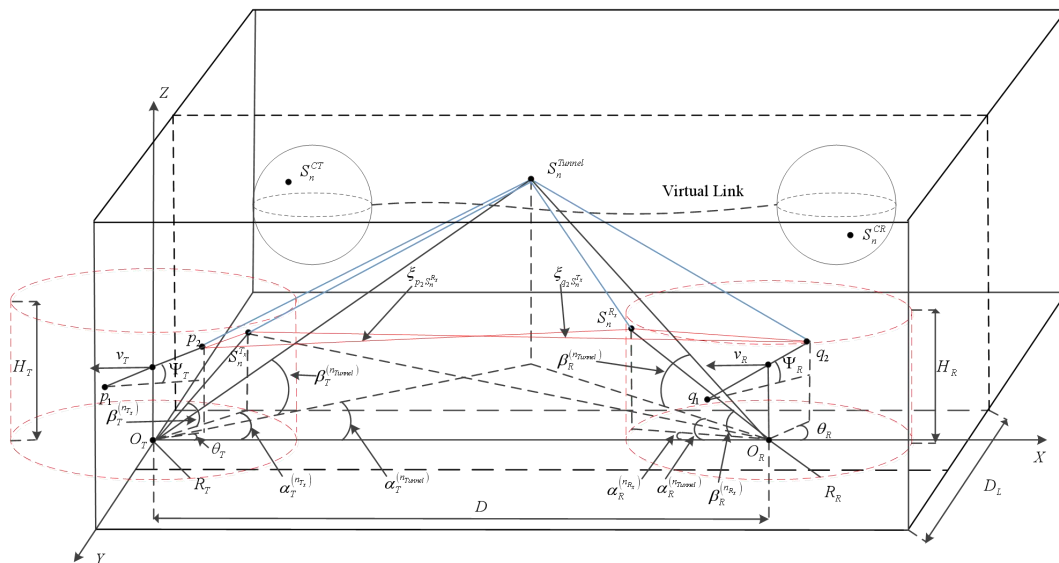


Fig. 5. Developed 3D V2V channel model and related parameters

Fig. 5 depicts the model that is being offered. 3D effective scattering elements between the Tx (Transmitter) and Rx (Receiver) are utilised to characterise the radio propagation environment. In the developed model, the symbol D represents the distance between Tx and Rx. Moreover, D_L denotes half width of the tunnel. To characterise the positions of both Tx and Rx, Cartesian coordinate systems (x, y, z) is used, which mathematically represent the locations of the mobile Tx and mobile Rx. Both Tx and Rx are assumed to locate on the x-axis. It should be mentioned that in V2V channels in this study, both the Rx and the Tx are non-static. Additionally, since the Tx and Rx are mobile, it is necessary to describe related parameters of them. The velocity direction of both Tx and Rx in our model is along the negative x-axis, meaning that the value of both azimuth angles γ_T and γ_R is π . Although Tx and Rx have the same moving direction, their velocities are not the same generally, that is, $v_T \neq v_R$. Besides, uniform linear array (ULA) antenna arrays are put into Tx and Rx. The antenna elements of the Tx and Rx are arranged in ULA including number of n_T and n_R , the inter-element spacings between the elements are δ_T and δ_R . According to the proposed model of the GBSM components, there are two cylinders surround Tx and Rx. $S_n^{T_x}$, $S_n^{R_x}$ and S_n^{Tunnel} denote the scatterers closed to Tx and Rx, distributed on the tunnel wall separately. LoS and SB path are considered in this study for GBSM components, including one LoS path and two SB paths. Additionally, $\xi_{pq, n_i} = \xi_{pn_i} + \xi_{n_i q}$ indicates the wave's travel distance via the i -th link $p \rightarrow S_n^{(i)} \rightarrow q$, where $i \in \{1, 2, 3\}$, $S_n^{(1)}$, $S_n^{(2)}$ and $S_n^{(3)}$ are employed to make $S_n^{T_x}$, $S_n^{R_x}$ and S_n^{Tunnel} simpler and enable them to be expressed as sums in mathematical formulas.

For the scattering cluster component, a twin-cluster is shown in Fig. 5. ClusterTx is defined as the cluster at the Tx which characterises the first path of the propagation multipath in the developed model while ClusterRx is defined as the cluster at the Rx which characterises the last path of that. Helmut Hofstetter et al. [65] and Shangbin Wu et al. [66] demonstrated that the propagation path from ClusterTx to ClusterRx can be abstracted as a stochastic cluster link or so-called virtual link, which is able to simplify the real propagation environment. Similar to that of the GBSM model, S_n^{CT} and S_n^{CR} represent the cluster groups closed to Tx and Rx individually. In this study, twin-cluster model is developed and analysed, both LoS and NLoS path are considered. The propagation wave's travel distance via the NLoS link is $p \rightarrow S_n^{CT} \rightarrow S_n^{CR} \rightarrow q$. The impact on channel characteristics of scatterers distributed on the tunnel wall is considered in the virtual link between two cluster groups. For ease of reference, the parameters are listed in TABLE I.

TABLE I

DEFINITION OF THE PARAMETERS USED IN THE PROPOSED V2V CHANNEL MODEL.

D	The separation of the Tx and Rx cylinder centres.
R_T, R_R	The individual radii of the Tx and Rx cylinders.
D_L	Half the width of the rectangular tunnel.
H_T, H_R	The many Tx and Rx cylinder heights.
θ_T, θ_R	The antenna arrays' individual orientations at Tx and Rx.
Ψ_T, Ψ_R	The individual antenna array elevations at Tx and Rx.
δ_T, δ_R	The separation, separately, between two neighbouring antenna elements at Tx and Rx.
n_T, n_R	The quantity of antenna elements that are used for transmission and receiving, respectively.
v_T, v_R	The separate velocities of the Tx and Rx.
γ_T, γ_R	The movement direction's azimuth angle at each Tx and Rx separately.
f_T, f_R	The maximum Doppler shift, separately at Tx and Rx.
$N_{T_x}, N_{R_x}, N_{Tunnel}, N_{CT}, N_{CR}$	The quantity of effective scatterers on the cylindrical surface around Tx, Rx, the tunnel, on the spherical surface around Tx, Rx, respectively.
$\alpha_T^{LoS}, \beta_T^{LoS}$	The AAoD and EAOD of the LoS path.
$\alpha_R^{LoS}, \beta_R^{LoS}$	The AAoA and EAOA of the LoS path.
$\alpha_T^{(n_{Tx})}, \beta_T^{(n_{Tx})}$	The AAoD and EAOD at $S_n^{T_x}$
$\alpha_R^{(n_{Rx})}, \beta_R^{(n_{Rx})}$	The AAoA and EAOA from $S_n^{R_x}$
$\alpha_T^{(n_{Tunnel})}, \beta_T^{(n_{Tunnel})}$	The AAoD and EAOD at S_n^{Tunnel}
$\alpha_R^{(n_{Tunnel})}, \beta_R^{(n_{Tunnel})}$	The AAoA and EAOA from S_n^{Tunnel}
$\alpha_T^{(n_{CT})}, \beta_T^{(n_{CT})}$	The AAoD and EAOD at S_n^{CT}
$\alpha_R^{(n_{CR})}, \beta_R^{(n_{CR})}$	The AAoA and EAOA from S_n^{CR}

4.3 CHANNEL IMPULSE RESEPONSE AND GEOMETRIC RELATIONSHIP DERIVATION

This section is dedicated to deriving the mathematical expressions for the Channel Impulse Response (CIR) and the associated geometric relationships that form the foundation of the proposed V2V channel model. The CIR characterises the channel's behavior by describing how a transmitted signal is dispersed over time due to multipath propagation. This dispersion is influenced by the environment's physical structure, including the positions of vehicles,

scatterers, and other obstacles that cause reflections, diffractions, and scattering of the signal. The CIR for both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions will be considered, incorporating the effects of the environment on signal propagation. The derivation will account for various factors such as the angles of departure and arrival, the distribution of scatterers, and the dynamic nature of the vehicle positions.

With the information provided above, this model can be explored, the space-time cross-correlation function (STCF) and channel impulse response (CIR) can be obtained for more research. In the proposed model, CIR for GBSM components and scattering cluster components will be considered separately. For GBSM components, examining the suggested model shown in Fig. 5, keep in mind that several waves from the antenna elements using Tx will immediately reach the antenna elements used at Rx, creating the LoS path. The SB path is formed by those that are single-bounced at the Tx, Rx, or tunnel. In order to reduce the computational complexity of the model, double-bounced transmission is neglected, which will lose a significant quantity of energy during the multipath transmission process and hence account for a little amount of power. Consequently, the channel impulse response indicated above can be written as a superposition of the LoS and SB rays using the superposition theorem. This can be defined as

$$h_{pq}(t) = h_{pq}^{LoS}(t) + \sum_{i=1}^3 h_{pq}^{SB_i}(t) \quad (4-1)$$

where the LoS component's CIR between antenna elements p and q is represented by the notation

$$h_{pq}^{LoS}(t) = \sqrt{\frac{K}{K+1}} e^{j\varphi_0} e^{-j\frac{2\pi}{\lambda} \xi_{pq}} e^{j\frac{2\pi}{\lambda} [v_T t \cos(\alpha_T^{LoS} - \gamma_T) \cos \beta_T^{LoS} + v_R t \cos(\alpha_R^{LoS} - \gamma_R) \cos \beta_R^{LoS}]} \quad (4-2)$$

where φ_0 indicates the random phase, f_c designates the carrier frequency, $\lambda = c / f_c$, and K is the Ricean factor. The LoS path's AAOD and EAOD are indicated by α_T^{LoS} and β_T^{LoS} , respectively, while its AAOA and EAOA are indicated by α_R^{LoS} and β_R^{LoS} . Next, the NLoS component's CIR will be calculated. The components that are single-bounced can be written as

$$h_{pq}^{SB_i}(t) = \sqrt{\frac{\eta_{SB_i}}{K+1}} \lim_{N_i \rightarrow \infty} \sum_{n_i=1}^{N_i} \frac{1}{\sqrt{N_i}} e^{j\varphi_{pq,n_i}} e^{-j\frac{2\pi}{\lambda} \xi_{pq,n_i}} e^{j\frac{2\pi}{\lambda} v_T t \cos(\alpha_T^{(n_i)} - \gamma_T) \cos \beta_T^{(n_i)}} e^{j\frac{2\pi}{\lambda} v_R t \cos(\alpha_R^{(n_i)} - \gamma_R) \cos \beta_R^{(n_i)}} \quad (4-3)$$

where $i \in \{1, 2, 3\}$, η_{SB_i} is, correspondingly, the amplitude gain of the n_i -th scattered wave. Additionally, as it is mentioned above, $\xi_{pq,n_i} = \xi_{pn_i} + \xi_{n_iq}$ indicates the wave's travel distance via the i -th link $p \rightarrow S_n^{(i)} \rightarrow q$. The suggested model states that $S_n^{(1)}$, $S_n^{(2)}$ and $S_n^{(3)}$ are utilised to make S_n^{Tx} , S_n^{Rx} and S_n^{Tunnel} easier to understand so that they can be expressed as sums in

mathematical formulas. Moreover, the relevant time-variant geometrical path lengths can be computed using the law of Euclidean distance as

$$\xi_{pq}(t) = \sqrt{\left(D - \xi_{pT_x} \cos \Psi_T \cos \theta_T + \xi_{qR_x} \cos \Psi_R \cos \theta_R + (v_T - v_R)t\right)^2 + \left(-\xi_{pT_x} \cos \Psi_T \sin \theta_T + \xi_{qR_x} \cos \Psi_R \sin \theta_R\right)^2 + \left(-\xi_{pT_x} \sin \Psi_T + \xi_{qR_x} \sin \Psi_R\right)^2} \quad (4-4)$$

$$\xi_{pn_1}(t) = \sqrt{\left(-\xi_{pT_x} \cos \Psi_T \cos \theta_T + R_T \cos \alpha_T^{(n_1)}\right)^2 + \left(-\xi_{pT_x} \cos \Psi_T \sin \theta_T + R_T \sin \alpha_T^{(n_1)}\right)^2 + \left(-\xi_{pT_x} \sin \Psi_T + R_T \tan \beta_T^{(n_1)}\right)^2} \quad (4-5)$$

$$\xi_{pn_2}(t) = \sqrt{\left(D - \xi_{pT_x} \cos \Psi_T \cos \theta_T + R_R \cos \alpha_R^{(n_2)} + (v_T - v_R)t\right)^2 + \left(-\xi_{pT_x} \cos \Psi_T \sin \theta_T + R_R \sin \alpha_R^{(n_2)}\right)^2 + \left(-\xi_{pT_x} \sin \Psi_T + R_R \tan \beta_R^{(n_2)}\right)^2} \quad (4-6)$$

$$\xi_{pn_3}(t) = \sqrt{\left(-\xi_{pT_x} \cos \Psi_T \cos \theta_T + R_L \cos \phi_L \sec \alpha_T^{(n_3)} + v_R t\right)^2 + \left(-\xi_{pT_x} \cos \Psi_T \sin \theta_T + R_L \cos \phi_L\right)^2 + \left(-\xi_{pT_x} \sin \Psi_T + R_L \tan \phi_L\right)^2} \quad (4-7)$$

$$\xi_{n_3q}(t) = \sqrt{\left(D - \xi_{qR_x} \cos \Psi_R \cos \theta_R + R_T \cos \alpha_T^{(n_3)} + (v_T - v_R)t\right)^2 + \left(-\xi_{qR_x} \cos \Psi_R \sin \theta_R + R_T \sin \alpha_T^{(n_3)}\right)^2 + \left(-\xi_{qR_x} \sin \Psi_R + R_T \tan \beta_T^{(n_3)}\right)^2} \quad (4-8)$$

$$\xi_{n_2q}(t) = \sqrt{\left(-\xi_{qR_x} \cos \Psi_R \cos \theta_R + R_R \cos \alpha_R^{(n_2)}\right)^2 + \left(-\xi_{qR_x} \cos \Psi_R \sin \theta_R + R_R \sin \alpha_R^{(n_2)}\right)^2 + \left(-\xi_{qR_x} \sin \Psi_R + R_R \tan \beta_R^{(n_2)}\right)^2} \quad (4-9)$$

$$\xi_{n_3q}(t) = \sqrt{\left(-\xi_{qR_x} \cos \Psi_R \cos \theta_R + R_L \cos \phi_L \sec \alpha_R^{(n_3)} + v_R t\right)^2 + \left(-\xi_{qR_x} \cos \Psi_R \sin \theta_R + R_L \cos \phi_L\right)^2 + \left(-\xi_{qR_x} \sin \Psi_R + R_L \tan \phi_L\right)^2} \quad (4-10)$$

$$\xi_{n_2}(t) = \sqrt{\left(D - R_T \cos \alpha_T^{(n_1)} + R \cos \alpha^{(n_2)} + (v_T - v_R)t\right)^2 + \left(-R_T \sin \alpha_T^{(n_1)} + R \sin \alpha^{(n_2)}\right)^2 + \left(-R_T \tan \beta_T^{(n_1)} + R \tan \beta^{(n_2)}\right)^2} \quad (4-11)$$

where ξ_{pT_x} is the travel distance between antenna element p and Tx, ξ_{qR_x} is the travel distance between antenna element q and Rx. k_p and k_q are used to simplify formulations, which can be represented as

$$\xi_{pT_x} = -k_p \delta_T \quad (4-12)$$

$$k_p = \frac{-2p + n_T + 1}{2} \quad (4-13)$$

$$\xi_{qR_x} = -k_q \delta_R \quad (4-14)$$

$$k_q = \frac{-2q + n_R + 1}{2} \quad (4-15)$$

The formulas of CIR for GBSM and scattering cluster are similar to each other. Since in twin-cluster model there are only LoS and DB (NLoS) paths rather than LoS and SB (NLoS) paths, there will be a difference when refer to multipath. The complex CIR for cluster model can be calculated as

$$h_{pq}(t) = h_{pq}^{LoS}(t) + h_{pq}^{NLoS}(t) \quad (4-16)$$

Where the CIR for LoS path is the same as derivation in GBSM component and the CIR for NLoS path can be calculated as

$$h_{pq}^{NLoS}(t) = \sqrt{\frac{1}{K+1}} \lim_{N_1 \rightarrow \infty} \lim_{N_2 \rightarrow \infty} \sum_{n_1=1}^{N_1} \sum_{n_2=1}^{N_2} \frac{1}{\sqrt{N_1 N_2}} \times e^{j(\varphi_{n_1} - 2\pi f_c \xi_{pq, n_1, n_2}(t)/c)} \times e^{j \frac{2\pi}{\lambda} v_T t \cos(\alpha_T^{(n_1)}(t) - \gamma_T) \cos \beta_T^{(n_1)}(t)} \times e^{j \frac{2\pi}{\lambda} v_R t \cos(\alpha_R^{(n_2)}(t) - \gamma_R) \cos \beta_R^{(n_2)}(t)} \quad (4-17)$$

