Bulletin of Electrical Engineering and Informatics
Vol. 13, No. 5, October 2024, pp. 3167~3186
ISSN: 2302-9285, DOI: 10.11591/eei.v13i5.7549

Handover management in vehicle communication: applications, techniques, issues, and challenges: a review

Hamzah Hadi Qasim, Husna Zainol Abidin, Syahrul Afzal Che Abdullah
Vehicle Intelligence and Telematics Lab, School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia

Article Info

Article history:

Received Sep 13, 2023
Revised Feb 16, 2024
Accepted Mar 20, 2024

Keywords:

Applications
Dedicated short-range communication
Handover management
LTE-V2X and NR-V2X
Vehicle-to-everything

ABSTRACT

Vehicle-to-everything (V2X) communication is an emerging technology that facilitates communication among vehicles and numerous environmental entities. However, it encounters certain challenges throughout the handover process. This study analyses the challenges and complexity of managing handover, specifically in maintaining uninterrupted connection and meeting the service criteria outlined in the 3GPP 5G new radio (NR) standard. Various applications of V2X technology that require handover management are explored, such as vehicle safety and traffic management, enhanced driver assistance, and autonomous driving. Furthermore, this paper illuminates the most recent developments in V2X communication, highlighting the significance of efficient handover management, resolving technical issues, based on the full potential of the use of V2X apps that contribute to the establishment of a transportation ecosystem that is characterized by enhanced safety, increased intelligence, and improved connectivity. This paper can be used as a starting point for thinking about how to improve C-V2X communication.

Corresponding Author:

Husna Zainol Abidin
Vehicle Intelligence and Telematics Lab, School of Electrical Engineering, College of Engineering
Universiti Teknologi MARA
Shah Alam 40450, Selangor, Malaysia
Email: husnaza@uitm.edu.my

1. INTRODUCTION

In an era of rapid technological advancement, intelligent transport systems (ITS) are emerging as a necessary solution to the growing challenges in the field of transportation [1]. These challenges include escalating traffic congestion [2], growing environmental pollution [3], and painful road accidents [4]. ITS systems rely on advanced technologies such as sensing and communication to improve traffic flow, reduce congestion, and enhance driver and pedestrian safety. Besides, these systems play an important role in improving air quality and the environment by reducing harmful emissions [5]. Our investment in the development and implementation of ITS systems represents an investment in the future of sustainable and safe transportation.

Technology aims to enhance the transportation experience through innovative techniques. The impact of vehicle-to-everything (V2X) technology stands out as a pivotal driver of development [6]. V2X serves as a means of communication between vehicles, infrastructure, and the driving environment, adding a new layer of understanding that enhances transportation system performance [7]. Through real-time information exchange, V2X alerts vehicles to potential hazards and weather conditions, thereby enhancing road safety and effectively reducing traffic accidents [8]. Furthermore, V2X contributes to improving traffic flow by providing detailed congestion information and concise guidance for alternative routes, optimizing road usage [9]. Notably, V2X also promotes transportation sustainability by enhancing fuel efficiency, thereby reducing emissions and improving air quality, aligning with sustainability objectives. In short, V2X represents an intelligent and feasible extension of smart transportation systems, enhancing road safety, traffic flow, sustainability, and ultimately the overall public transportation experience.

V2X technology employs dedicated short-range communication (DSRC) for efficient communication [10]. DSRC is a wireless protocol enabling real-time data exchange among vehicles and infrastructure [11]. This allows vehicles to share critical information like location and speed, enhancing safety and decision-making. DSRC's short-range nature ensures focused communication, while its reliability and low latency are ideal for safety applications [12]. In essence, V2X utilizes DSRC to create a connected system that improves road safety and traffic efficiency.

Alongside the advancements of DSRC in V2X technology, there are certain limitations to consider. DSRC, operating within a specific frequency band, is constrained in terms of range, making it less effective for long-distance communication [13]. This range limitation can hinder its utility in scenarios that require information exchange over extended distances. Furthermore, due to its dedicated frequency band, DSRC can experience interference with other wireless communication systems, potentially impacting the reliability and consistency of data transmission [14]. Consequently, the coverage and scalability of DSRC-based systems may be restricted compared to alternatives.

As a response to these limitations and with the aim of enhancing V2X communication, cellular vehicle-to-everything (C-V2X) technology has gained prominence. C-V2X operates through cellular networks, leveraging their infrastructure to facilitate communication between vehicles, infrastructure, and other elements [15]. This approach not only provides a wider coverage area but also seamlessly integrates with modern communication systems, including 4G and 5G networks [16]. C-V2X technology adds cellular network characteristics to allow low-latency and high-reliability vehicle network connections [17]. C-V2X has garnered significant attention from experts in the fields of information technology, automotive engineering, and transportation engineering, both within academia and industry. The advancement of cellular networks from 4G LTE to 5G has led to the evolution of C-V2X technology, transitioning from LTE to V2X with new radio technology (NR-V2X) [18].

Continuing to explore V2X technologies is an important development, as they are based on the new 5G standard for cellular networks. The NR-CV2X offers ultra-reliable, low-latency communication capabilities, enabling real-time data exchange for safety-critical applications [19]. Unlike LTE-CV2X, NR-CV2X operates in the wider 5G frequency range [20], which contributes to increased data flow and improved performance in challenging conditions. Its integration with 5G networks makes it compatible and widely covered with 5G deployments globally, marking it as an effective force in transforming V2X communications to enhance safety and efficiency.

In the domain of connected cars, wireless vehicle communication is gaining importance due to the continuous development of technology. NR-CV2X technology is an intelligent and dependable means of facilitating communication between vehicles and the road infrastructure. With numerous innovative and future applications, NR-CV2X in handover is one of the keys to success in delivering a seamless and effective communication experience for drivers [21]. When we speak of NR-CV2X in handover, we are referring to the capacity to seamlessly transition from one service cell to another using this technology [22]. This handover is essential for maintaining the vehicle's constant and uninterrupted connection to the road infrastructure. As a result of ongoing research and development in this area, NR-CV2X in handover is now capable of attaining faster handover rates and better communication quality.

To effectively utilize NR-CV2X in the transfer process, certain standards and technical specifications must be in place. This necessitates constant upgrades to the road infrastructure and vehicle equipment in order to support this advanced technology. When these conditions are met, NR-CV2X in handover can provide stable and dependable communication while transitioning between distinct service cells. The handover of NR-CV2X is a significant move towards improving vehicle communication with the road infrastructure, thereby contributing to improved traffic safety and providing drivers with a seamless and enjoyable driving experience. This paper addresses a number of significant challenges in handover management, including unnecessary handovers, frequent handovers, ping-pong handovers, failures in handover execution, and delays in handover execution. These problems can result in inefficient resource utilization, communication disruptions, packet loss, increased latency, service disruptions, and diminished user experiences. The organization of the rest of the paper is as follows. Section 1 begins with the introduction. Section 2 provides in-depth explanations of the fundamentals of V2X communication, such as the V2X communication: type, V2X application, and V2X networking standards. In section 3, we discuss V2X's challenges. In section 4, we deliverables handover management in V2X, highlighting handover definition, handover classification, handover issues, and challenges. Section 5 provides related work.

Section 6 discuss the open issues and outlines the future research directions. Finally, section 7 concludes this review paper. Figure 1 depicts the organizational structure of the review paper.