To calculate the distance between the elements of Tx and Rx through the link $p \rightarrow S_n^{CT} \rightarrow S_n^{CR} \rightarrow q$ to derive the CIR, we can use

$$\xi_{pq, n_1, n_2} = \xi_{pn_1} + \xi_{n_2q} + \xi_{n_1, n_2} = \xi_{pn_1} + \xi_{n_2q} + c\tau_{n_1 n_2} \quad (4-18)$$

where c represents the velocity of light or electromagnetic wave and $\tau_{n_1 n_2}$ denotes the propagation delay between the scatterer n_1 which is distributed on the surface of the clusterTx and n_2 which is distributed on the surface of the clsterRx. Since the geometric paths of GBSM and scattering cluster are almost the same, for the sake of simplicity, specific formulas are not listed below.

4.4 SCATTERERS DISTRIBUTION

One noteworthy development is the widespread adoption of closed-form representations of scatterer distributions in the existing literatures. The accurate modelling of scatterer distribution is critical for understanding the complex multipath propagation environment within tunnels in V2V communication scenarios. In this part the methods used to define and simulate scatterer distributions are explored, particularly focusing on the angular parameters that influence signal propagation. These parameters are modelled using a combination of von Mises, cosine distributions and exponential distributions, which are chosen for their suitability in capturing the angular spread of scatterers in a tunnel environment. Since formulas of GBSM and scattering cluster considering the azimuth angle and elevation angle of scatterers closed to Tx and Rx are similar to each other, only GBSM are focused on to demonstrate. To obtain formulas of scattering cluster part, simply replace symbols $S_n^{T_x}$, $S_n^{R_x}$ with S_n^{CT} and S_n^{CR} . The difference between the GBSM and scattering cluster is the distribution of the scatterers on the tunnel wall. In GBSM, the distribution is assumed to follow cosine distribution while in scattering cluster methods it is assumed to follow exponential distribution to simplify the calculation based on references from many literature sources.

The von Mises distribution is an effective tool for modelling angular parameters, particularly the azimuth angles of departure (AAoD) and arrival (AAoA). This distribution is often referred to as the circular normal distribution due to its similarity to the normal distribution in terms of its bell-shaped curve but on a circular domain. The probability density function (PDF) of the von Mises distribution is expressed as:

$$f(\theta) = \frac{e^{\kappa \cos(\theta - \mu)}}{2\pi I_0(\kappa)} \quad (4-19)$$

where θ is the angle, μ represents the mean direction, κ is the concentration parameter, and

$I_0(\kappa)$ is the zeroth-order modified Bessel function of the first kind. The mean direction μ indicates the expected value of the angle, reflecting the central tendency of scatterers' orientations. The concentration parameter κ controls the spread of the angles around the mean direction. A higher κ value indicates a sharper concentration around the mean, while a lower κ results in a more uniform distribution. By substituting the relevant parameters from this study into the formula above and combining them with the constraints, we can obtain

$$f(\alpha_i) = \frac{k_i \cos(\alpha_i - \alpha_{\mu_i})}{2\pi I_0(k_i)}, -\pi \leq \alpha_i \leq \pi \quad (4-20)$$

where $i \in \{1, 2\}$. Observe that the scatterers $S_n^{T_x}$, $S_n^{R_x}$ are arranged differently on each cylinder. α_1 , α_2 are utilised in this context to simplify $\alpha_T^{(n_{T_x})}$, $\alpha_R^{(n_{R_x})}$ in order to make them suitable for writing as sums in mathematical formulas; as a result, they are referred to separately as the AAoD at and the AAoA from. The purpose of the real-valued concentration parameter k_1 and k_2 is to regulate the angle and order distribution. The von Mises distribution is particularly advantageous in modelling the AAoD and AAoA in tunnel environments because it provides flexibility in representing both highly concentrated and more dispersed scatterer orientations. This adaptability is crucial in tunnels where the geometry can cause certain scatterers to have highly directional reflections, while others may contribute to a broader spread of angles.

For modelling the elevation angles of departure (EAoD) and arrival (EAoA) for the scatterers distributed on the tunnel wall, the cosine distribution is utilised due to its simplicity and effectiveness in representing angular spreads that are typically symmetric around a central direction. The PDF of the cosine distribution is given by:

$$f(\phi) = \frac{1}{2}(1 + \cos(\phi - \phi_0)) \quad (4-21)$$

where ϕ is the angle, and ϕ_0 is the central angle or the mean direction. ϕ_0 represents the mean elevation angle, which indicates the predominant direction of the scatterers. The cosine distribution is symmetric around ϕ_0 , making it particularly useful for scenarios where the elevation angles are expected to be uniformly distributed around a central value, such as reflections off the tunnel walls or ceiling. The cosine distribution is well-suited for describing EAoD and EAoA in tunnel environments where the elevation angles are influenced by the tunnel's geometry, leading to reflections that are generally symmetric around a central axis. Using the aforementioned formula with the pertinent research parameters substituted and the

limitations added, we can get

$$f(\beta_i) = \frac{\pi}{4\beta_{i,\max}} \cos\left(\frac{\pi}{2} \frac{\beta_i - \beta_{i,u}}{\beta_{i,\max}}\right), \beta_{i,u} - \beta_{i,\max} \leq \beta_i \leq \beta_{i,u} + \beta_{i,\max} \quad (4-22)$$

where in the same way, for the cosine distribution, β_1 and β_2 denote, respectively, the EAoD at $S_n^{T_x}$ and the EAoA from $S_n^{R_x}$. The primary direction of β_1 and β_2 , respectively, is indicated by $\beta_{1,u}$ and $\beta_{2,u}$. The variance of each, β_1 and β_2 , is shown by the variables $\beta_{1,\max}$ and $\beta_{2,\max}$.

Since it is mentioned that the propagation path between two clusters is abstracted as a virtual link rather than real path via scatterers on the tunnel wall, it is necessary to derive and analyse the characteristics of that link. The exponential distribution is widely used in communication theory to model the time between events in a Poisson process. In the context of V2V communication channels, it is particularly relevant for modelling the propagation distances between scatterers in twin-cluster models. In the twin-cluster model, which is commonly used to represent NLoS propagation, the complex CIR between the transmitting and receiving antennas is influenced by the scattering that occurs in two distinct clusters, namely ClusterTx and ClusterRx. These clusters represent the regions where significant scattering occurs, and the signal travels between these clusters via what is termed as a “virtual link”. The distance that the signal travels between these two clusters plays a crucial role in determining the overall CIR. This distance is not fixed; instead, it varies according to the distribution of scatterers within each cluster. Here, the propagation distance between ClusterTx and ClusterRx is modelled using an exponential distribution, which is defined as:

$$f(\xi) = \lambda e^{-\lambda\xi}, \quad \xi \geq 0 \quad (4-23)$$

where ξ represents the distance between the clusters and λ is the rate parameter, which is the inverse of the mean distance between scatterers. The choice of an exponential distribution for modelling the virtual link between scatterers is based on its memoryless property, meaning the probability of the next scatterer being a certain distance away does not depend on the distance already travelled. This is particularly useful in the context of V2V communication, where scatterers within tunnels are often assumed to be randomly distributed without any significant spatial correlation. A higher λ value indicates that scatterers are more closely spaced, leading to shorter average distances between them, whereas a lower λ value suggests that scatterers are more spread out. Rate parameter λ is crucial as it determines the spread of the exponential distribution. The use of the exponential distribution also simplifies the mathematical treatment of the model. Since the exponential distribution is relatively straightforward, it facilitates the derivation of closed-form expressions for the CIR, which can

then be used to simulate and analyse the performance of V2V communication systems under various conditions. Moreover, this approach is adaptable to different types of tunnels and environments. By adjusting the rate parameter λ , the model can be fine-tuned to match different scenarios, whether it's a narrow urban tunnel with closely spaced scatterers or a wide highway tunnel where scatterers are more sparsely distributed. To apply the exponential distribution to the virtual link and the birth-death process, we have

$$P_{CT} = e^{-\lambda_G \frac{\delta_T}{D_c}} \quad (4-24)$$

$$P_{CR} = e^{-\lambda_R \frac{\delta_R}{D_c}} \quad (4-25)$$

where D_c is the scenario-dependent correlation factor on the array axis, λ_G and λ_R stand for the cluster generation rate and recombination rate, respectively. The average number of freshly generated clusters on the array axis can be computed using the birth-death process. The survival probability $P_s(\Delta t)$ can be calculated as

$$P_s(\Delta t) = e^{-\lambda_R \frac{P_m(\overline{v_R} + \overline{v_T})\Delta t}{D_c}} \quad (4-26)$$

where Δt represents the time interval, $\overline{v_R}$ and $\overline{v_T}$ are the average relative movement velocities of the Tx and Rx, respectively, and P_m represents the proportion of movement clusters. For every instant $t + \Delta t$, a Poisson distribution produces a random number with mean

$$\mathbb{E}[N(t + \Delta t)] = \frac{\lambda_G}{\lambda_R} (1 - P_s(\Delta t)) \quad (4-27)$$

where $\mathbb{E}[\cdot]$ denotes the expectation operation, $N(\cdot)$ represents the newly generated clusters. To further enhance the realism of the model, scatterers are distributed along the tunnel walls using a coordinate system. In this approach, the scatterer coordinates are defined within a three-dimensional space. The positions of scatterers are assumed to be both continuous and independent random variables, which allows for a flexible and accurate representation of the scatterer distribution within the tunnel. The number of effective scatterers in the proposed model is theoretically infinite, enabling the model to account for the continuous nature of scatterer distributions along the tunnel walls. The continuous distribution of scatterers is crucial for accurately capturing the complex interactions between the transmitted signals and the tunnel environment, including multiple reflections and diffractions. Given the continuous and independent nature of the scatterer positions, the PDFs for the angular parameters can be derived based on the relationships between these coordinates. The distributions discussed here are integral to the accurate simulation of V2V communication channels within tunnels.

By incorporating the von Mises, cosine distributions and exponential distributions, the model can more realistically represent the complex angular spreads of scatterers, leading to more accurate predictions of signal propagation characteristics. This is particularly important in tunnel environments, where the confined space and reflective surfaces create challenging conditions for signal transmission. The use of these distributions also allows for the customisation of the model based on specific tunnel characteristics, such as shape, size, and material properties. This adaptability is crucial for designing robust V2V communication systems that can operate effectively in a wide range of tunnel environments, from urban underpasses to long highway tunnels.

4.5 MODEL IMPLEMENTATION

In this part, codes and demonstration of the proposed model will be presented. GBSM model is used to demonstrate the process of implementation.

4.5.1 PARAMETERS DEFINITION

First work is to define parameters used in the scenario including tunnel length, radius of cylinders, velocity of vehicles and so on, which is shown in Fig. 6 and Fig. 7. Those value of parameters can be changed to analyse impact of different parameters on the statistics of channel. For the sake of convenience for calculation, the model establishes a coordinate system based on the geometric center of a rectangular prism. The initial position of Tx is located at the center of the leftmost lane of the rectangular tunnel (two lanes in total). The Tx coordinates are $(x, y, z)=[0, 1/4 * \text{tunnel_width}, H_T/2]$, and the Rx coordinates are $(x, y, z)=[D, 1/4 * \text{tunnel_width}, H_R/2]$. Moreover, two vehicles are assumed to travel in the same direction and in a straight line, and the angle and height of the antenna are all the same. Hence, the formulas for channel impulse response are simple and does not require so many parameters. There are some fixed parameters including $\text{num_scatterers}=3$ (there are 3 different areas for distribution of scatterers including Tx, Rx and tunnel wall), $f_c=5.9\text{e}9$ (carrier frequency of V2V communication is constricted to 5.9GHz in real environment), $c=3\text{e}8$ (the speed of electromagnetic wave is $3*10^8$ m/s) and so on.

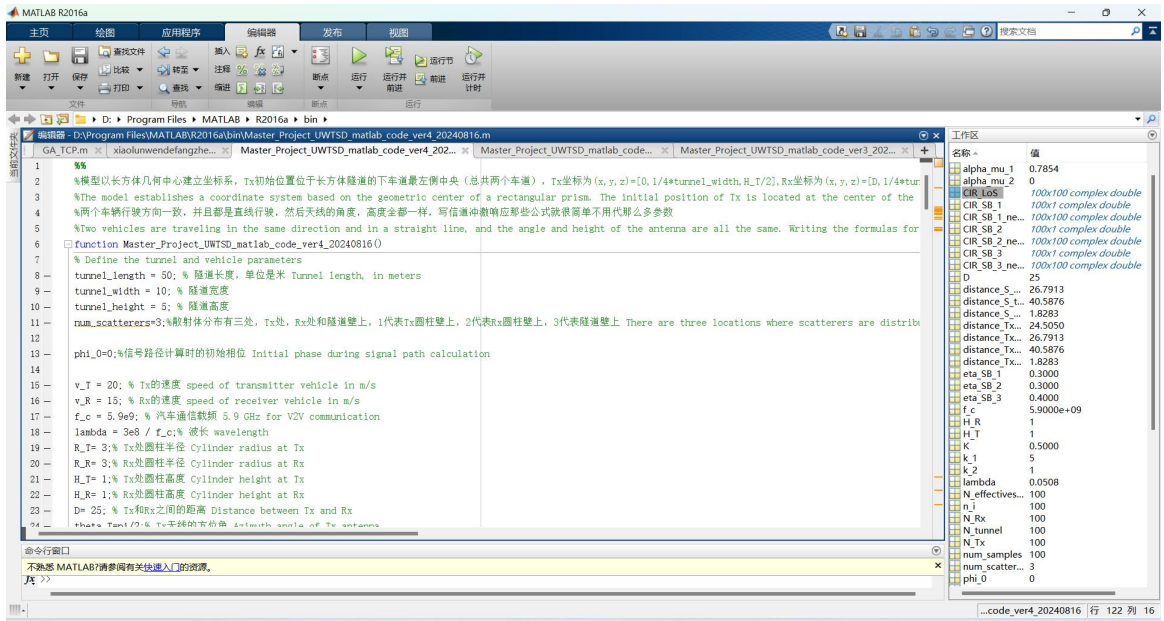


Fig. 6. Part one of defining parameters

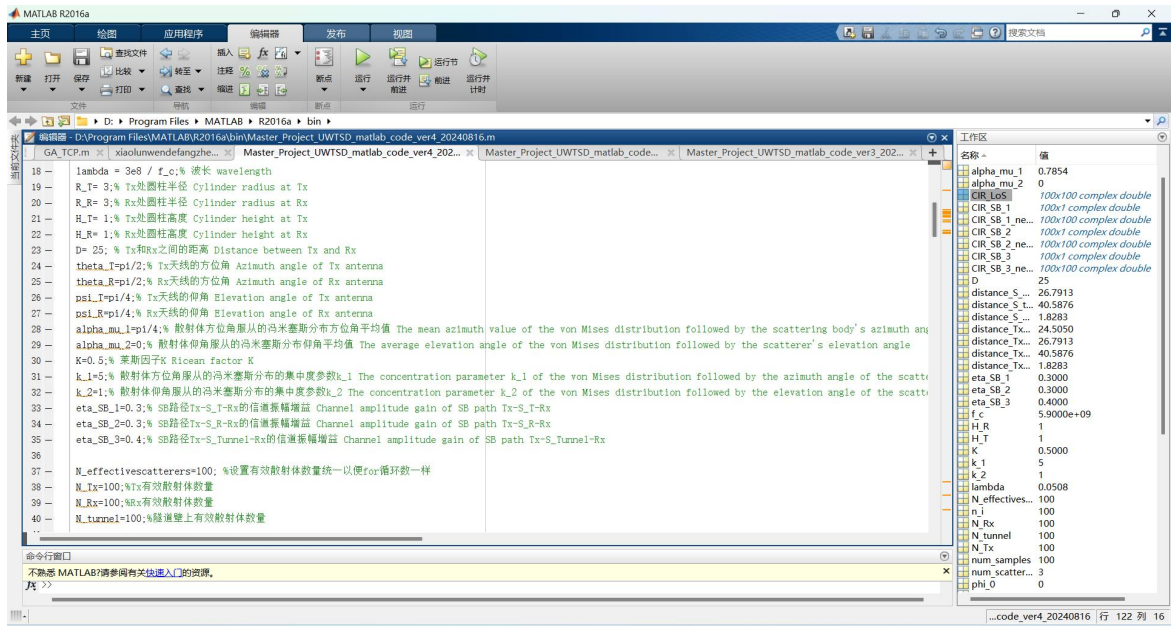


Fig. 7. Part two of defining parameters

Then, parameters for sampling simulation can be set. In formulas of CIR and STCF, there are always infinite integrals and variables. However, if serious calculations of infinite symbol integrals are taken to calculate, it will take a large amount of time for each iteration. To get rid of complex calculation and enable to show during viva, sampling simulation is chosen for this study. In Fig. 8, the number of time samples are set to 100, 1000, 10000 and so on. The time interval is set to 0.001 because the time duration to study is very short as the characteristics of channel are changing very fast due to the velocity of vehicles, different

positions of other vehicles and surface of tunnel walls. According to above, different sample time can be derived. After that, initial positions are denoted by Tx_initial_position and Rx_initial_position. To calculate easier, they are set as tx_initial_position = [0, tunnel_width / 4, tunnel_height / 2] and rx_initial_position = [D, tunnel_width / 4, tunnel_height / 2]. Before we proceed to the calculation of CIR, to increase the speed of running programmes (if not do this, MATLAB will send a warning), it is important to pre-allocate the matrices for different CIRs. This operation indicates the size of CIRs. To consider the need of summing and averaging different CIR with different scatterers at the same time t, the matrix is set to zeros(num_samples,N_effectivescatterers). When use sum(CIR,2), it can sum to a matrix with size of num_samples*1.

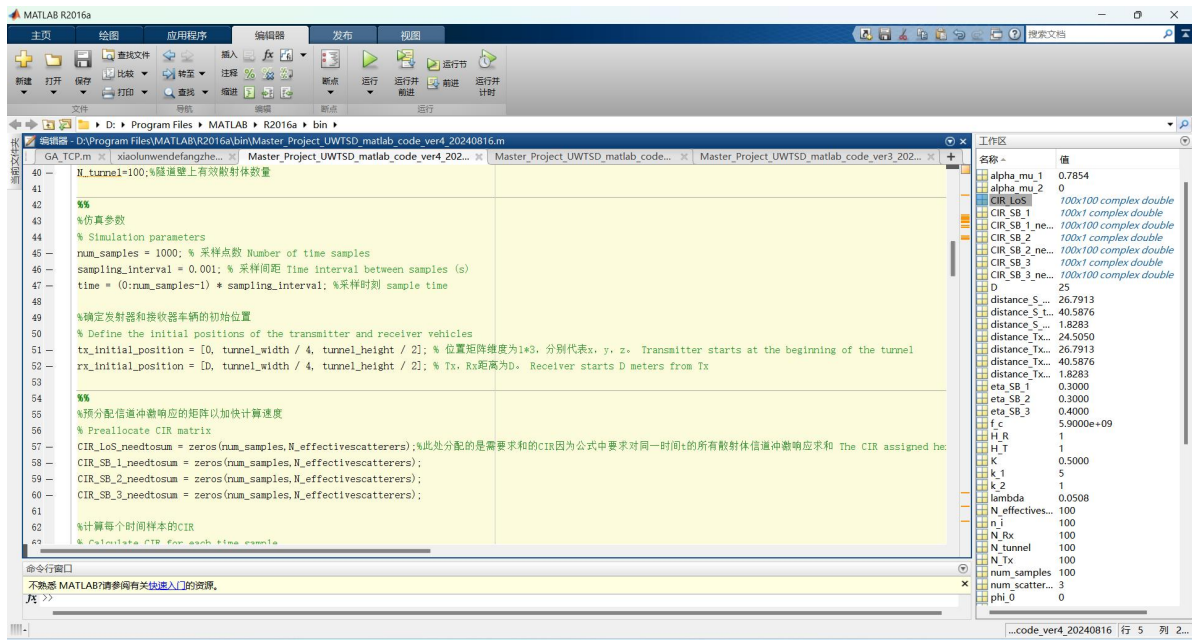


Fig. 8. Parameters for sampling

4.5.2 CALCULATION OF DISTANCES AND CIRs

Since the channel is not static in this study because of the movement of vehicles mainly, after the definition of sampling parameters, the positions of Tx and Rx can be calculated based on their initial positions, velocity of vehicles and the time point in Fig. 9. As it is mentioned above that two vehicles will proceed in the same direction and the path is a straight line, the incremental position on the y-axis and z-axis is 0. Additionally, another factor to cause non-static is the randomness of scatterers, scatterers are distributed on the surface of cylinders of Tx end, cylinders of Rx end and tunnel wall. To simplify the calculation, only the left and the right tunnel walls are considered in this study, then the y-

axis orientation can be chosen from a binary array “catterers_positions_tunnelwall_y=[-1/2 * tunnel_width, 1/2 * tunnel_width]”. However, in real environment, the left, right, top and ground of the tunnel wall can reflect electromagnetic wave but the top and ground are ignored in this study and this will be a part of the future work.

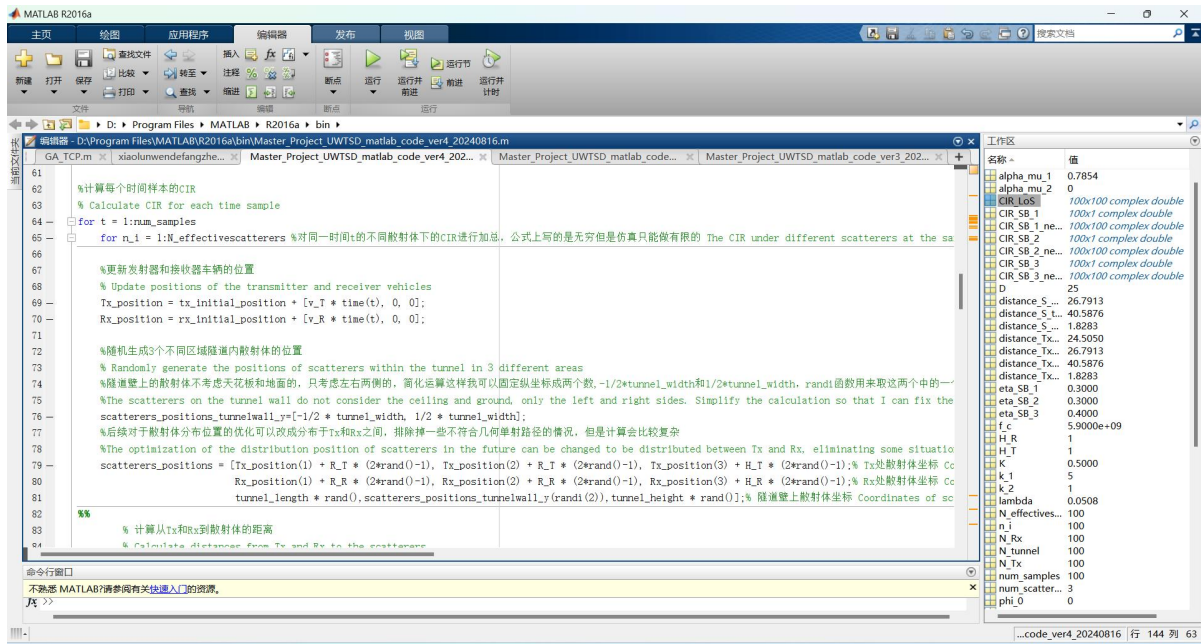


Fig. 9. Part one of CIR and relevant formulas calculation

The 3×3 scatterers_positions matrix includes positions of scatterers distributed on the surface of the Tx cylinder, the surface of the Rx cylinder, and the surface of the tunnel wall. The three columns of the matrix represent the x, y, and z coordinates, respectively. Rand() function is used in this study to generate the possible position of scatterers on the surface of the regular GBSM model. Then, distances between Tx as well as Rx and different scatterers can be derived in Fig. 10 using Cartesian distance. After this, CIR can be calculated according to formulas (4-2) and (4-3).

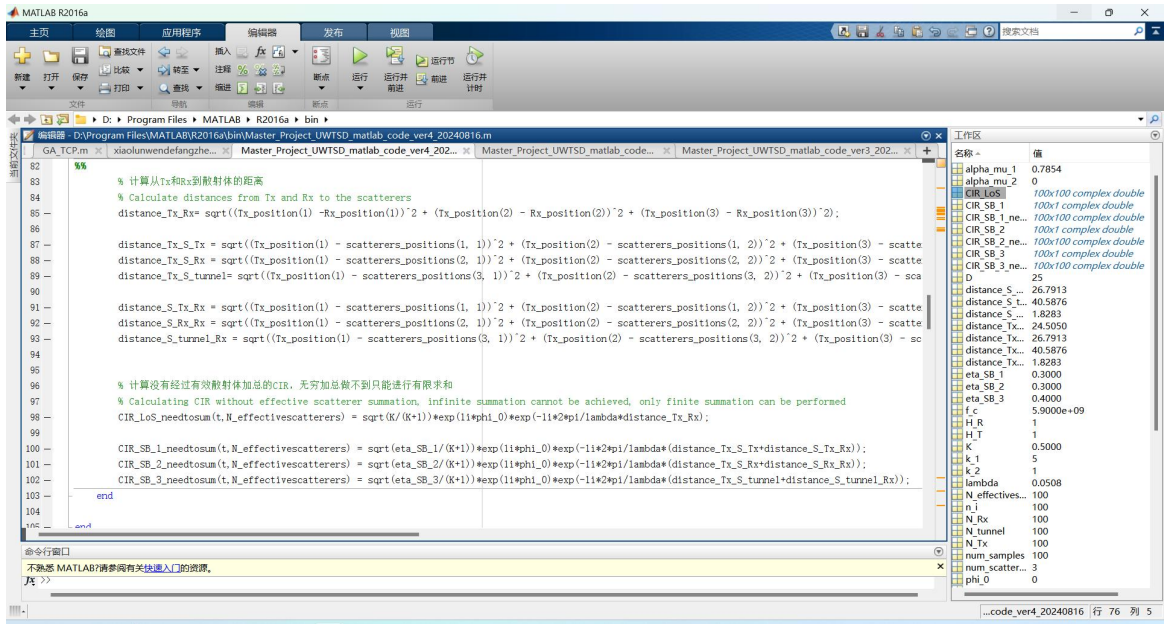


Fig. 10. Part two of CIR and relevant formulas calculation

4.5.3 ANALYSE OF CIRs BASED ON PARAMETERS

To analyse the channel characteristics, the process of CIR comparison is presented in this part. In Fig. 11, total CIR is summed based on `sum(CIR,2)` function using superposition theory. Plot function is used to generate different images for comparison.

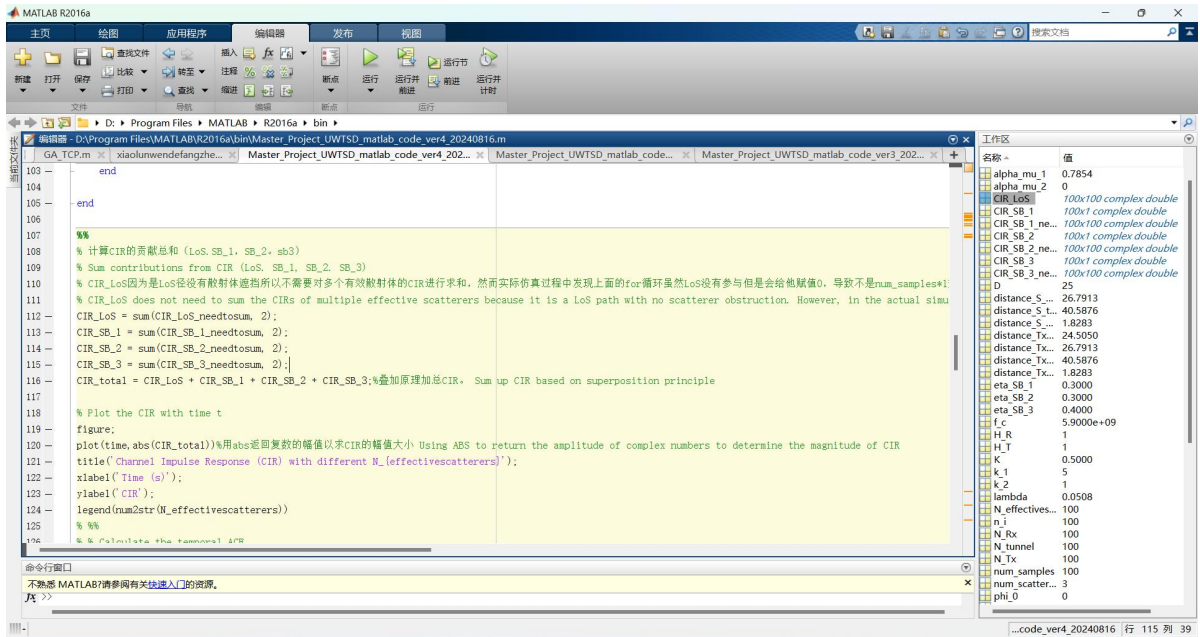


Fig. 11. Sum and plot of CIRs with time t

First is to analyse the impact of `N_effectivescatterers` (number of effective scatterers) on

CIR. N_effectivescatterers=10, 100, 1000, 10000 are set to plot, shown in Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16 separately. It can be seen obviously that the CIR fluctuates as the time goes by which proves that the channel is not static.