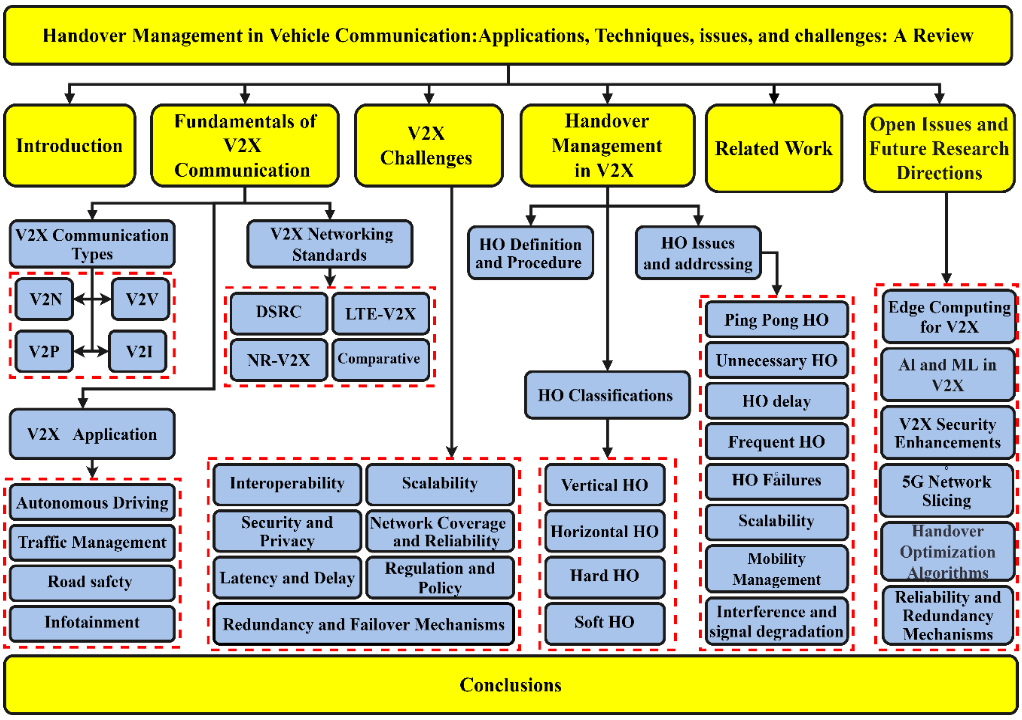

Figure 1. Structure of the review paper

2. FUNDAMENTALS OF V2X COMMUNICATION

V2X communications is a transformative and advanced technology that facilitates seamless communication among vehicles, infrastructure, pedestrians, and cellular networks. This cutting-edge system enables the exchange of vital safety information, real-time traffic updates, and warnings among vehicles, resulting in increased road safety and decreased accident rates. V2X uses multiple communication protocols, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N) [23]–[25]. These communication modes rely on advanced technologies like DSRC and C-V2X, which enable efficient data transmission and continuous connectivity [26], [27]. However, guaranteeing a seamless handover between these various communication modalities presents significant obstacles, such as interoperability and network coverage. V2X communications pave the way for a more intelligent and interconnected future of transit by addressing these complexities. In this section, we will explore the fundamentals of V2X communications and explain how this essential technology for connected transportation functions. This section explains the fundamental components of V2X communications, V2X applications, the standards used, the evolution of networks, and the devices involved in this innovative technology, through comparative analysis.

V2X Communications represent a significant breakthrough in the realm of transportation technology. This innovative approach facilitates communication among cars, as well as with the broader transportation ecosystem, including infrastructure, people, and network services [28]. V2X communication types have a significant impact on transforming road safety, traffic management, and driving experiences by facilitating smooth data transmission and real-time connection [29], [30]. Figure 2 describes the types of vehicle communications.

Vehicle-to-infrastructure (V2I), communication allows automobiles to communicate with road infrastructure through the V2X network [31]. This comprises traffic lights, roadside devices, tollbooths, and other smart transportation infrastructure. A V2I connection gives cars real-time traffic, road, and signal information [32]. A vehicle approaching an intersection may interact with the traffic signal to optimise traffic flow and reduce congestion. V2I communication helps build intelligent traffic management systems, improving traffic control and reducing environmental impact.

Vehicle-to-pedestrian (V2P) involves communication between vehicles and pedestrians that utilise phones or wearables [33]. It allows V2V or V2I vehicles to recognise and warn pedestrians and drivers. A pedestrian distracted by their phone may be warned to cross the street carefully, while a driver may be warned to prevent collisions. This communication prevents mishaps in busy cities and schools [34].

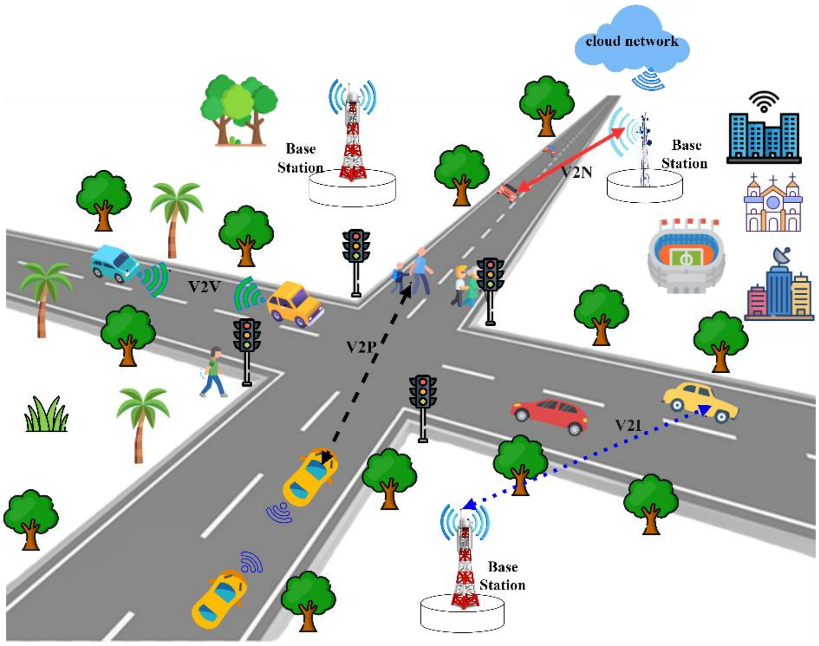

Figure 2. Types of vehicle communications

Vehicle-to-network (V2N) communication connects automobiles to cloud-based services and centralised networks, expanding V2X connections [35]. Vehicles may access many services and real-time data by integrating with cellular networks or other wireless communication systems. Over-the-air software upgrades, live traffic statistics, and real-time road condition -based route suggestions are included. V2N communication allows cars to remain connected and get the latest data to enhance performance and safety [36].

Vehicle-to-vehicle (V2X) technology relies on V2V communication for real-time data transmission between neighbouring cars. Vehicles communicate speed, position, acceleration, and direction through V2V communication [37]. Vehicles share this information to be aware of each other. V2V communication can notify drivers of impending collisions and emergencies, improving road safety. This technology is especially useful such as when a vehicle's sensors identify risks near blind corners or in bad weather [38].

As depicted in Figure 3. Vehicular networks contain a range of V2X applications that include traffic management, road safety, and comfort and entertainment applications [39], [40]. Road safety applications cover a diverse array of techniques and technologies that have been specifically developed to increase safety on highways. These characteristics include danger warning systems and driver assistance software, among other functionalities [41], [42]. Traffic management applications include the use of remote car diagnostics and the monitoring of air pollution levels. Infotainment apps comprise a range of functions that are targeted towards entertainment, including the ability to download music and programmes that enhance user comfort.

Road safety: the goal is to achieve a zero-tolerance policy for road incidents and a reduction in driving-related fatalities in the foreseeable future [43]. The system has collision avoidance capabilities as well as the capacity to identify both mobile and stationary road obstructions. It also facilitates the dissemination of meteorological information. Among the many additional road safety applications are emergency electronic brake lighting, post-crash notifications, and road hazard alerts [44].

Traffic management: this category of V2X technology aims to enhance the efficiency of traffic movement [45], leading to increased predictability, improved coordination, and enhanced productivity in driving experiences [46]. Additionally, it contributes to the reduction of air pollution caused by vehicle emissions.

Infotainment: the infotainment category is specifically designed to enhance the user’s experience by providing sophisticated entertainment components inside the automobile. The aforementioned features include online gaming [47], alerts about points of interest [48], and the provision of high-speed internet access while on-board [49].

Autonomous driving: the concept of autonomous driving refers to the ability of a vehicle to operate and navigate without human intervention. V2X technology serves as a crucial enabler for enhancing advanced driver assistance systems (ADAS) [50], and facilitating the progression towards achieving completely autonomous driving cars in the foreseeable future. The objective will be accomplished by establishing wireless communication between the many sensors installed on board and the infrastructure located beside the route [51], [52].