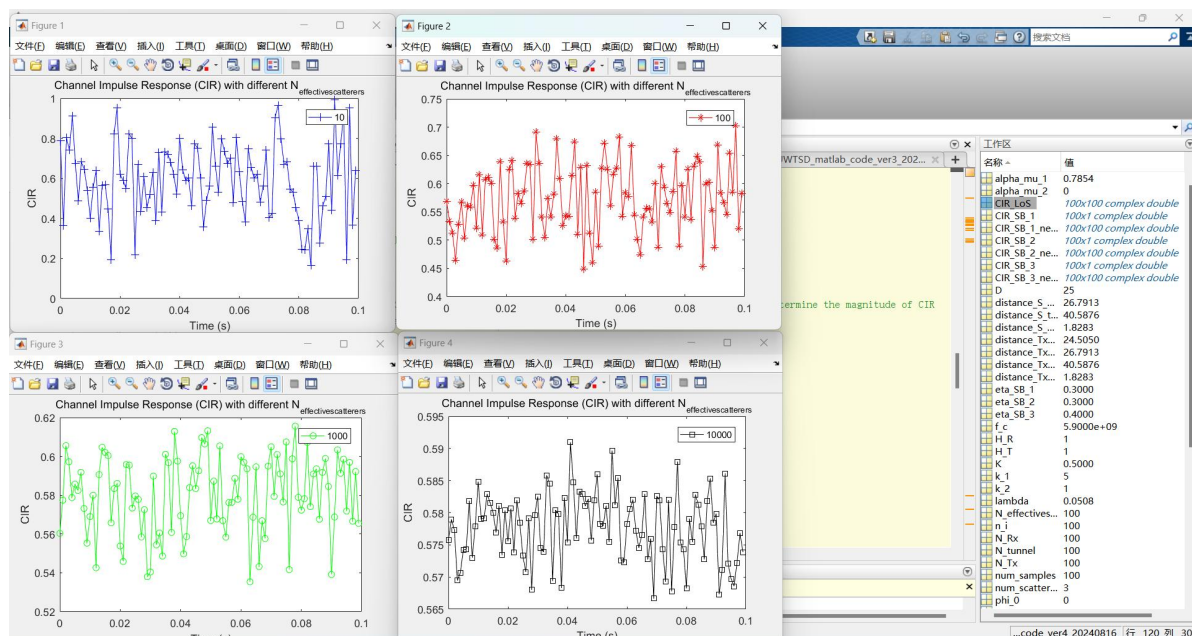


Fig. 12. Overall plots of CIRs with different $N_{\text{effective}}$ scatterers at time t

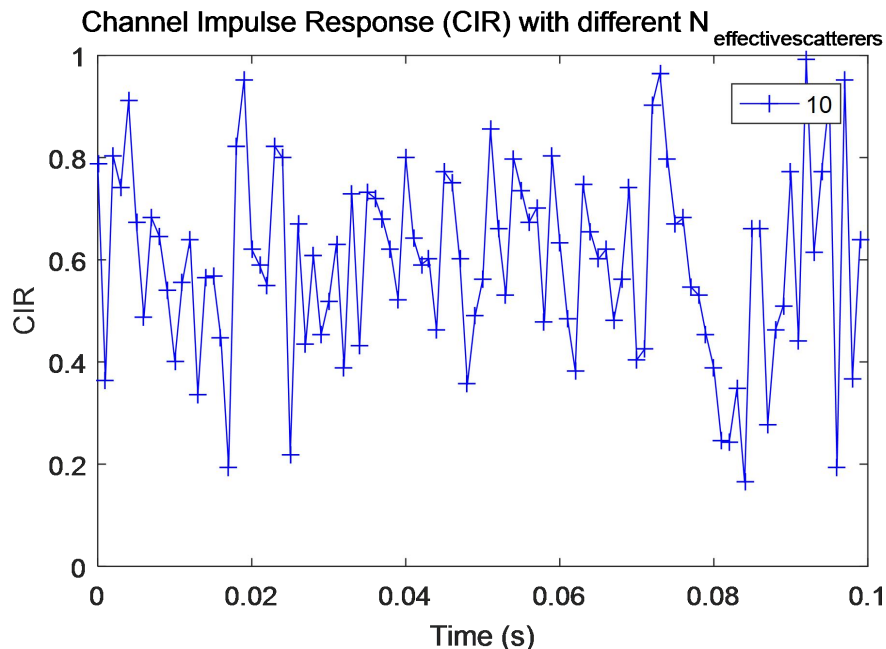


Fig. 13. Plot of CIR with $N_{\text{effectivescatterers}}=10$ at time t

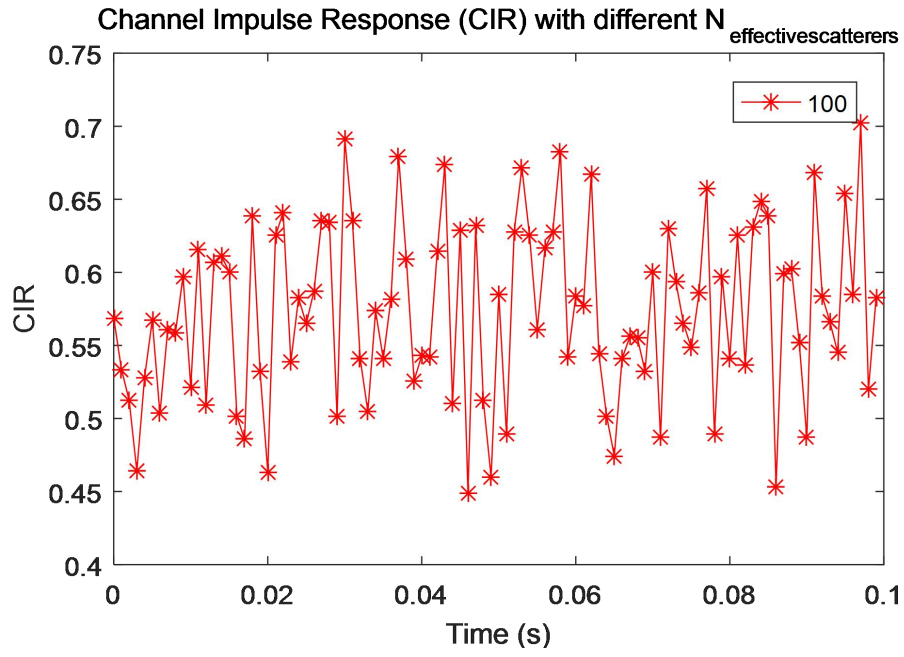


Fig. 14. Plot of CIR with N_{effectivescatterers} = 100 at time t

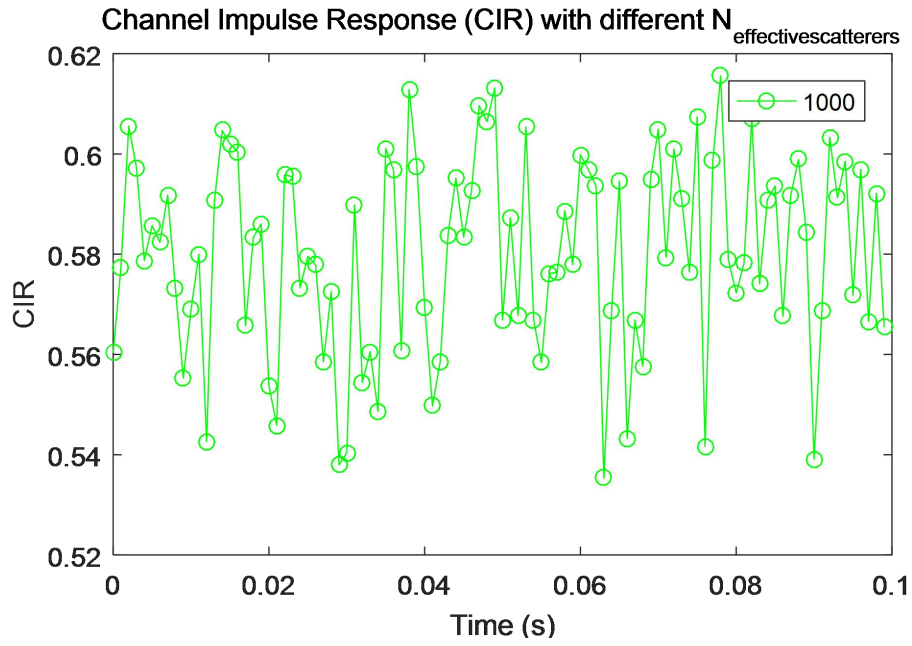


Fig. 15. Plot of CIR with N_{effectivescatterers} = 1000 at time t

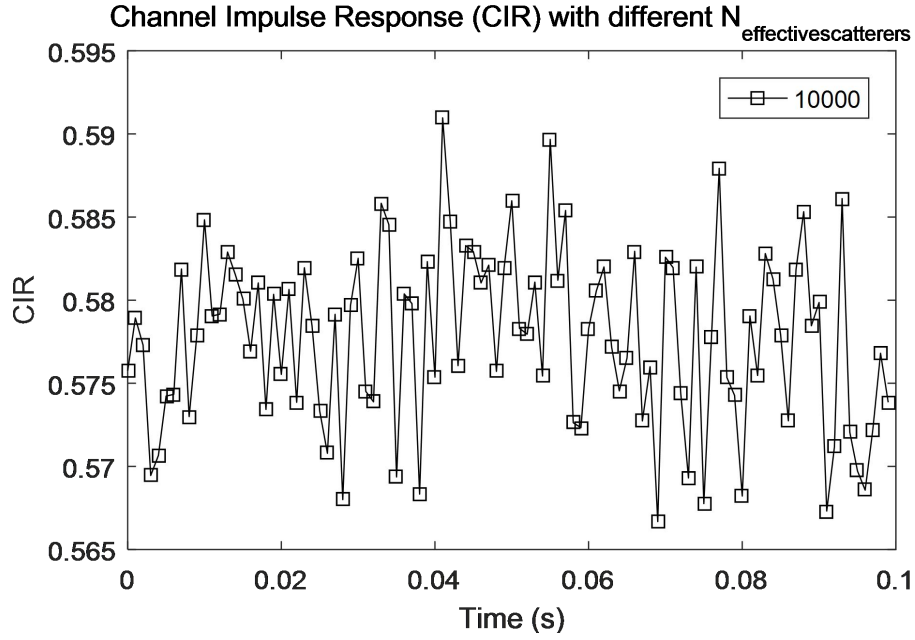


Fig. 16. Plot of CIR with $N_{\text{effectivescatterers}} = 10000$ at time t

Another thing to analyse is the amplitude of CIRs. It can be seen that the upper limit of CIR is decreasing as the $N_{\text{effectivescatterers}}$ goes up. This seems to go against intuition about formulas because it's $h_{pq}^{SB_i}(t) = \sqrt{\frac{\eta_{SB_i}}{K+1}} \lim_{N_i \rightarrow \infty} \sum_{n_i=1}^{N_i} \frac{1}{\sqrt{N_i}} e^{j\phi_0} e^{-j\frac{2\pi}{\lambda} \frac{z}{r_{pq,n_i}}}$ and the growth rate of the CIR should be approximately $\sqrt{N_i}$ since the scatterers are randomly distributed. The reason for this phenomenon is shown in Fig. 17, Fig. 18 and Fig. 19. It is shown that those values of CIR are very small, approximately to zero. When it is summed up based on the number of scatterers, there are different positive and negative numbers like $-0.285813586272530 + 0.497989403630970i$ and $0.255807316547430 - 0.516586689313594i$ because the non-static characteristic of the channel cause different positions of scatterers and it leads to the phenomenon “phase cancellation” in communication area. When the number of scatterers increase, this phenomenon will be more pronounced. Moreover, in the formulas of the CIR_{SB}, it is divided by $\sqrt{N_i}$. So it will lead the CIR of SB to approach zero. As a result, the total CIR is approximately to CIR of LoS.