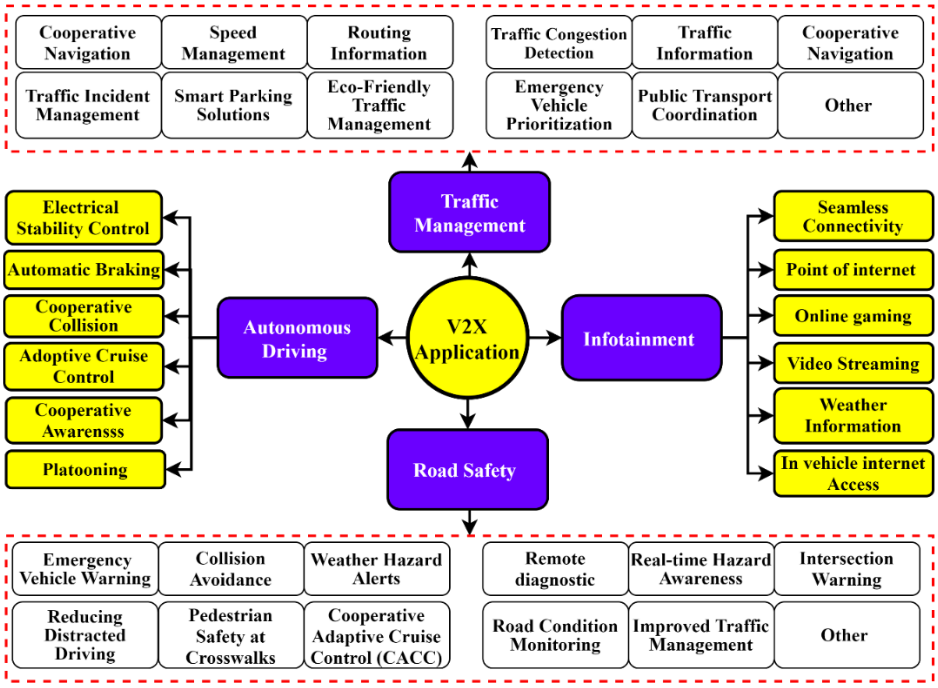

Figure 3. V2X applications in vehicle contexts

2.1. V2X communication standards architecture

V2X communication standards introduce a transformative era in transportation by enabling vehicles to exchange real-time data with their environment. This dynamic exchange enhances road safety, optimizes traffic flow, and opens doors to innovative applications, propelling us towards a connected and safer future of mobility. DSRC and wireless access in vehicular environments (WAVE) are two prevalent examples of such open standards for vehicle networks [53]. The primary objective of these protocols is to demonstrate communication architecture, frequency sharing, application management, security methods, and messaging. Cellular systems are currently being developed to provide connections for V2X services in 5G and LTE networks [54]. Cellular networks are increasingly being used to link V2X devices because of their high data rates, low latency, regulated quality of service (QoS) [55], and dependability, which allow for greater coverage capacity and worldwide deployment [56]. To be more precise, the 3GPP standards organization specifies V2X services in the LTE network (releases 14) and improved V2X for 5G new radio in future version 15 and 16 [57]. The following is a description of critical communication standards for vehicle networks.

2.1.1. Dedicated short range communication (DSRC)

In the context of V2X communication, DSRC technology has several potential uses, especially in the realm of safety. In 1999, the US Federal Communication Commission developed and standardised DSRC technology, which is based on IEEE 802.x9 [58]. Various standards groups, including IEEE 1609.x, IEEE 802.11p [59], and ETSI ITSG5 [60] created a variety of DSRC communication standards. The aforementioned specifications all provide V2V and V2I communications via the use of a CSMA CA-based architecture [61]. Consequently, the DSRC technologies are very region-specific and dependent on the supporting standard, the allotted frequency band, and the V2X application [62].

As can be seen in Figure 4, DSRC uses the 5.9 GHz licenced spectrum and is composed of seven channels [63]. Two of the seven channels, at the extremes of the spectrum, are reserved for special purposes. The middle channel, known as the control channel (CCH) [64], is used in safety-related purposes. The CCH's only purpose is to ensure secure communications. Service channels are the leftover spectrum slots. It's important to note that the service channels are used for both safety-related and non-safety-related reasons.

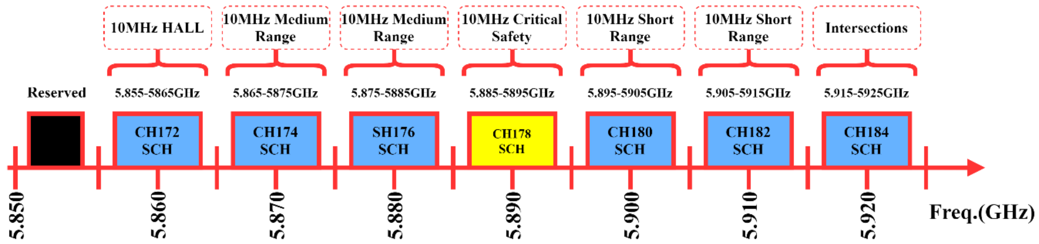

Figure 4. DSRC spectrum

2.1.2. LTE-V2X

The long-term evolution vehicle-to-everything (LTEV2X) refers to a communication technology known as CV2X [65], which has been officially documented in release 14 by the third generation partnership project (3GPP) [66]. LTE radio interfaces provide D2D communication [67]. Release 12 included D2D/Sidelink connectivity [68]. PC5, a new interface, joins the LTE-Uu interface. PC5 has four TMs. Modes 3 and 4 matter in vehicle communication [69]. These modes provide fast data transmission, compatibility with high velocities, and a new way to access scattered channels. In Mode 3, the cellular network, especially the eNodeB, allocates resources. Thus, cellphone coverage is necessary [70]. Mode 4 uses decentralised scheduling and congestion management to let devices choose tهheir radio resources [71]. LTE-V2X may replace IEEE 802.11p since Mode 4 is the basic mode. The LTE-V2X system uses LTE's uplink single-carrier frequency-division multiple access (SCFDMA) scheme to reduce OFDM's high peak-to-average power ratio (PAPR). LTEV2X also supports turbo coding [72], quadrature phase-shift keying (QPSK) [73], 16-QAM [74], and 64-QAM (added in release 15) [75]. The LTE radio interface has these traits. A 15 kHz subcarrier spacing improves mobile channel distortion resilience over IEEE 802.11p's 156.25 kHz. Radio resources are more granular, allowing for more flexible distribution. LTEV2X's PHY is more advanced than IEEE 802.11p's.

2.1.3. NR-V2X

The 5th generation of mobile communication technology [76], new radio, was launched by 3GPP in 2019 [77]. Release 15 specifies a new wireless radio interface for a variety of use cases and application domains, including improved mobile broadband (eMBB) [78] and ultra reliable low latency communications (URLLC) [79], as well as V2X interaction. Release 16 is expected to provide comprehensive eMBB, URLLC, and vehicular communication details [80]. NR-V2X is meant to enable V2X applications that LTE-V2X doesn't support, not replace them. Both technologies will be in newer vehicles [81].

NR-V2X meets a broad range of transmission needs in line with the 5G mobile network concept. It is suited for V2X applications that need periodic traffic transmission or the dependable delivery of aperiodic communications, as well as various use cases demanding different levels of throughput, latency, and reliability. In order to provide additional flexibility, NR-V2X will feature unicast and groupcast communication modes. mmWave bands are also being investigated, although this functionality is expected to be developed in future versions (like release 17). NRV2X uses sidelinks and two modes like LTEV2X [82]. NR-V2X Modes 1 and 2 behave like LTEV2X Modes 3 and 4. gNodeBs allocate resources in Mode 1, requiring cellular service [83]. Devices only communicate directly. Mode 2 requires no gNodeB coverage [84]. LTEV2X-like resource allocation methods are predicted by the proposed system. Mode 2 should also include many submodes. These features are still being designed, but their distribution is intended to provide flexibility for V2X use cases.

NRV2X's physical layer inherits new radio capabilities and adds V2X upgrades. NR supports two uplink transmission methods: orthogonal frequency division multiplexing (OFDM) and discrete fourier transform spread OFDM (DFTsOFDM) [85]. The former is preferred for its high throughput efficiency, while the latter is suited for low link budget devices. The gadget works in two frequency ranges: sub-6 GHz and mmWave [86]. As previously said, later publications will elaborate on this issue. Scalable OFDM numerology also benefits from it. Sub-6 GHz frequency ranges use 15, 30, and 60 kHz subcarrier spacing, whereas frequency bands above 6 GHz use 60 and 120 kHz. Lowering latency using greater subcarrier spacing the frame structure is also improved compared to LTE, allowing for more flexible resource allocation. New radio technology uses a slot structure with 14 OFDM symbols. Subcarrier spacing determines the number of slots in a sub-frame. Radio resources may be assigned per slot, unlike LTE, which has a minimum transmission time interval (TTI) of one subframe, or one millisecond. NR technology uses mini-slots (two, four, or seven OFDM symbols) to transmit data with less latency [87]. These mini-slots have no slot limits, which is interesting. Multiple antennas at the reception and transmitter ends may be used for spatial diversity or spatial multiplexing to increase data transmission rate or reliability. NRV2X may transport user data using LDPC codes and QPSK, 16-QAM, and 64-QAM modulation techniques. Polar codes and the cyclic redundancy check (CRC) help regulate data transfer.

The information presented in Table 1 provides an in-depth comparison of the most recent versions of DSRC and C-V2X in terms of a variety of components, functions, and methods. Based on the findings of the 5G automotive association (5GAA) [88], [89] it has been determined that C-V2X technology has the potential to support fundamental safety applications on a global scale [90]. This is achieved through the utilisation of device-to-device connectivity, specifically operating on the 5.9 GHz bandwidth, which is widely recognised as a primary and commonly used spectrum. One of the primary benefits of C-V2X, in comparison to DSRC, lies in its ability to facilitate direct communication for the purpose of achieving interoperable service. Table 1 illustrates the benefits of C-V2X over DSRC [91].

Table 1. Comparative analysis of DSRC and C-V2X communications [92]

Features	DSRC-V2X	LTE-V2X	NR-V2X
Radio bands of operation	5.9 GHz	5.9 GHz	5.9 GHz
Completion of specifications	3/2012	Rel-14: 3/2017.Rel-15, 6/2018.	Rel-16: 12/2019Rel-17: 6/ 2021
Evolution path	compatibility with IEEE802.11bd	compatibility with NR-V2X	LTE-V2X backward compatibility
Latency	Low V2V latency	Rel-14: 20 ms, Rel-15: 10 ms	3 ms or lower
Modulation	64QAM	64QAM	256QAM
Waveform	OFDM	SC-FDM	CP-OFDM
Data rate	6 Mbps	30 Mbps	Not determined
Reliability	No guaranteed reliability	Rel-14: >90%, Rel-15: > 95%	99.999%
Operation bandwidth	10 MHz	Flexible: 1.4/5/10/20 MHz	sub-6 GHz: max. 100 MHz mmWave: max. 400 MHz
Channel estimation	Preambles only	DMRS: 4/sub-frame	DMRS: flexible
Channel coding	BCC	Turbo codes	Data: LDPCControl: Polar with CRC

3. CHALLENGES AND REQUIREMENTS FOR V2X

V2X communication, including several modes such as V2V, V2I, V2P, and V2N, presents a wide range of advantages for interconnected transportation. Nevertheless, the process of achieving a seamless shift across different communication modalities presents notable difficulties and requires certain prerequisites in order to guarantee a seamless and effective transfer. This discussion will explore the many issues and prerequisites related to V2X handover.

- Latency and delay: to facilitate real-time decision-making, V2X communication necessitates low-latency data exchange. To sustain seamless information transmission between vehicles, infrastructure, and pedestrians, the handover between various communication modalities should minimise latency and delay. Reducing communication latencies is crucial for achieving rapid response times, particularly in safety-critical circumstances [93].
- Interoperability: obtaining interoperability between various communication technologies is one of the primary obstacles in the V2X transition. V2X systems may employ various wireless protocols, such as DSRC and C-V2X, and it is essential that they are able to communicate with one another without interruption. Standardisation and compatibility between these technologies are required for vehicles to maintain continuous connectivity when transitioning between various communication types [94].
- Network coverage and reliability: V2X communication relies significantly on network connectivity for effective information exchange [95]. In regions with limited or unreliable network coverage, obstacles arise, which can result in communication gaps and reduce the efficacy of the V2X transition. Vital to the success of V2X communication systems is the provision of consistent and dependable network coverage, particularly in rural or remote areas.
- Security and privacy: V2X communication entails the interchange of sensitive information, such as driving behaviour and location data. To prevent unauthorised access, data tampering, and potential cyberthreats, it is of the uttermost importance to ensure the security and privacy of this data during transfer. Implementing strong encryption and authentication mechanisms is crucial for protecting V2X communications [96], [97].
- Scalability: the V2X network must be able to scale effectively as the number of connected vehicles and devices increases. The system must be able to manage a high volume of data exchanges between vehicles and infrastructure without degrading performance. Scalability ensures that V2X communication in an expanding transportation ecosystem remains effective and reliable [98].
- Redundancy and failover mechanisms: V2X systems need redundancy and failover to maintain communication. Redundant communication channels and backup mechanisms reduce communication breakdowns in V2X environments [99].

- Regulation and policy: establishing a transparent regulatory framework and policies for V2X communication is essential for its widespread adoption. To assure a consistent and standardised V2X environment, governments and regulatory bodies must resolve data privacy, spectrum allocation, and standardisation issues [100].
- Handover in V2X communication presents several challenges due to its dynamic nature and the need for uninterrupted data exchange. Challenges include seamless switching between different network types (e.g., DSRC and cellular) [101], ensuring low latency during handover, maintaining data integrity, addressing security concerns during transitions, and managing signal strength fluctuations to avoid disruptions. Overcoming these challenges is crucial for maintaining the reliability and effectiveness of V2X communication systems.

The successful resolution of these issues and the fulfilment of the necessary criteria are of utmost importance in order to fully harness the capabilities of interconnected transportation. Through the successful navigation of these challenges, V2X communication has the potential to profoundly transform road safety, traffic efficiency, and the entire driving experience, therefore contributing to a more intelligent and interconnected future.

4. HANDOVER MANAGEMENT IN VEHICLES COMMUNICATIONS OVERVIEW

Within the dynamic and ever-evolving domain of connected transportation, V2X communications have evolved into a revolutionary technology, fundamentally modifying how vehicles interact with one another and the surrounding infrastructure [102]. The foundation of V2X technology is the concept of handover, a fundamental mechanism that enables seamless and uninterrupted connectivity as vehicles traverse various network coverage zones.

Handover is the process of transferring an active communication session from one network cell to another as a vehicle traverses different coverage areas [103]. The primary goal of handover in V2X is to maintain continuous and seamless connectivity between the vehicle and the network, ensuring reliable communication as the vehicle traverses various regions. V2X communications rely significantly on handover because of the mobility of vehicles [104]. As they move through different communication network coverage areas, vehicles may pass by a variety of base stations or access points. Without efficient handover mechanisms, the communication link may be disrupted or lost as the vehicle departs the cell's coverage area. This interruption in communication can be detrimental, particularly for safety-critical applications that require real-time data exchange for collision avoidance and other safety services [105]. Therefore, when discussing related handover topics, the three major phases must be taken into account: handover information gathering and initiation, handover decision making, and handover execution, in accordance with Figure 5. In the sections that follow, the three phases are discussed in detail.

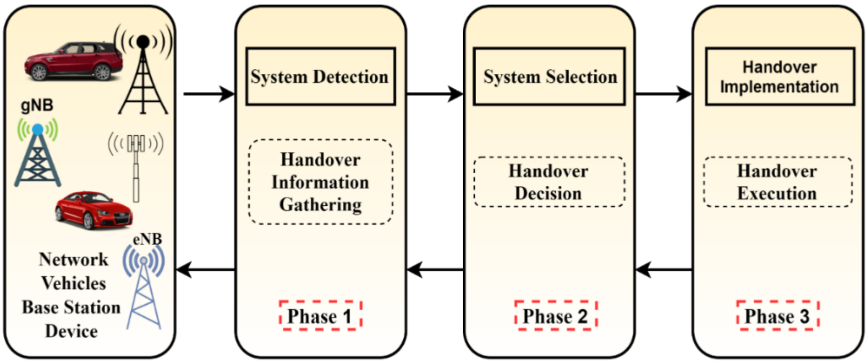

Figure 5. Handover management procedure

The phase of handover information collection includes the collection of network information as well as information pertaining to other system components, including network attributes, base stations, and user preferences. Due to this rationale, this stage is referred to by numerous labels in the literature, including system detection, handover initiation [106], network discovery [107], system discovery, and handover information collection [108]. Data is collected and examined throughout this stage to inform handover decisions. The availability of neighbouring network lines may be affected by different variables and can be determined by considering various factors, including RSS, throughput, cost, packet loss ratio, handover rate, signal-to-interference ratio (SIR), binary digit (Bit), channel impulse response (CIR), quality of service (QoS), distance, and bit error rate (BER), and location parameters [109], [110]. These parameters provide valuable information regarding the performance and reliability of neighbouring network links.

The HO decision-making process evaluates wireless access networks [111]. A vehicle first discovers the available networks, then gathers the data required to identify the target network for its affiliation. The source [112] sends the measurement report to the control unit (CU). The CU chooses the optimum BS for connection maintenance based on resource availability and network demand. The handover decision-making process is centralised or decentralised depending on where it is made. If a handover is needed, the CU alerts the target base station (BS) to prepare a connection and enables the source BS to transmit handover orders to the vehicle.