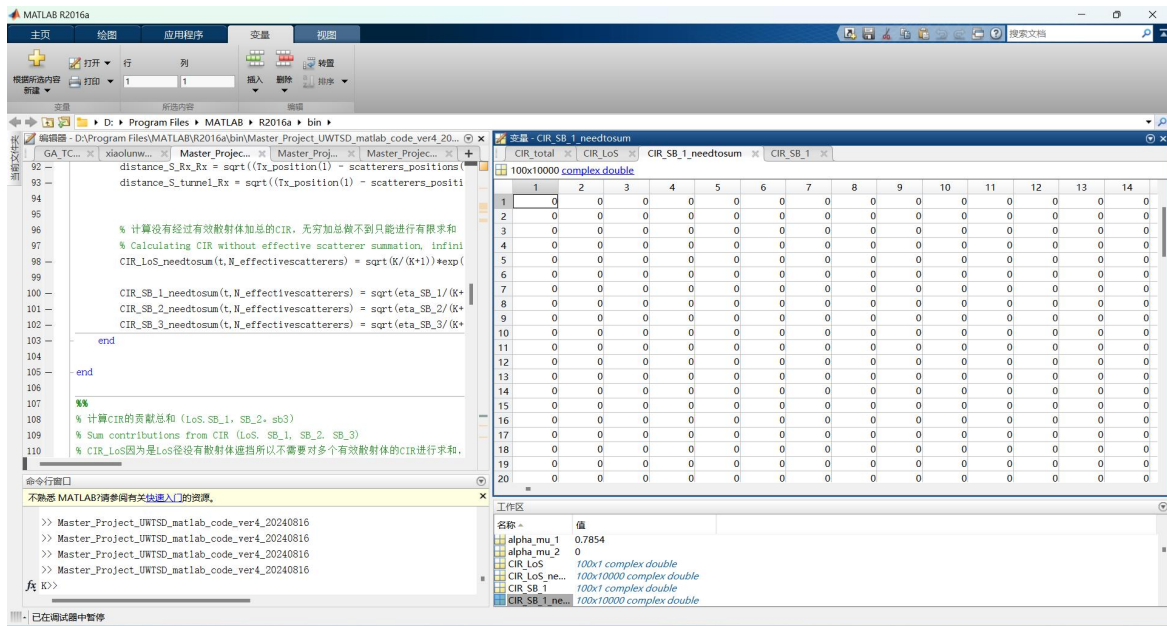


Fig. 17. Part one of workspace variables

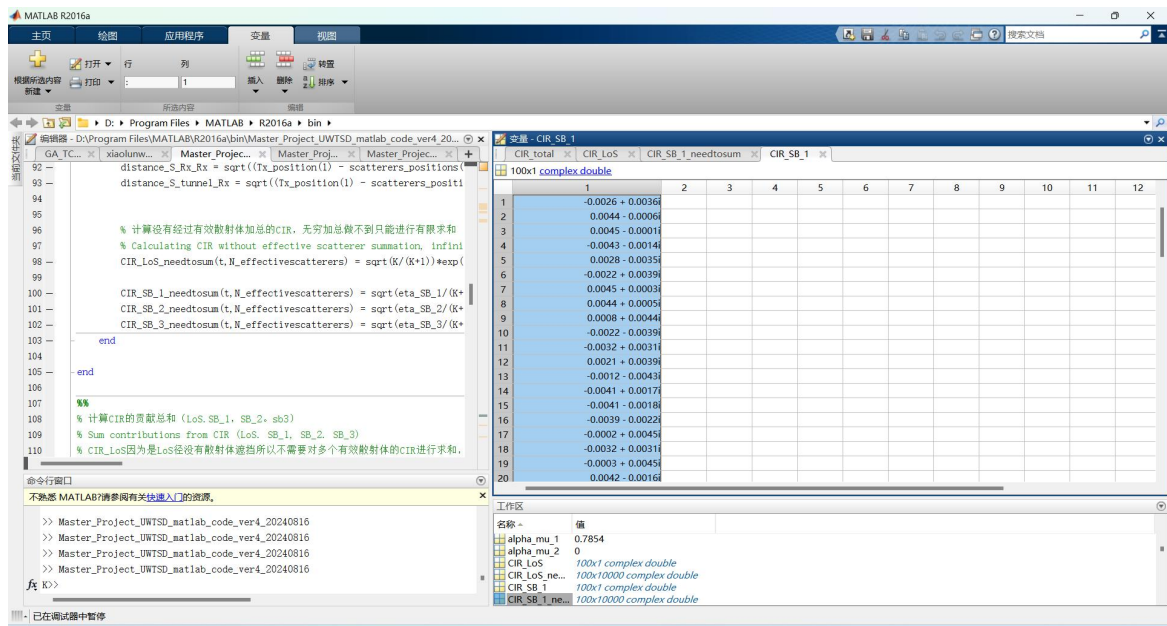


Fig. 18. Part two of workspace variables

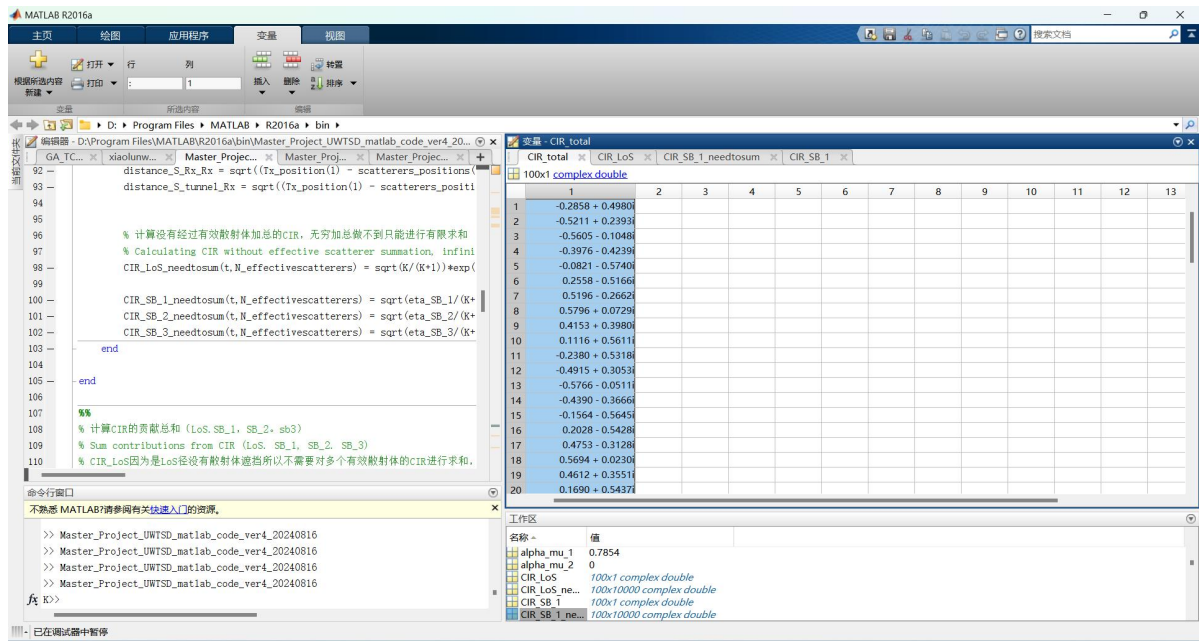


Fig. 19. Part three of workspace variables

According to formulas of CIRs, the Recian factor and the amplitude gain will have impact on CIRs. In Fig. 21, Fig. 22 and Fig. 23, different CIRs with different Recian factor K are shown. The graphical results are consistent with the theoretical analysis that when K rises, CIR will go higher because of the coefficient $\sqrt{\frac{K}{K+1}}$. Recian factor is an important parameter describing the fading model of wireless channels. When signals travel through objects or the atmosphere in wireless communication, they are subject to diffraction and scattering, which causes fluctuations in the signal strength throughout transmission. The proportional contributions of direct and dispersed components to variations in signal strength are reflected in the Recian factor. There is greater scattering in the wireless channel and more noticeable signal fading when the Recian factor is high because the energy of the dispersed component is more relevant. The energy of the direct component is more substantial and the signal fading is comparatively moderate when the Recian factor is minimal.

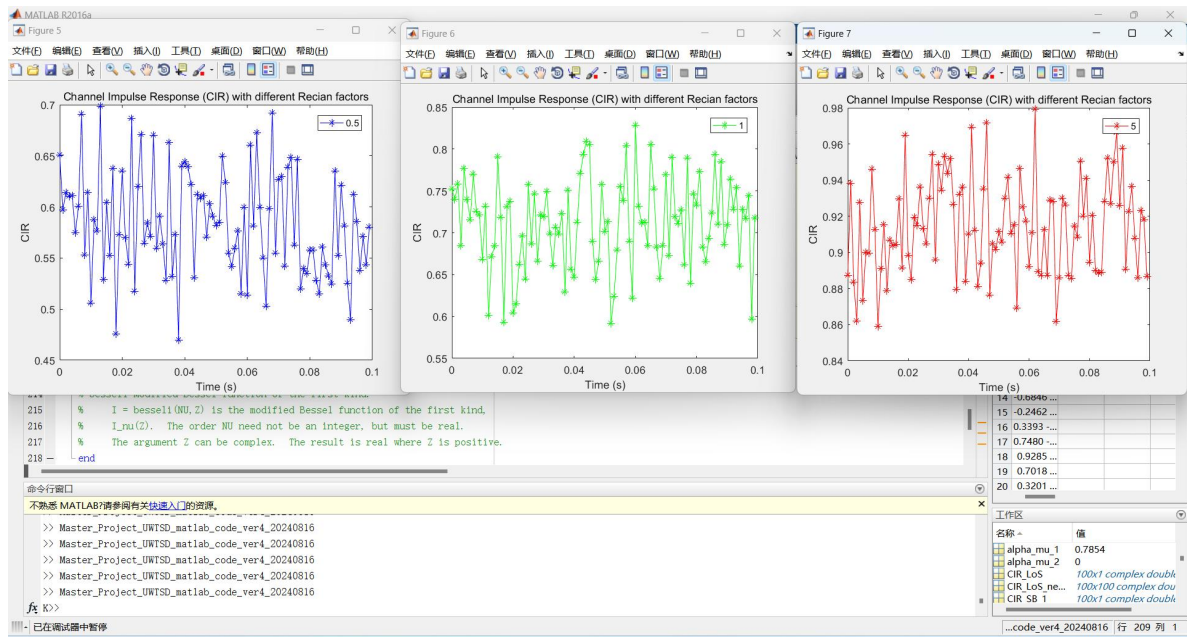


Fig. 20. Overall plots of CIRs with different Recian factor K at time t

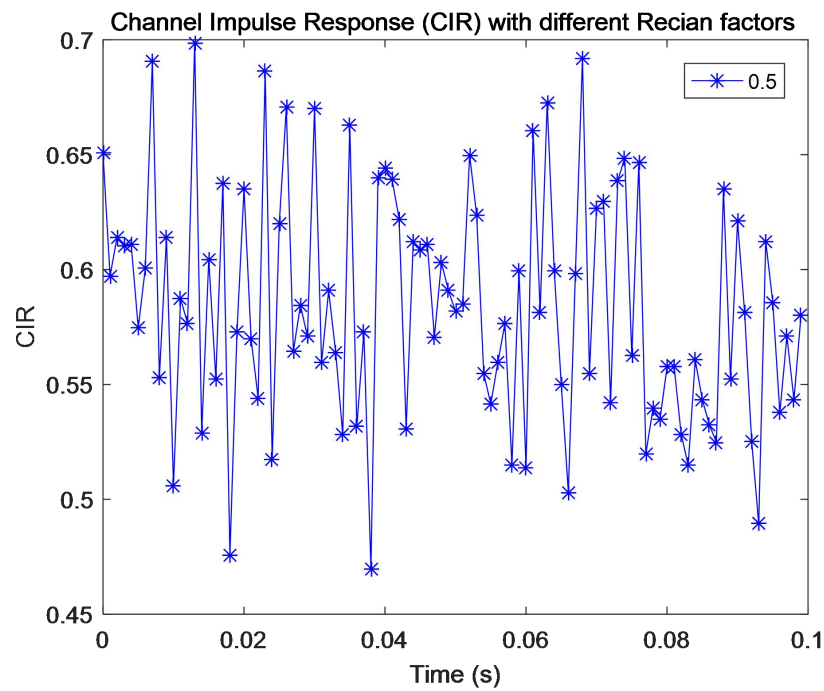


Fig. 21. Plot of CIR with Recian factor K=0.5 at time t

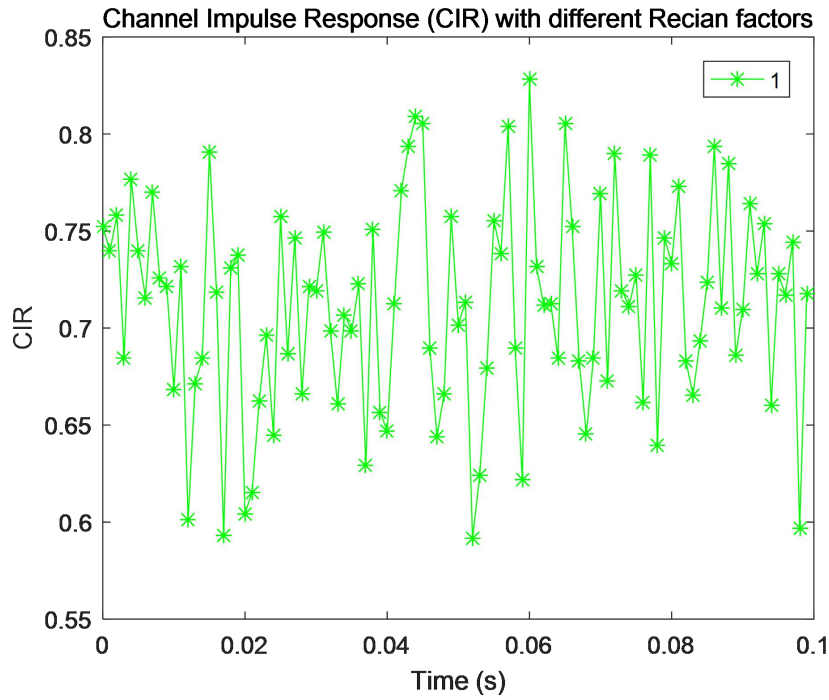


Fig. 22. Plot of CIR with Recian factor K=1 at time t

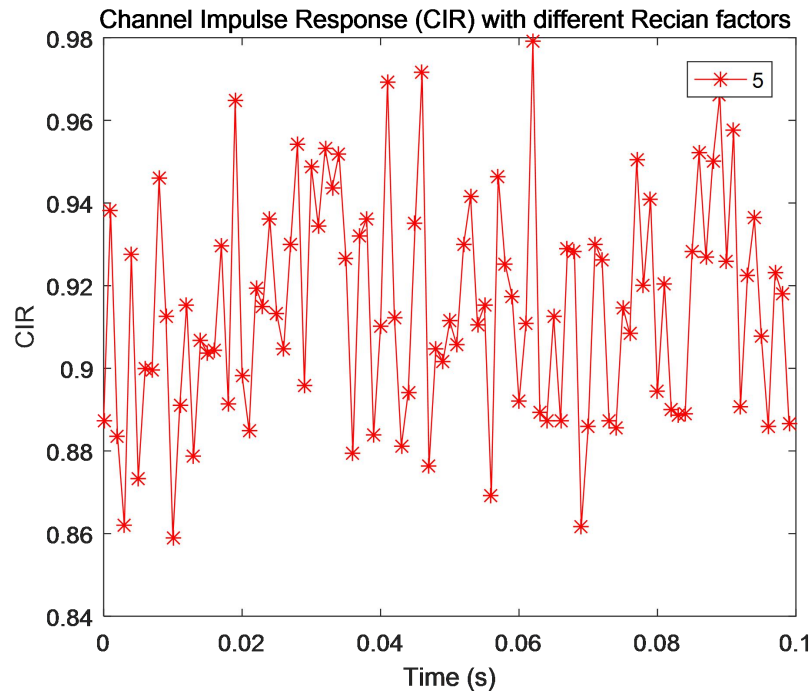


Fig. 23. Plot of CIR with Recian factor K=5 at time t

The parameter amplitude gain η_{path} is the averaging coefficient of different multipaths. However, it's hard to analyse because there are many variables when there are different paths. In this study, it only contains single-bounced path and 3 paths of that. Since then, it is

converted to a problem of finding extremum for binary functions. Unfortunately, the function includes lots of complex numbers and are not suitable for solutions of the problem in real number. Results are presented in Fig. 24, Fig. 25, Fig. 26, Fig. 27 and Fig. 28. Images indicate that the change in amplitude gain has no significant impact on the model. To go deep in analysis, the amplitude gain for 3 paths are set to zero and the result in Fig. 28 shows that even there is no single-bounced path, the CIR reaches 0.91287 which is very close to the upper limit 0.98 when there are 3 single-bounced paths. This phenomenon shows that in this model, the LoS path contributes most power of the V2V communication. The single-bounced paths only contribute a small part of signal power. It proves that even the multipaths including double-bounced path are ignored, it will not significantly influence the performance of the V2V communication generally.

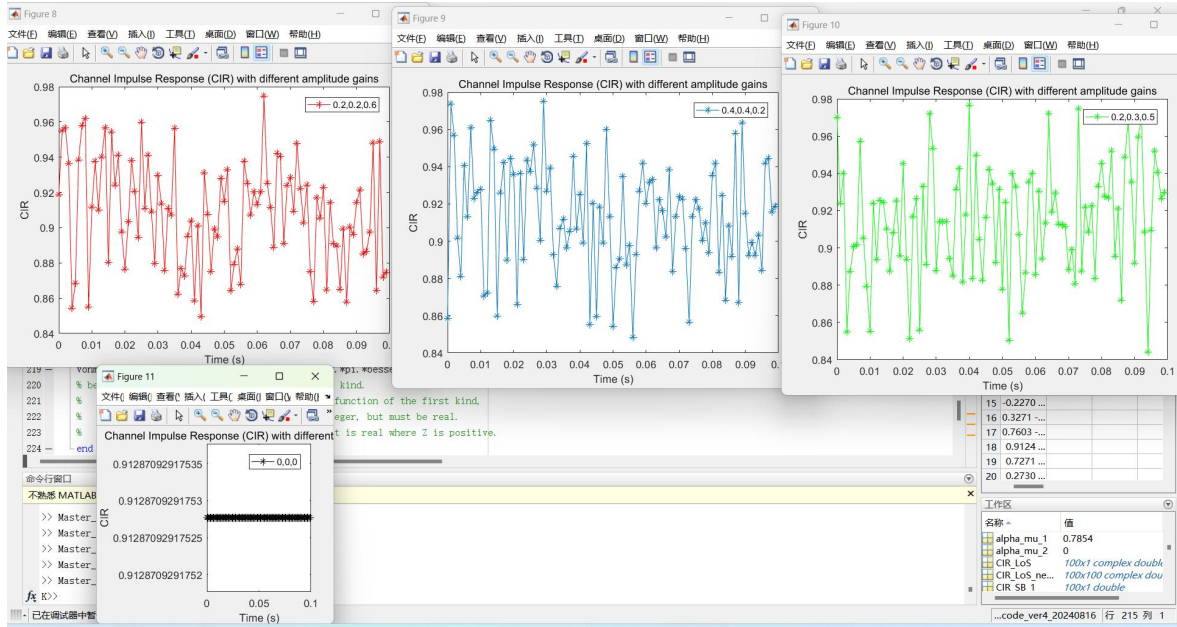


Fig. 24. Overall plots of CIRs with different amplitude gain at time t

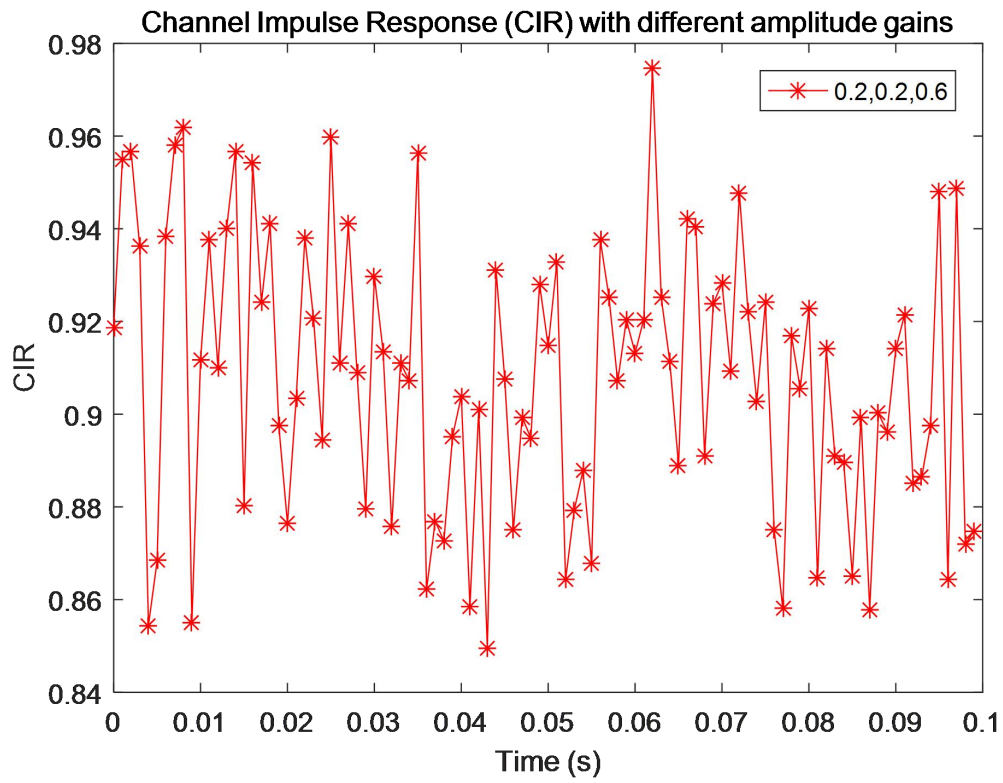


Fig. 25. Plot of CIR with amplitude gain=0.2,0.2,0.6 at time t

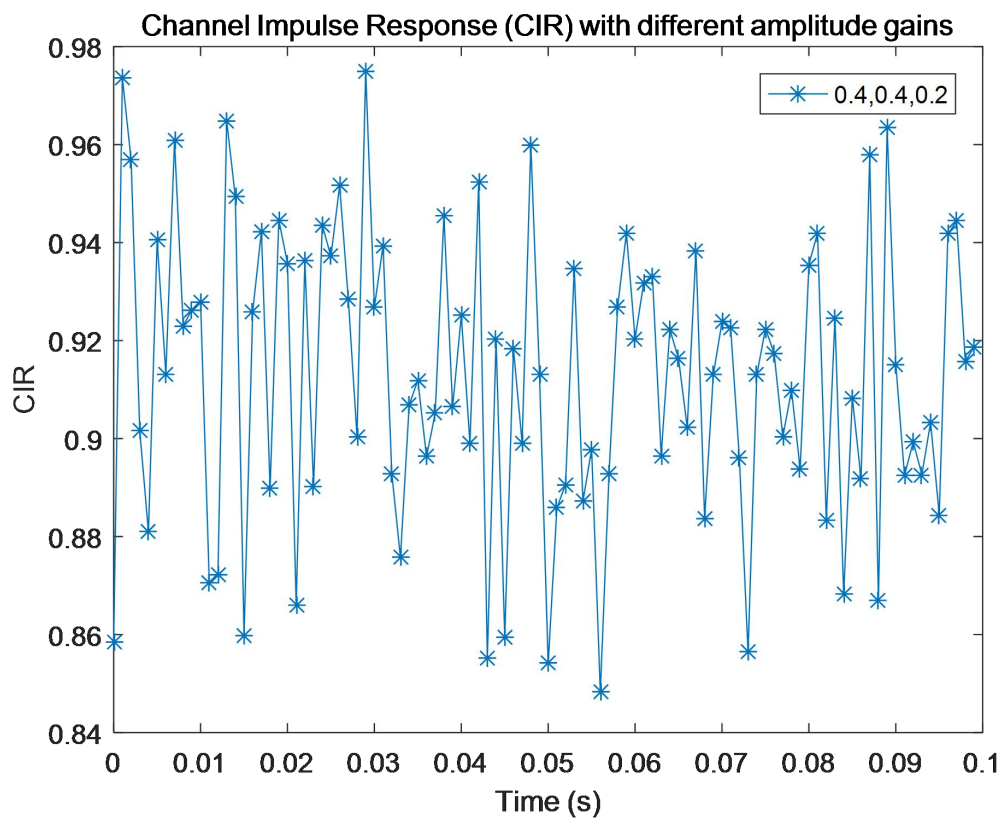


Fig. 26. Plot of CIR with amplitude gain=0.4,0.4,0.2 at time t

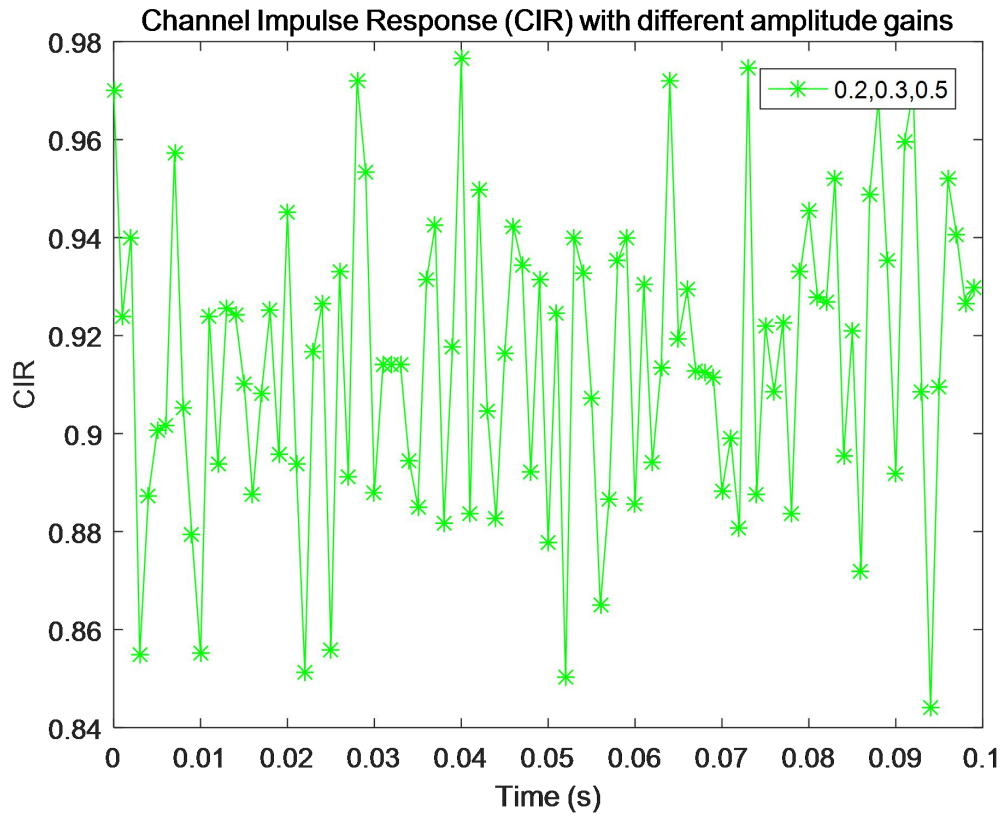


Fig. 27. Plot of CIR with amplitude gain=0.2,0.3,0.5 at time t

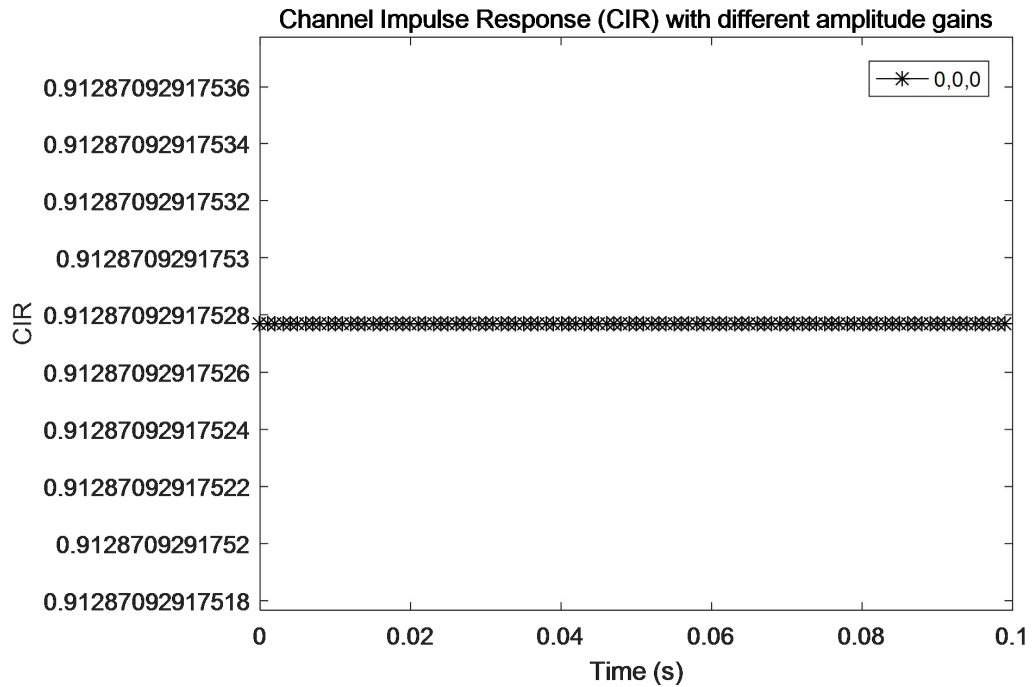


Fig. 28. Plot of CIR with amplitude gain=0,0,0 at time t

5. CHARACTERISTICS OF THE PROPOSED MODEL AND SIMULATION

RESULTS AS WELL AS ANALYSIS

In fifth chapter, key functions that describe channel correlation features are simulated and analysed in MATLAB. The established model's channel characteristics, such as Doppler power spectrum density and spatial-temporal correlation functions, are also calculated and analysed. In order to confirm that the derived formulas are accurate and that they match the measured data curves in the section on the review of literature, the temporal auto-correlation function, spatial cross-correlation function, and Doppler power spectrum density are the main functions that are simulated and analysed in this report. Furthermore, an analysis and comparison are conducted between each function's attributes and the causes behind its modifications based on the simulation findings.

5.1 INTRODUCTION

In this section, the characteristics of the proposed 3D V2V channel model is delved into by deriving key statistical functions and analysing their behaviours through simulation. To thoroughly understand the performance and applicability of the model in real-world scenarios, essential metrics such as the Space-Time Cross Correlation Function (STCF) and Doppler Power Spectrum Density (PSD) are focused on. These functions are pivotal in characterising the dynamic nature of vehicular communication channels, capturing how signal properties evolve over time and space in response to the mobility of vehicles and the complex propagation environment. The derivation of these functions is rooted in the underlying geometric relationships and stochastic processes governing the channel model. By formulating these mathematical expressions, various factors—such as vehicle speed, scatterer distribution, and how signal frequency affect the temporal and spatial characteristics of the received signal can be predicted. Following the derivation, the results of simulations conducted in MATLAB are presented, where these functions are evaluated under different scenarios. The simulations provide a comparative analysis between the Geometric-Based Stochastic Model (GBSM) and the Scattering Cluster method, offering insights into how each approach captures the nuances of signal propagation in vehicular environments. By comparing the results from both models, the author aims to highlight the strengths and limitations of each method, considering aspects such as their ability to represent spatial correlation, Doppler shifts, and time-variant channel behaviours. This comparative analysis not only validates the proposed model but also provides a deeper understanding of how

different modelling approaches impact the accuracy and reliability of V2V communication systems.