Execute is the final phase; after selecting a suitable target network for handover, the vehicle implements the handover for its re-association with the target network [113], [114]. The vehicle acquires resources from a new network while simultaneously relinquishing them from the old. During this phase, the vehicle or the network executes and manages the actual handover. These procedures clearly involve numerous wireless and data exchanges. In addition, there may be a time requirement to complete the transfer.

The handover procedure is a crucial part of V2X communications because it entails the seamless transmission of communication from one network to another as a vehicle travel through various coverage areas. Handover management is crucial for sustaining uninterrupted connectivity and ensuring the dependability of V2X applications, such as safety-critical services and infotainment. On the basis of certain criteria, the concept of handover can be classified into various categories as shown in Figure 6.

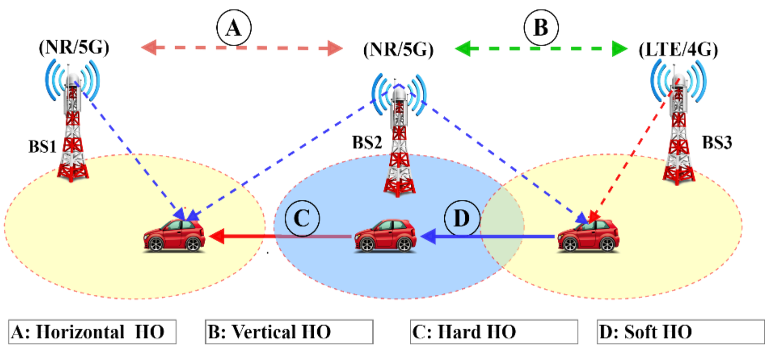

Figure 6. Classifications of handover management

Horizontal handover also known as intra-technology handover [115], horizontal handover occurs when a vehicle's connection from one cell or access point to another within the same communication network is changed. Within a NR/5G, a horizontal transition occurs when a vehicle transfers from one base station (BS1) to (BS2) as shown in Figure 6. The objective of horizontal handovers is to permit vehicles to maintain continuous communication as they traverse diverse coverage areas within a single network infrastructure [116]. Vehicles can maintain network connectivity by seamlessly transitioning between access points, assuring continuous data exchange and V2X application support.

Vertical handover also known as inter-technology handover [117], is the transmission of a vehicle between distinct communication technologies or networks. Vertical handover occurs, for example, when a vehicle travels from NR/5G coverage area to an LTE/4G coverage area. A seamless integration of V2X communication technologies requires this type of handover. Vertical handover ensure that vehicles maintain continuous connectivity while adapting to changes in the network environment, optimising communication performance and dependability [118].

Hard Handover unlike soft handover, hard handover involves a complete disconnection from the current network before establishing a connection to the new network [119]. As the vehicle transfers between networks during a challenging transition, there may be a brief interruption in communication [120]. Occasionally, forceful handovers are required for effective network management, particularly in cellular-based V2X technologies, where transferring the connection quickly can optimise network resources and prevent unnecessary data duplication. However, the challenge lies in ensuring that the transfer process is rapid enough not to disrupt safety critical V2X applications.

Soft handover allows a vehicle to maintain simultaneous connections to multiple network cells or access points before transferring the communication entirely to the new network [121]. During a delicate turnover, the vehicle's data is split between the current and target networks to ensure a smooth and flawless transition. Multiple data sources can be accessed through this overlapping connection, which increases the communication's reliability. Soft handovers are particularly advantageous in areas with a minor overlap in network coverage [122], as they reduce the risk of communication disruptions and ensure robust connectivity for safety-critical V2X applications.

4.1. Handover issues and challenges

Efficient management of handovers is of utmost importance in the domain of V2X communications to guarantee a smooth and uninterrupted connection experience for vehicles as they move between various network cells. The term "handover" refers to the procedure of shifting a continuous communication session from one cell to another while the vehicle traverses within the range of coverage [123]. Nevertheless, this procedure may encounter several obstacles, which might have an adverse effect on the overall efficiency and dependability of V2X connections. This section will explore the challenges associated with handover management in V2X communications, including issues such as superfluous handover, frequent handover, ping pong handover, handover failures, and handover delay [124]–[127]. The efficacy of V2X applications may be significantly impacted by each of these difficulties, particularly in situations with high mobility where vehicles depend on real-time communication for safety-critical duties and other services.

- Frequent handovers: when a vehicle is travelling at high speeds or through areas with dense network coverage, frequent handovers may occur [128]. As the vehicle's position changes swiftly, handovers between various cells may be triggered to maintain continuous connectivity. Frequent handovers can introduce handover latency and signalling overhead, impeding the seamless delivery of V2X services. To address this issue, predictive handover mechanisms that predict handover events based on vehicle trajectory and network conditions can be employed to reduce the frequency of handovers.
- Handover delay: handover delay refers to the amount of time required to complete the handover procedure, which includes scanning neighbouring cells, making handover decisions, and establishing a connection in the destination cell. Excessive handover latency can cause communication disruptions and reduce the responsiveness of V2X applications in real time. Minimising handover delay calls for efficient handover signalling protocols, rapid handover decision-making algorithms, and seamless network entity coordination [129].
- Unnecessary handover: unnecessary handover occurs when a vehicle transitions between communication networks even though the signal quality of the present network is adequate. This can result in increased signaling costs and communication disruptions that are unnecessary. To address this issue, handover decision algorithms must be improved by taking into account additional parameters such as signal stability, historical handover patterns, and network quality measurements. By implementing hysteresis thresholds, it is possible to reduce superfluous handovers and ensure that handovers only occur when the network's quality deteriorates substantially [130].
- Ping pong handover: the phenomenon known as the ping pong effect arises when a vehicle undergoes frequent and quick handovers between two neighbouring cells as a result of fluctuating signal intensities at the border of these cells. The frequent alternation between different states might potentially result in instability within the communication connection and a superfluous use of resources. The use of sophisticated handover algorithms using hysteresis and signal filtering techniques may effectively address the issue of the ping pong effect, thereby minimising unwanted handover oscillations.
- Handover failures: handover failures occur when a vehicle cannot effectively complete a seamless handover [131]. These failures may be caused by network congestion, insufficient handover preparations, or handover signalling errors. Robust handover mechanisms with error recovery procedures are required to guarantee seamless handover transitions and continuous communication during mobility.
- Low latency: V2X communications require low latency to assure the exchange of vital and safety-related data between vehicles and infrastructure in real time [132]. Response mechanisms should be designed to reduce the accuracy of time-in-transit, as any delay may result in message loss or delay, influencing the overall safety and efficacy of the system.
- Mobility management: the operational environment of vehicles is a rapidly-changing environment in which vehicles move at different velocities and in different directions [133]. Maintaining continuous communication links necessitates that the management of responsiveness overcome obstacles posed by high-speed mobility, rapid shifts, and frequent responses.
- Interference and signal degradation: the quality of the communication link may degrade as a result of interference and obstructions, or as vehicles move away from the access point or primary antennas, causing the communication signal to weaken [134]. To maintain the dependability of the connection, responsiveness management must ensure that signal changes are managed and a seamless transition is achieved.

– Scalability: as the number of connected vehicles rises, the V2X response management system must be scalable to accommodate the increase [135]. Scalability guarantees the system's effectiveness even in densely connected vehicle areas.

5. RELATED WORK

The use of handover management is crucial in ensuring uninterrupted service provision while a vehicle is transitioning between adjacent cells. The handover method entails the substitution of the main serving base station with a new one. Numerous issues arise during the handover process while transitioning the vehicle's connection from one base station (BS) to another, potentially leading to service disruptions until a subsequent connection is established. In this part, we provide a comprehensive overview of the research conducted in academic literature, which has proposed multiple methodologies with the primary goal of accomplishing efficient handover in diverse contexts. Each methodology has been designed to address specific objectives unique to its own environment. Table 2 provides recent publications that apply various handover management techniques.

Aljeri and Boukerche [136] use two-tier handovers in vehicles. In the first layer, long short-term memory (LSTM) models predict received signal strength indicator (RSSI) values. Prediction minimises lost packets and unnecessary handovers. Stochastic Markov models and vehicle motion estimations decide the second layer's access point. 0-30 m/s. In vehicle networks, LSTM beats simple moving average (SMA), social media marketing (SMM), and exponential smoothing. Two-tier design decreased lost packets 18%. Optimised handover trigger time improved packet delivery. Future updates should account for access point load and QoS.