5.2 CHARACTERISTICS OF THE PROPOSED MODEL

In the area of V2V wireless communication area, it is common practice to characterise the temporal and spatial correlations between two complex sub-channels, p_1q_1 and p_2q_2 , using their STCF, which is represented as

$$\rho_{p_1q_1, p_2q_2}(t, \tau) = \mathbb{E}[h_{p_1q_1}(t)h_{p_2q_2}^*(t + \tau)] \quad (5-1)$$

where the complex conjugate operation is defined as $(\cdot)^*$. In order to define the space-time-frequency cross-correlation function as a superposition of multipath using the superposition theorem, it is assumed that the processes of LoS and NLoS propagations are independent of one another and do not interfere with one another during the propagation process. For GBSM, it's LoS and SB path, for scattering cluster, it's LoS and DB path. Consequently, the STCF for GBSM can be written as

$$\rho_{p_1q_1, p_2q_2}(t, \tau) = \rho_{p_1q_1, p_2q_2}^{LoS}(t, \tau) + \sum_{i=1}^3 \rho_{p_1q_1, p_2q_2}^{SB_i}(t, \tau) \quad (5-2)$$

while the STCF for scattering cluster can be written as

$$\rho_{p_1q_1, p_2q_2}(t, \tau) = \rho_{p_1q_1, p_2q_2}^{LoS}(t, \tau) + \rho_{p_1q_1, p_2q_2}^{DB}(t, \tau) \quad (5-3)$$

Substitute the CIR expression for LoS path into the STCF expression, LoS components of both GBSM model and scattering cluster model can be expressed as

$$\rho_{p_1q_1, p_2q_2}^{LoS}(\delta_T, \delta_R, t, \tau) = \frac{K}{K+1} e^{j\frac{2\pi}{\lambda}[\xi_{p_1q_1}(t) - \xi_{p_2q_2}(t)]} e^{j\frac{2\pi}{\lambda}\tau[v_T \cos(\alpha_T^{LoS} - \gamma_T) - v_R \cos(\alpha_R^{LoS} - \gamma_R)]} \quad (5-4)$$

Similarly, SB components of GBSM model can be expressed as

$$\rho_{p_1q_1, p_2q_2}^{SB_i}(\delta_T, \delta_R, t, \tau) = \frac{\eta_{SB_i}}{K+1} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} e^{-j\frac{2\pi}{\lambda}[\xi_{p_1q_1, n_1} - \xi_{p_2q_2, n_2}]} e^{j\frac{2\pi}{\lambda}v_T\tau[\cos(\alpha_T^{(i)} - \gamma_T)\cos(\beta_T^{(i)})]} e^{j\frac{2\pi}{\lambda}v_R\tau[\cos(\alpha_R^{(i)} - \gamma_R)\cos(\beta_R^{(i)})]} f(\alpha_{R/T}^{(i)}, \beta_{R/T}^{(i)}) d\alpha_{R/T}^{(i)} d\beta_{R/T}^{(i)}, \quad (5-5)$$

For scattering cluster model, we have DB path rather than SB path in GBSM model. DB components of scattering cluster model can be calculated as

$$\begin{aligned} \rho_{h_{p_1q_1}, h_{p_2q_2}}^{NLoS}(\delta_T, \delta_R, t, \tau) &= \frac{1}{(K+1)N_1N_2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} e^{-j\frac{2\pi}{\lambda}[\xi_{p_1q_1, n_1} - \xi_{p_2q_2, n_2}]} e^{j\frac{2\pi}{\lambda}v_T\tau\cos(\alpha_T^{(1)} - \gamma_T)\cos(\beta_T^{(1)})} \\ &\times e^{-j\frac{2\pi}{\lambda}v_R\tau\cos(\alpha_R^{(2)} - \gamma_R)\cos(\beta_R^{(2)})} e^{-j\frac{2\pi}{\lambda}D_c\tau} f(\alpha_T^{(1)}, \beta_T^{(1)}) f(\alpha_T^{(1)}, \beta_T^{(1)}) f(\alpha_R^{(2)}, \beta_R^{(2)}) d(\alpha_R^{(2)}, \beta_R^{(2)}) \end{aligned} \quad (5-6)$$

It is important to note that the temporal ACF expression of the propagation paths in the suggested model can be produced by imposing $\delta_T = 0$, $\delta_R = 0$, the spatial CCF expression of

the propagation paths can be obtained by imposing $\tau = 0$. The distributions of the Doppler power spectral densities (PSDs) are affected by the components with LoS and NLoS propagations in the channel model that is presented in this research. Then, it's easy to construct the closed form expression of the Doppler PSD by taking the Fourier transform of $\rho_{pq}(t, \tau)$ in terms of the time period τ . The form of Doppler PSD for both GBSM and scattering cluster is the same. We can compute the suggested Doppler PSD as

$$S(f, t) = \int_{-\infty}^{\infty} \rho_{pq}(t, \tau) e^{-j2\pi f \tau} d\tau \quad (5-7)$$

5.3 ANALYSIS OF SIMULATION RESULTS

In this part, simulation results of ACF, CCF, PSD in MATLAB will be presented, analysed and compared. The simulation results of CIRs are already presented in chapter 4.

The first study focuses on the image where the value of CCF changes with the variation of antenna spacing. The simulation parameters are listed as follows. $k_1 = [1, 3, 7]$, $t = 0.1$, $\tau = 0$, $\Delta T = \lambda * (0:10/99:10)$. It is mentioned above that when fix the time t and impose the time delay to 0, the CCF can be obtained from STCF. The result is shown in Fig. 29. There are 4 curves in the picture, where the blue curve's $k_1 = 1$, yellow curve's $k_1 = 3$ and purple curve's $k_1 = 7$. A red curve among them is a tenth order polynomial fitting curve which is in order to make the curve smooth. However, it is found not useful because the STCF fluctuates intensely. It can be seen that there is no much difference between these three curves because the assumption in this study is that two vehicles are moving in the same direction, their antennas' azimuth angles and elevation angles are all the same. Hence in the STCF formulas, the distance term $\xi_{p_1 q_1}(t) - \xi_{p_2 q_2}(t)$ is fixed when the time is fixed. So that the changing term is the discretisation summation term which is used to replace the integral with to reduce the computation time $e^{\frac{j2\pi}{\lambda} \gamma_T \tau [\cos(\alpha_T^{(i)} - \gamma_T) \cos(\beta_T^{(i)})]} e^{\frac{j2\pi}{\lambda} \gamma_R \tau [\cos(\alpha_R^{(i)} - \gamma_R) \cos(\beta_R^{(i)})]} f(\alpha_{R/T}^{(i)}, \beta_{R/T}^{(i)}) d\alpha_{R/T}^{(i)} d\beta_{R/T}^{(i)}$. In the simulation, the scatterers are distributed randomly so the value of this term will change randomly which lead to the fluctuation of the curves.

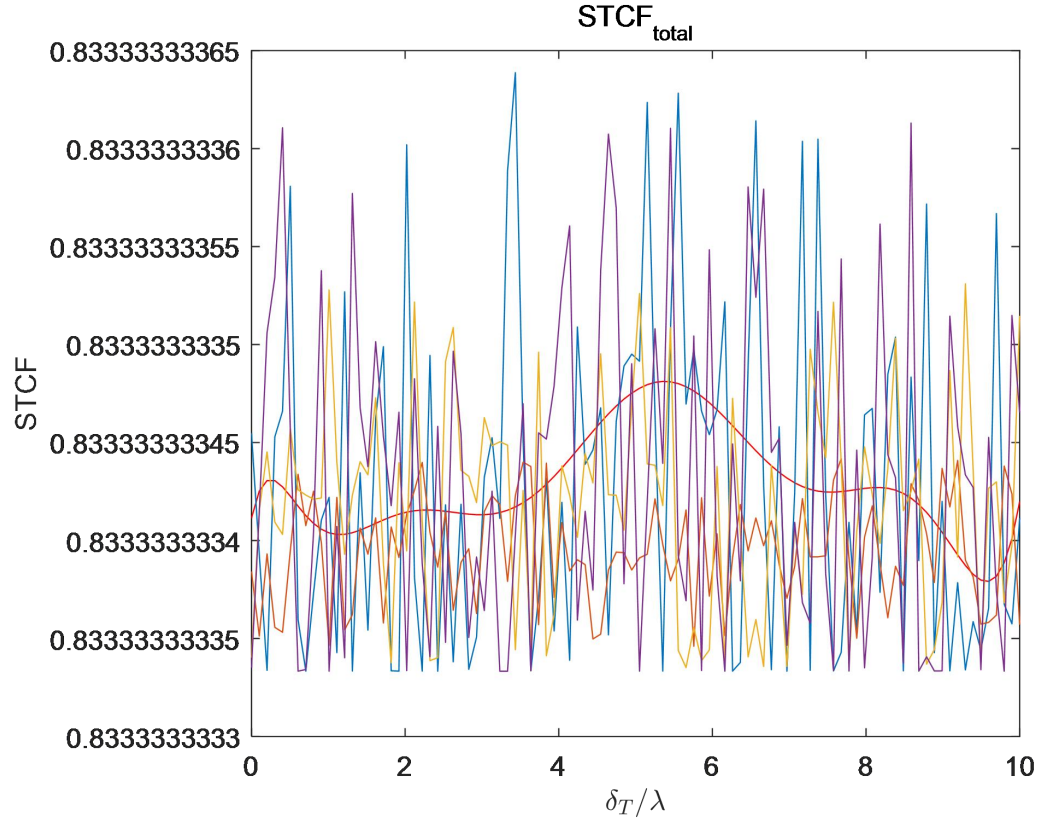


Fig. 29. Image of CCFs with antenna spacing of Tx for different local distributions of Tx under former assumption

To analyse the impact of concentration parameter on CCF, the assumption is changed: two vehicles are not moving in the same direction anymore, Tx travels along the upper right corner at a 45 degree angle with the x-axis at the speed of v_T , while Rx continues to travel straight in the positive direction of the x-axis at the speed of v_R . The image of CCF under this assumption is shown in Fig. 30. It can be seen that the difference of three curves can be told. When the value of k_1 rises, the CCF increased slowly. That's because the k_1 parameter is the concentration parameter of the von-mises distribution of azimuth angles for S_{Tx} and S_{Rx} . When k_1 rises, it means that the azimuth angles of scatterers distributed on the surface of cylinders around Tx and Rx will get closer to each other, which increases the cross correlation. Another thing to mention is that although there is a difference between these three curves, the difference is very subtle. That's because the k_1 parameter doesn't have influence on the CCF_LoS. It only influences the CCF of 3 SB paths. In the proposed model, the three SB paths only contribute a small power to the total so that k_1 can't significantly impact the value of the CCF.

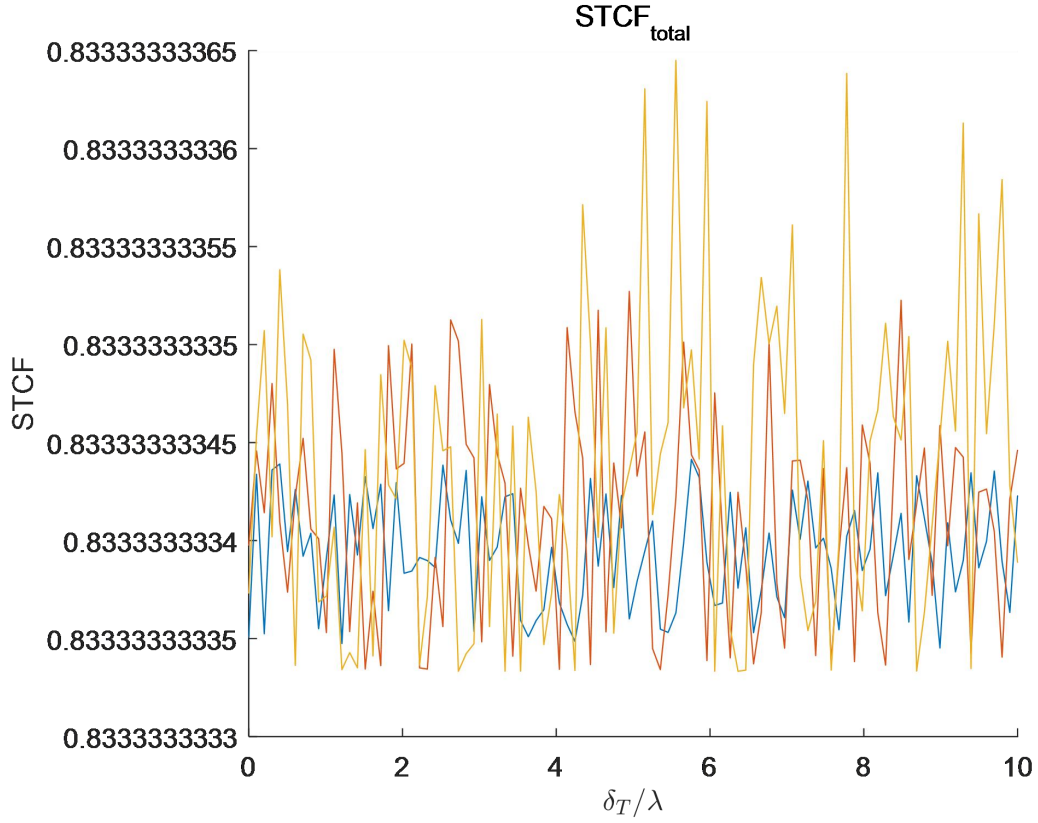


Fig. 30. Image of CCFs with antenna spacing of Tx for different local distributions of Tx under latter assumption

The next thing to analyse is the impact of moving time t on ACF. The test value is $t = [0, 1, 2]$. $\gamma_T = [\pi/4, \pi/8]$ are tested. In Fig. 31, blue, red, green curves' moving time t are 0, 1, 2 separately. The azimuth angle of velocity of Tx is $\pi/4$. In Fig. 32, the azimuth angle of velocity of Tx is $\pi/8$. It seems that there is not much difference among these three curves from these two figures. However, it is known that the moving time t will have impact on ACFs since the channel is non-static and at every moving time t , the characteristic of channel will vary.

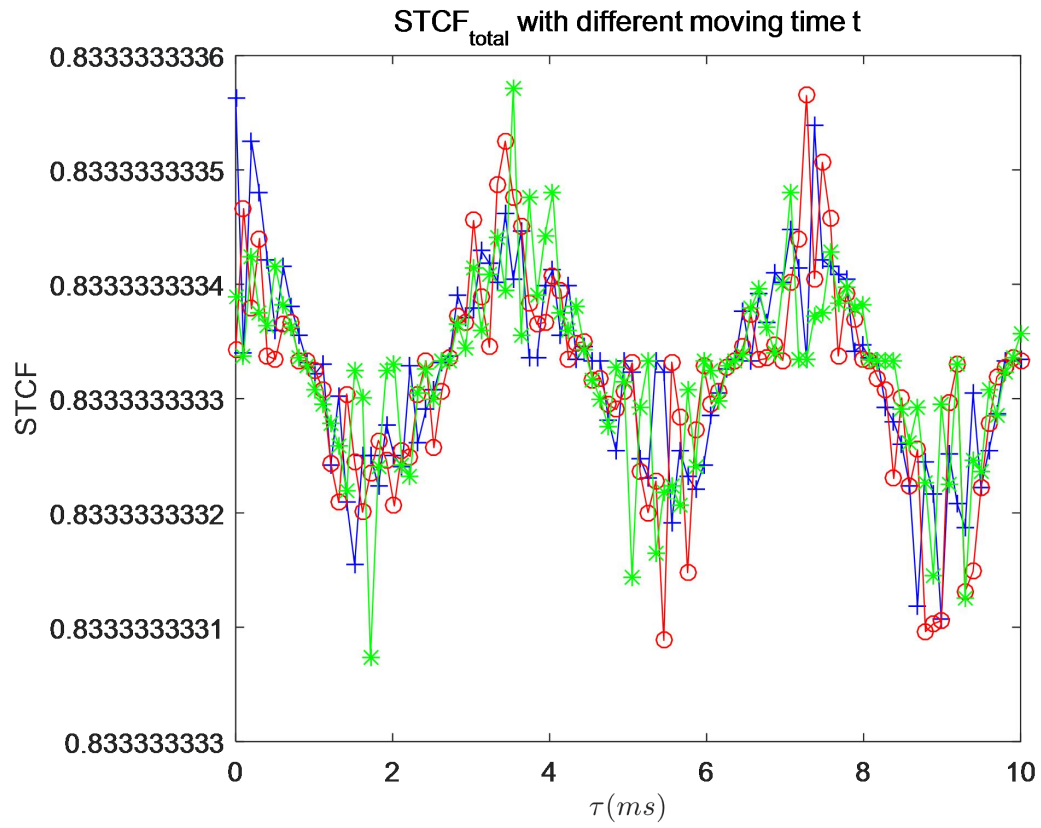


Fig. 31. Image of ACFs with time delay tau for different moving time t under $\gamma_T = \pi/4$

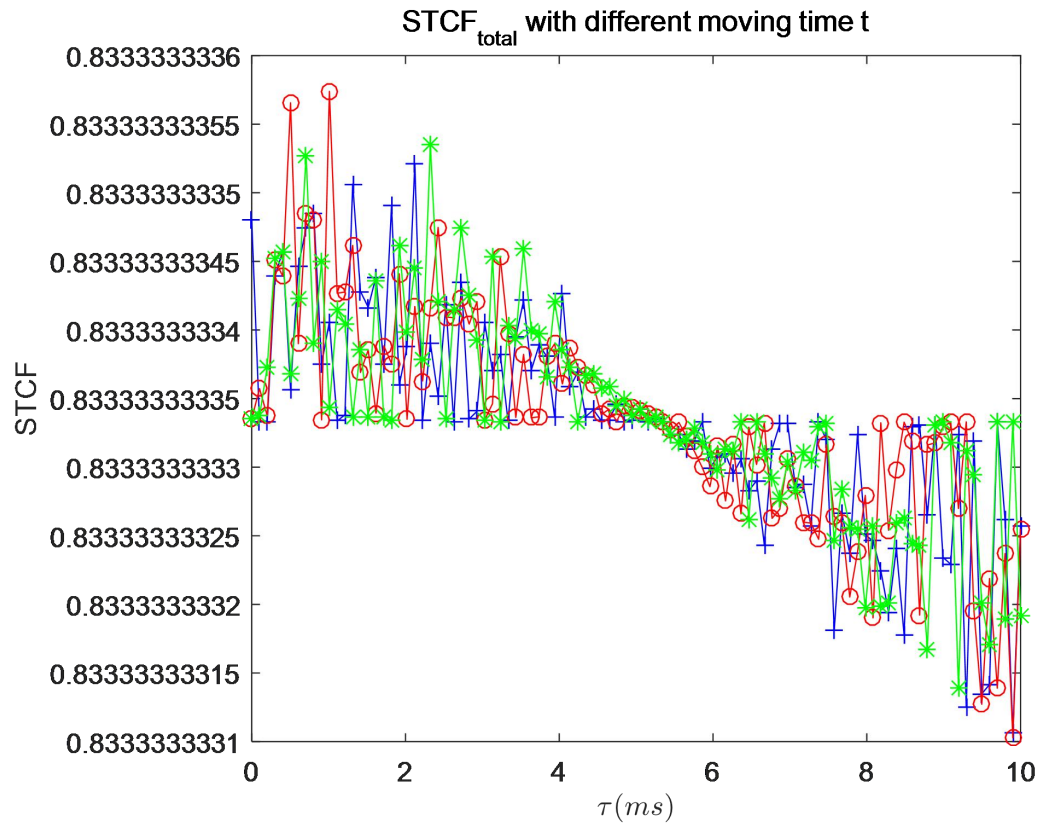


Fig. 32. Image of ACFs with time delay tau for different moving time t under $\gamma_T = \pi/8$

Then come to the impact of Recian factor K on PSD. The test value is $K = [3, 5, 7]$. In the image Fig. 33, there are three curves where blue, red, green curves represent PSDs with $K=3, 5, 7$. Different notations including plus, circle, star are added to distinguish them. It can be seen that generally the PSD decreases with the increment of Recian factor K . It is mentioned that the Recian factor K is defined as the power of the scattering component to the power of direct path component. When K is low, the LoS component dominates. This results in a more focused power spectral density around the zero Doppler shift because the direct path typically has no Doppler shift or a very small one if there is movement along the line of sight. As K increases, the scattered components become more significant. Scattered components cause multiple Doppler shifts due to reflections from various moving or stationary objects. This broadens the PSD because the signal's power is now spread across a wider range of Doppler frequencies. When it is observed that the PSD decreases as K increases, it is because the total energy is now distributed over a wider range of Doppler frequencies due to the increased influence of scattered components. The energy in the PSD is conserved, but since it is spread over a broader range, the peak values (amplitudes) in the PSD will decrease.

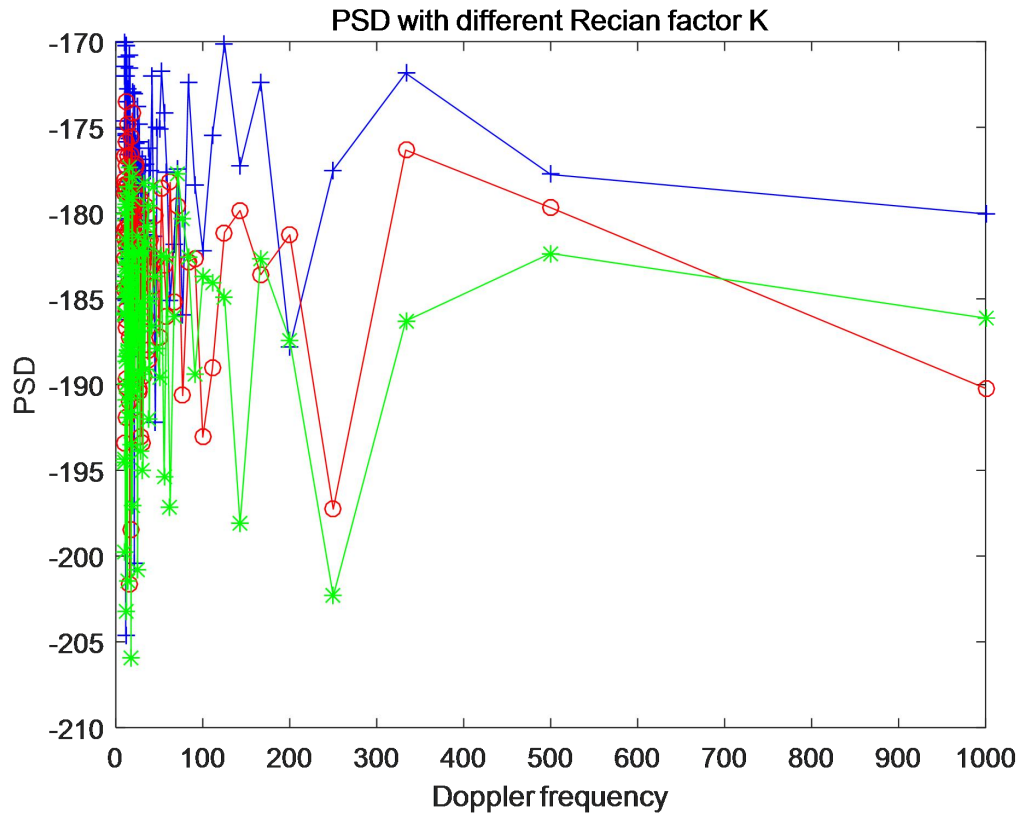


Fig. 33. Image of PSDs with doppler frequency for different Recian factor K

6. CONCLUSIONS

The report's summary, included in Chapter 6, examines and condenses the report's study findings.

6.1 SUMMARY

This study explored the development and analysis of a non-stationary three-dimensional (3D) channel model for vehicle-to-vehicle (V2V) communication in tunnel environments. The model, combining a Geometry-Based Stochastic Model (GBSM) with scattering cluster methods, was developed to simulate and characterise the dynamic channel behaviour in such specialised scenarios.

In this study, literatures relevant to V2V, GBSM, scattering cluster are reviewed in detail. The methodology of GBSM and scattering cluster is introduced and demonstrated. Then, the proposed GBSM comprised with scattering cluster model is presented. Formulas are derived and implemented in MATLAB. The developed 3D V2V channel model accurately captures the geometric and stochastic characteristics of tunnel environments. By defining and simulating various parameters, such as tunnel dimensions, vehicle velocities, and scatterer distributions, the model provides a flexible framework for studying V2V communication channels under realistic conditions. The CIR analysis revealed that the channel in tunnel environments is highly dynamic, with significant variations over time due to vehicle motion and the random distribution of scatterers. The CIR results, particularly when varying the number of effective scatterers and the Recian factor K , underscore the importance of both direct and scattered components in the overall signal behaviour.

Other than simulations of CIRs, through MATLAB simulations, key channel characteristics were examined, including the temporal auto-correlation function (ACF), spatial cross-correlation function (CCF), and Doppler power spectral density (PSD). The simulation results demonstrate that the proposed model closely aligns with theoretical expectations and empirical data from previous studies, confirming its validity in capturing the essential features of V2V channels. The model's flexibility in adjusting parameters such as scatterer positions, vehicle speeds, and signal frequency makes it a valuable tool for investigating different V2V communication scenarios in tunnels. The ability to simulate

various conditions and analyse their effects on channel characteristics ensures the model's applicability in real-world V2V communication systems.

To recap on the study's aim and objectives, in this study a thorough analysis of the body of research on geometry-based channel modelling methods is performed. A novel geometry-based channel model for V2V communication tunnel environment is developed, important parameters are considered in the description of channel characteristics. Simulations to analyse the channel characteristics are performed. However, evaluating the model's performance in terms of criteria including throughput, latency and so on is not performed in this study due to the time constraints.

6.2 FUTURE WORK

Based on the findings of this research, several recommendations for future work and practical applications can be made. First of all, while this study focused on tunnel walls and basic scatterer distributions, future research should consider the impact of additional environmental factors, such as varying surface materials, tunnel curvature, and the presence of other vehicles or obstacles. Incorporating these factors could enhance the accuracy of the model in more complex real-world scenarios. Moreover, although the model was validated against theoretical expectations and empirical data, further validation using extensive real-world measurements in diverse tunnel environments would strengthen its reliability. Such validation efforts could involve collaborations with industry partners to collect and analyse V2V communication data in different tunnel settings. Besides, the model's application can be extended to other types of tunnel scenarios, such as urban tunnels, highway underpasses, and rail tunnels, each presenting unique propagation challenges. Research focused on these alternative scenarios could provide a broader understanding of V2V communication in various tunnel environments, contributing to the design of more resilient and adaptable communication systems.

For future work in specific MATLAB simulations, some things can be optimised. In specific simulation process, many assumptions were made like only consider the single bounce from left and right tunnel walls and ignore the top and ground of tunnel walls, impose the antenna elevation angles and azimuth angles to the same, assume two vehicles are moving in the same direction and so on. More figures can be analysed when alter different values of

parameters. Additionally, the structure of codes can be optimised through systematic software engineering process, I found that I need to change many parameters and structures of codes when do different simulations. Then I need to debug many times. It actually needs me to generalise the application of codes. Additionally, when analysed the ACF with different moving time t (x-axis is the time delay τ), I found that my simulation results did not reflect the impact of different time points on ACF (or did not reflect a significant impact) but it is known that the ACF will be influenced when the moving time changes. Due to time constraints, this part did not undergo further research and analysis. In addition, the scattering cluster component is not simulated in this study due to the limitation of time too. The model is to use scattering cluster to introduce an exponential process to simulate the DB and propagation multipath.

7. REFLECTIONS

In this section, the reflections on the study are presented through the master's program at UWTSD, particularly focusing on the learning outcomes, gains, and achievements from completing my master's project, the positive aspects and challenges faced, and the future directions for research in the context of the study.

Throughout the master's program at UWTSD, the diverse range of modules significantly contributed to the successful completion of my dissertation. The course on agile development and software devops provided me with a solid foundation in agile methodologies and devops practices, which were instrumental in managing the project lifecycle efficiently. The iterative development and continuous integration practices learned in this course helped streamline the development and testing phases of the model. The research methods and professional development course deepened my understanding of various research methodologies, which was directly applied in formulating the research design and methodology for my project. It equipped me with the skills needed to conduct a thorough literature review, design robust experiments, and analyse data effectively. Additionally, other lectures including artificial intelligence, application of machine learning and so on all helped me gain knowledge to complete the master dissertation.

Completing this master's project has been a rewarding experience, offering numerous gains and achievements. A profound understanding of V2V communication technologies and the mathematical modelling of channel characteristics is developed in this study. Establishing the GBSM combined with scattering clusters in tunnel environments was a significant achievement, contributing novel insights and methodologies to the field. Additionally, hands-on experience with MATLAB for simulation and data analysis enhanced my practical skills. Developing and validating the channel models using MATLAB simulations deepened my understanding of spatial-temporal correlation functions, Doppler power spectral density, and their practical applications.

Several positive aspects have enriched my project experience. The integration of knowledge from various courses, such as AI, data security, and cloud computing, enriched the depth and breadth of my research. This interdisciplinary approach enhanced the innovation and applicability of my work. Besides, the guidance and support from faculty and

peers at UWTSD were invaluable. Regular feedback sessions and collaborative discussions provided the necessary support to navigate challenges effectively. Furthermore, utilising cutting-edge tools and technologies, such as MATLAB for simulations and the latest research databases, greatly facilitated the development and validation of my model.

Despite the successes, several challenges were encountered throughout the project. Developing a non-stationary 3D channel model with GBSM and scattering clusters presented significant technical challenges. Accurately modelling the tunnel environment and ensuring the model's fidelity to real-world conditions required extensive research and iterative testing. Also, access to comprehensive and high-quality data for validating the channel model was limited, necessitating the development of innovative solutions to approximate real-world conditions, which sometimes complicated the validation process. In addition, time management is an issue. Balancing project work in UWTSD as well as WHUT and personal commitments was challenging. Effective time management and prioritisation were crucial to meet deadlines and maintain the project's momentum.

Looking ahead, several avenues for future research and development are evident. First is to enhanced model refinement. Further refinement of the GBSM and scattering cluster model to include additional environmental factors and vehicle dynamics could enhance its accuracy and applicability. Exploring advanced machine learning techniques to optimise the model parameters and improve predictive accuracy is also recommended. The second is field testing and validation. Conducting real-world field tests to validate the model's performance in actual tunnel environments would provide invaluable insights and help bridge the gap between theoretical models and practical applications. The third is standardisation and collaboration. Engaging with industry stakeholders and standardisation bodies to promote the adoption of the developed model in industry standards would be beneficial. Collaborative research projects with automotive manufacturers and telecommunications companies could accelerate the practical implementation of V2V communication technologies.

In conclusion, this master's project has not only deepened my understanding of V2V communication channels but also equipped me with critical skills and knowledge essential for a career in advanced wireless communication technologies. The journey has been challenging yet immensely rewarding, paving the way for future innovations in the field of intelligent transportation systems.

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9. APPENDICES