In a study conducted by [36], deep reinforcement learning (DRL) and deep q-network (DQN) were used to minimise the duration of handover decision-making and enhance the overall vehicle throughput. The use of DQN has been seen to enhance the stability of training in DRL and provide improved convergence for the deep DQN approach. The reference signal received power (RSRP) of each vehicle from neighbouring base stations is monitored by a central agent, which selects a base station if necessary. Measurement data from E-UTRAN is helpful since it is the seamless combining of the proposed design into an actual cellular network, offering a high degree of flexibility. The use of DRL results in a reduction in changeover triggering time by 10.04 seconds and a drop in cumulative packet loss by 42.62% when compared to the A3 RSRP method.

Lin *et al.* [137] provide a novel strategy that employs DRL and deep deterministic policy gradient (DDPG) to address the issue of handover latency in user-centric clustered migration of high-speed vehicle users. The effectiveness of this methodology relies upon the collaboration between roadside units (RSUs), and V2Vcommunication. Vehicular user equipments use a clustering methodology that is based on many characteristics, including their geographic locations, detectable RSUs, vehicle access points (APs), and the transmitters connected with them in earlier time periods. When the number of RSUs approaches or exceeds 14, the DRL technique demonstrates a decrease in handovers (HOs) by at least 50% compared to the baseline solutions. The benchmarkers' utility function and data rate demonstrate a minimum drop of 30% in comparison to the clustered arrangement.

In this study, Khosravi *et al.* [138] introduce the reinforcement learning algorithm (RLA) as a potential solution for minimising the occurrence of handovers. The researchers employed two sparsely deployed mmWave networks and one densely deployed mmWave network. The approach described in this study is compared with two benchmark methods, namely multi-connectivity handover and SMART handover. The suggested methodology demonstrates significant superiority over the baseline methods in both the quantity of handovers and, notably, the consistency of connection throughout the trajectory.

In their study, Liu *et al.* [139] present a framework that utilises RL and function approximation techniques to effectively reduce the occurrence of unnecessary handovers in mobile, heterogeneous environments. The proposed solution based on RL demonstrates a reduction in latency of 58%, 37%, and 19% while simultaneously achieving an improvement in throughput of around 12%, 5%, and 7% when compared to the RSRP method. The topics of discussion are Q-learning and state aggregation, in that order. When compared to the conventional RSRP method, the suggested reduction technique demonstrates a decrease of approximately 18% in superfluous handovers.

Lee *et al.* [140] propose a DRL-based double deep Q-network (DDQN) for 5G mmWave dual active protocol stack (DAPS) handover. DAPS links source and destination cells following regular handovers. Event-based handovers presume constant channel conditions and are unsuitable for volatile mmWave networks. To avoid radio connection failures, DDQN uses user equipment (UE) learning agents to learn when to handover. For various UE velocities (600 MBps @ 12 m/s), DDQN surpasses DAPS and CHO. Arwa *et al.* [141] performed a study in which they proposed the use of DRL as a viable approach to mitigate handover incidents and improve the overall performance of the vehicle network. The use of DRL leads to a decrease in the occurrence of adverse outcomes (HO) and an increase in the overall cumulative reward value.

Table 2. Research publications on handover management in vehicular networks

Technique	Ref	Scenario	Method	Objective	Conclusion
ML	2023 [36]	Scenario in the real world	(DRL) and (QDL)	Maximising throughput and reducing handover decision time	In comparison to the A3 RSRP baseline, the suggested technique exhibits a reduction in packet loss of 25.73% and a drop in handover latency of 11.56 seconds.
	2019 [136]	Access points at random	LSTM	Minimize the occurrence of unnecessary handovers	The use of a machine learning-based handover trigger method demonstrates a reduction in the number of lost packets in comparison to a hybrid solution, with 80000 packets dropped as opposed to 140000 packets. The LSTM model has superior accuracy in comparison to many forecasting methods.
	2020 [137]	Multiple-lane urban motorway	(DRL) and (DDPG)	Reduced handovers based on average user data rate	The proposed method reduces handovers to 20 compared to 100 for RSS-based transition systems. Considering the typical per-user data rate, fewer handovers are desirable.
	2021 [138]	Sparse mmWave network and Dense mmWave network	RL	Reduce number of handovers	The suggested methodology demonstrates significant superiority over the baseline methods in both the quantity of handovers and, notably, the consistency of connection throughout the trajectory.
	2021 [139]	Heterogeneous	RL	Minimize unnecessary handovers	The proposed solution based on RL demonstrates a reduction in latency of 58%, 37%, and 19% while simultaneously achieving an improvement in throughput of around 12%, 5%, and 7% when compared to the RSRP method. The topics of discussion are Q-learning and state aggregation, in that order.
	2022 [140]	5G mmWave stations	DRL based on DDQN	Maintain the maximum throughput with minimal radio link failure risk	The DDQN-based approach consistently outperforms DAPS and CHO for varied UE velocities (600 MBps at 12 m/s).
	2023 [141]	Vehicle platoon	DRL	decrease handovers (HO) to improve vehicle network performance	The suggested model reduces HO and boosts cumulative reward.
	2020 [142]	Road system in the form of a grid	Table-based Q-learning in RL	to minimize the number of handovers	When compared to a self-centered reference point, the suggested system exhibits a decrease in the frequency of handovers by 16.2% and an increase in the average length of connectivity by 16.9%.
	2020 [143]	mm-wave UDN	DDRL	minimize the frequency of Hos	DDRL technique reduction in the number of frequent handovers (HOs) by a range of 20% to 69% when compared to the RBH and 7% to 49% when compared to the SMART.
Other	2021 [28]	Internet of vehicles (IoV)	Jellyfish, dynamic Q learning, and fuzzy CNN	Select best network and route, to reduce unnecessary handovers	The performance of handover is enhanced by 45 to 50%, the throughput is improved by 40 to 45%, and the end-to-end latency is reduced by 10 to 15% compared to the present methods.
	2020 [144]	VANET	Cluster based handover and DEBCK	to reduce expenses in the cluster formation process and mitigate packet loss rates	The suggested strategy has the potential to strengthen and improve coherence in communication during the handover process.
	2020 [145]	Heterogeneous	ML-based on multilayer perceptron (MLP)	The decrease in handover rate	The use of this approach effectively mitigates the occurrence of frequent handovers while concurrently enhancing the quality of service experienced by consumers.
	2021 [146]	Heterogeneous	FAHP	Reduce handover time	In contrast to the benchmark network selection techniques, the suggested method exhibits a reduction in changeover times ranging from 10.85% to 29.12%.
	2021 [113]	Heterogeneous	MCDM, SAW approach	to maintain user QoS during a handover	The V2I-MHA system offers a reduced occurrence of handovers for applications that exhibit sensitivity to delays.

Souza *et al.* [142] use RL and Tabular Q-learning to decrease vehicular fog computing handovers. The agent decides whether the car should connect, stay connected, disengage, or stay detached to an access point (AP). The agent interacts with the environment via a state space that includes the mobile device's current location, it is previous position (east, west, north, or south), and its connection status (either disconnected or connected to one of the access points). RL reduced handovers by 16.2% and increased unbroken connections by 16.9% across all conditions.

The research conducted by Mollel *et al.* [143] introduced double deep reinforcement learning (DDRL) as a method to reduce the occurrence of frequent HOs in a millimetre wave (mmwave) ultra-dense network (UDN) scenario. The researchers took into account the signal-to-noise ratio (SNR) as well as several environmental variables, including obstacles and topographical characteristics. DDRL technique demonstrates a reduction in the number of frequent HOs by a range of 20% to 69% when compared to the RBH method. Additionally, DDRL exhibits a decrease in HOs by 7% to 49% when compared to the SMART technique. Furthermore, the dynamic data rate DDRL technique enhances the overall system throughput for the RBH and self-managed adaptive rate tuning (SMART) algorithms by a range of 19% to 40% and 24% to 37%, respectively.

Awan *et al.* [144] designed a cluster-based handover and proposed that a dynamic edge backup node (DEBCK) could effectively reduce cluster construction costs and packet loss rate. Additionally, DEBCK increased capacity and ensured a stable connection. Both the cluster head and the standby mobile edge vehicle determined which vehicle to transmit control to. One of its primary drawbacks is the failure of its mobile edgednode standby. In addition, cluster heads should not be utilised whenever there is a demand, as their use could result in faulty handover or even payment.

Qi *et al.* [145] proposes federated learning (FL) for proactive handover in a heterogeneous network. This network uses MBSs and SBSs in the mmWave frequency spectrum. MBS users worldwide get a comprehensive model. Every mobile user gets the global model and trains a local multi-layer perceptron (MLP) to discover the next connected small base station (SBS) based on SNR. All MBS users train and submit their local models asynchronously. It updates the global model. This plan aims to decrease handovers, boost worldwide training participation, and improve storage capacity. FL lowers reactive handovers. User velocities between 15-20 m/s reduce handovers from 30 to 14 compared to a baseline system. Regional QoS improves as user SNR grows.

Other techniques to handover menagemet utilize different method. Hussain *et al.* [28] examined a variety of methods and technologies utilised in the internet of vehicles (IoV). Three techniques were described to assist handover, network selection, and routing in an IoV scenario. The researchers employed dynamic q-learning (DQL) to determine a dynamic threshold using the Shannon entropy rule to enable handover. According to the researchers, the DQL system decreases unnecessary handovers. Fuzzy convolutional neural network (CNN) was utilised by researchers to find the best network. To find the best route, researchers employed Jellyfish optimisation. OMNet++ simulated the system's creation. Latency, packet loss, throughput, and handover were used to evaluate performance.

Tong *et al.* [146] present a fuzzy analytic hierarchical process (FAHP) method as a means to decrease handover time. The researcher takes into account many factors like user preferences, service requirements, network features, and user mobility patterns. The algorithm that utilises FAHP with location information demonstrates significant reductions in handover times when compared to the RSS-based, multi-criteria group decision making (MCGDM), and FTOPSIS algorithms. These reductions amount to 39.18%, 29.12%, and 10.85% correspondingly. In comparison to the FAHP method that lacks position information, the approach under consideration demonstrates a reduction in handover times by 20.61%

Ndashimye *et al.* [113] the proposed technique is referred to as the multi-criteria-based V2I handover algorithm (V2I-MHA) for short. This study aims to evaluate the effectiveness of V2IMHA in comparison to four existing handover techniques, namely V2I-MoLoHA, V2I-DHA, traditional, and ANDSF-assisted, with respect to two key performance metrics: HOFR and packet loss. The V2I-MHA algorithm demonstrates superior performance compared to current handover approaches. The HOFR of V2I-MHA is 16% lower than that of V2I-MoLoHA, 51% lower than V2I-DHA, 57% lower than traditional, and 62% lower than ANDSF-assisted.

The above analysis yields several significant findings. The management of handovers in vehicle scenarios is often addressed as a matter focused on reducing the frequency of handovers. Moreover, it is important to acknowledge that centralised architectures are commonly utilised as a result of the intrinsic attributes of handovers. The training process in this case is conducted by a centralised entity, such as a base station. The aforementioned organisation collects feedback from individuals operating vehicles, proceeds to develop a centralised model using this data, and afterwards carries out actions based on the model that has been trained. Distributed approaches are evident in scenarios where the training process occurs autonomously on individual vehicles or base stations. The training process within this particular context encompasses a central entity, that is, a base station, which collects data from users of vehicles, trains a central model, and afterwards makes decisions based on the insights derived from this model, according to the existing scholarly works. The use of DRL in the context of NR-CV2X handover has not been extensively adopted. It is anticipated that there will be a rise in the adoption of DRL methodologies. Additionally, it is important to highlight that DRL does not require a labelled dataset, in contrast to supervised learning, as the agent gains knowledge directly from its surroundings. The optimisation of Vertical handover management in NR-CV2X will be conducted using DRL techniques.

6. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

As handover based V2X communication continues to gain traction in the automotive and transportation industries, researchers and industry experts are actively investigating innovative solutions to resolve the obstacles and expand the capabilities of this revolutionary technology. Handover-based V2X entails the seamless transfer of communication connections between multiple access points or base stations as vehicles pass through coverage areas, enabling continuous and reliable communication in intelligent transportation systems. In the sections that follow, we will look at specific open questions and possible future research directions that could make handover based V2X communication much more effective, reliable, and safe.

6.1. Handover optimization algorithms

The research of handover optimisation algorithms has significant importance in the realm of handover based V2X communication. In order to ensure uninterrupted communication, it is essential to effectively perform a smooth handover while vehicles navigate across different coverage regions. Academic researchers are now exploring a range of machine learning methodologies, such as supervised and unsupervised learning, with the objective of creating intelligent algorithms that can accurately forecast the most advantageous handover time and access point. These algorithms take into account many parameters such as vehicle speed, network circumstances, handover delay, and QoS needs for different V2X applications.

Machine learning models have the capability to examine both past handover data and real-time information in order to make judgements based on that data. This enables the achievement of smooth and efficient transfer transitions. The objective is to decrease the duration of interruptions during the handover process and enhance the decision-making process for handover by considering dynamic network circumstances and the movement patterns of vehicles. The use of these algorithms has the potential to enhance the overall efficacy and reliability of handover based V2X communication via continuous learning and adaptation to the ever-changing environment.

6.2. V2X edge computing

Edge computing can improve V2X communication performance. Traditional cloud-based systems may cause significant communication delays between cars and faraway data centres. Edge servers and mini data centres near RSUs and base stations deliver computer resources to automobiles. Edge computing allows network-boundary data processing and decision-making in real time. This decreases round-trip data transmission time, improving communication latency and response times. Peripheral computing may offload computational tasks from the core cloud infrastructure, lowering network congestion and enhancing V2X communication. Data dissemination, task allocation, and V2X system integration are being considered in peripheral computing architecture designs. V2X applications may benefit from real-time data processing by improving edge computing infrastructure and techniques.

6.3. V2X security enhancements

Security is crucial in V2X communication because cars and infrastructure communicate sensitive data such as vehicle locations, traffic patterns, and driver conduct. To protect V2X communication and user data from cyberattacks, researchers are designing new security measures. Secure authentication solutions are being researched to guarantee that only authorised cars and infrastructure may participate in V2X communication. V2X data is encrypted to prevent unauthorised access and monitoring. Researchers are also creating intrusion detection systems that continually monitor the network for unusual activity and alert users of possible security weaknesses. Privacy-protecting solutions are also emphasised in V2X security research. Homomorphic encryption encrypts data during transmission and processing, protecting privacy. Secure multi-party computing allows several people to collaborate without revealing their private information, ensuring V2X communication secrecy. For users and stakeholders to trust handover-based V2X communication and accelerate its adoption, V2X security must be rigorous.

6.4. AI and machine learning in V2X

AI and ML in V2X communication might boost network performance and safety. Academics are using AI models to forecast traffic patterns, congestion, and driving behaviours using vehicle-to-everything (V2X) data. Machine learning algorithms can assess large amounts of real-time data from cars, infrastructure, and road sensors to make smart judgements.

6.5. Reliability and redundancy mechanisms

V2X communication reliability is crucial for safety-critical applications. Redundancy methods that offer multiple communication pathways and minimize communication failures are being studied to ensure continuous connection. Multi-path routing lets V2X devices create numerous communication pathways. During transfer, a backup route may quickly take over if one channel fails. Real-time multi-path routing enhances V2X communication dependability. Cellular and DSRC are being studied for hybrid communication solutions. Hybrid techniques provide dependable communication in low-coverage regions by combining their strengths. Hybrid methods effortlessly switch between communication channels during handover, improving V2X dependability.

6.6. 5G network slicing

Network slicing is becoming more popular for adapting communication services to V2X applications due to 5G networks. Network slicing lets V2X services create bespoke virtual networks. V2X applications, including car safety alerts, traffic congestion updates, and infotainment services may be optimised for QoS and latency on every network slice. Safety-critical V2X services may need minimal latency and high dependability. Infotainment services may prioritise high data rates and minimal latency. Researchers are studying V2X network slicing implementations. Define appropriate slice properties, implement resource allocation techniques, and manage slice handovers. Network slicing lets V2X apps customise network resources. This adjustment improves V2X communication by smoothing network slice transitions.

7. CONCLUSION

V2X communications are a revolutionary development in the field of connected transportation. This innovative technology enables vehicles to communicate not only with each other (V2V) but also with infrastructure (V2I), pedestrians (V2P), and network services (V2N), as well as other elements of the transportation ecosystem. V2X communication types play a pivotal role in revolutionising road safety, traffic management, and driving experiences in general by facilitating seamless data exchange and real-time connectivity. Establishing a cohesive and interconnected ecosystem in which vehicles can share vital information and interact with their environments is fundamental to V2X communications. V2X enables vehicles to make intelligent judgements, receive real-time traffic updates, and improve pedestrian safety, all of which contribute to a safer and more efficient transportation network. However, accomplishing seamless V2X handover between various forms of communication presents a number of obstacles and requirements. Interoperability, network coverage, low latency, security, scalability, redundancy, and regulatory frameworks are among the critical factors that must be addressed to ensure a seamless and dependable V2X handover. In spite of these obstacles, the promise of V2X communications cannot be denied. By overcoming obstacles and meeting requirements, V2X has the potential to revolutionise how we navigate on roads and in urban areas. It contains the key to a wiser, safer, and more sustainable future of transportation, in which vehicles and infrastructure optimise traffic flow, reduce incidents, and create a more seamless and connected mobility experience. In the end, the development of V2X communications represents a major step towards the realisation of intelligent and autonomous transportation. V2X promises to reshape the transportation landscape and pave the way for a future in which vehicles and their environs seamless sly collaborate, ultimately redefining how we will move and interact on the roadways of the future.

ACKNOWLEDGEMENTS

This work was supported by the Ministry of Higher Education under the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2021/ICT11/UITM/02/1). We would also like to extend our gratitude to the School of Electrical Engineering, Universiti Teknologi MARA (UiTM) Shah Alam, and all individuals who have contributed to this study.

REFERENCES

[1] Z. Lv and W. Shang, “Impacts of intelligent transportation systems on energy conservation and emission reduction of transport systems: A comprehensive review,” *Green Technol. Sustain.*, vol. 1, no. 1, p. 100002, 2023, doi: 10.1016/j.grets.2022.100002.

[2] T. Afrin and N. Yodo, “A survey of road traffic congestion measures towards a sustainable and resilient transportation system,” *Sustain.*, vol. 12, no. 11, pp. 1–23, 2020, doi: 10.3390/su12114660.

[3] Z. Lv, Y. Li, H. Feng, and H. Lv, “Deep Learning for Security in Digital Twins of Cooperative Intelligent Transportation Systems,” *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 9, pp. 16666–16675, 2022, doi: 10.1109/TITS.2021.3113779.

[4] L. Tan *et al.*, “Speech Emotion Recognition Enhanced Traffic Efficiency Solution for Autonomous Vehicles in a 5G-Enabled Space-Air-Ground Integrated Intelligent Transportation System,” *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 3, pp. 2830–2842, 2022, doi: 10.1109/TITS.2021.3119921.

[5] G. Díaz, H. Macià, V. Valero, J. Boubeta-Puig, and F. Cuartero, “An Intelligent Transportation System to control air pollution and road traffic in cities integrating CEP and Colored Petri Nets,” *Neural Comput. Appl.*, vol. 32, no. 2, pp. 405–426, 2020, doi: 10.1007/s00521-018-3850-1.

[6] A. Moubayed, A. Shami, P. Heidari, A. Larabi, and R. Brunner, “Edge-Enabled V2X Service Placement for Intelligent Transportation Systems,” *IEEE Trans. Mob. Comput.*, vol. 20, no. 4, pp. 1380–1392, 2021, doi: 10.1109/TMC.2020.2965929.

[7] C. Creß, Z. Bing, and A. C. Knoll, “Intelligent Transportation Systems Using External Infrastructure: A Literature Survey,” *arXiv*,

pp. 1–18, 2021, doi: 10.1109/TITS.2023.3343434.
[8] B. Liu, C. Han, X. Liu, and W. Li, “Vehicle Artificial Intelligence System Based on Intelligent Image Analysis and 5G Network,” *Int. J. Wirel. Inf. Networks*, vol. 30, no. 1, pp. 86–102, 2023, doi: 10.1007/s10776-021-00535-6.
[9] I. P. Chochliouros *et al.*, “C-V2X communications for the support of a Green Light Optimized Speed Advisory (GLOSA) use case,” *J. Telecommun. Inf. Technol.*, vol. 2021, no. 2, pp. 93–106, 2021, doi: 10.26636/jtit.2021.152321.
[10] A. Mukhopadhyay and V. A. Bharadwaj, “V2X based Road Safety Improvement in Blind Intersections,” *Proc. 2nd Int. Conf. Inven. Res. Comput. Appl. ICIRCA 2020*, pp. 964–968, 2020, doi: 10.1109/ICIRCA48905.2020.9183253.
[11] S. M. Hussain, K. M. Yusof, S. A. Hussain, and A. B. Khan, “An Efficient Interface Selection Scheme (DSRC/LTE) of Vehicles for Data Dissemination Enabling V2V Communication to Support Internet of Vehicles (IoV)," *Soft Comput. Signal Process.*, 2022, pp. 573–581, doi: 10.1007/978-981-16-1249-7_54.
[12] S. M. Hussain, K. M. Yusof, R. Asuncion, S. A. Hussain, and A. Ahmad, “An Integrated Approach of 4G LTE and DSRC (IEEE 802.11p) for Internet of Vehicles (IoV) by Using a Novel Cluster-Based Efficient Radio Interface Selection Algorithm to Improve Vehicular Network (VN) Performance," *Sustain. Adv. Comput.*, 2022, pp. 569–583, doi: 10.1007/978-981-16-9012-9_46.
[13] G. Collodi, M. Righini, and A. Cidronali, “A New Varactor-Tuned 5.8 GHz Dielectric Resonator Band-Stop Filter for ITS and C-V2X Coexistence with Vehicular DSRC,” *Electron.*, vol. 12, no. 2, 2023, doi: 10.3390/electronics12020453.
[14] E. Plascencia, H. Guan, L. Chassagne, O. Barrois, O. Shagdar, and A. M. Căilean, “A Comprehensive Investigation on Multi-User Interference Effects in Vehicular Visible Light Communications,” *Sensors*, vol. 23, no. 5, 2023, doi: 10.3390/s23052553.
[15] Y. Cao, S. Xu, J. Liu, and N. Kato, “Toward Smart and Secure V2X Communication in 5G and Beyond: A UAV-Enabled Aerial Intelligent Reflecting Surface Solution,” *IEEE Veh. Technol. Mag.*, vol. 17, no. 1, pp. 66–73, 2022, doi: 10.1109/MVT.2021.3136832.
[16] P. Bhattacharya *et al.*, “Amalgamation of blockchain and sixth-generation-envisioned responsive edge orchestration in future cellular vehicle-to-anything ecosystems: Opportunities and challenges,” *Trans. Emerg. Telecommun. Technol.*, no. December, 2021, doi: 10.1002/ett.4410.
[17] K. L. Chen, W. Y. Chen, and R. H. Hwang, “Optimizing Resource Allocation With High-Reliability Constraint for Multicasting Automotive Messages in 5G NR C-V2X Networks,” *IEEE Trans. Veh. Technol.*, vol. 72, no. 4, pp. 4792–4804, 2023, doi: 10.1109/TVT.2022.3226215.
[18] S. Chen, J. Hu, Y. Shi, L. Zhao, and W. Li, “A Vision of C-V2X: Technologies, Field Testing, and Challenges with Chinese Development,” *IEEE Internet Things J.*, vol. 7, no. 5, pp. 3872–3881, 2020, doi: 10.1109/JIOT.2020.2974823.
[19] J. Marquez-Barja *et al.*, “Enabling cross-border tele-operated transport in the 5G Era: The 5G Blueprint approach,” *2021 IEEE 18th Annu. Consum. Commun. Netw. Conf. CCNC 2021*, 2021, doi: 10.1109/CCNC49032.2021.9369619.
[20] M. M. Saad, M. T. R. Khan, S. H. A. Shah, and D. Kim, “Advancements in Vehicular Communication Technologies: C-V2X and NR-V2X Comparison,” *IEEE Commun. Mag.*, vol. 59, no. 8, pp. 107–113, 2021, doi: 10.1109/MCOM.101.2100119.
[21] J. M. Marquez-Barja *et al.*, “5G-Blueprint : Next Generation Connectivity for Enhanced , Safe , Efficient Transport & Logistics,” 2021.
[22] J. M. Marquez-Barja *et al.*, “Enhanced teleoperated transport and logistics: A 5G cross-border use case,” *2021 Jt. Eur. Conf. Networks Commun. 6G Summit, EuCNC/6G Summit 2021*, pp. 229–234, 2021, doi: 10.1109/EuCNC/6GSummit51104.2021.9482459.
[23] E. Farsimadan, F. Palmieri, L. Moradi, D. Conte, and B. Paternoster, “Vehicle-to-Everything (V2X) Communication Scenarios for Vehicular Ad-hoc Networking (VANET): An Overview," *Comput. Sci. Appl. – ICCSA 2021*,” 2021, pp. 15–30, doi: 10.1007/978-3-030-87010-2_2.
[24] P. V. Wadatkar, R. G. Garroppo, and G. Nencioni, “5G-MEC Testbeds for V2X Applications,” *Futur. Internet*, vol. 15, no. 5, pp. 1–32, 2023, doi: 10.3390/fi15050175.
[25] M. A. J. Khan, M. A. J. Khan, A. Beg, S. Malik, and H. El-Sayed, “An overview of the 3GPP identified Use Cases for V2X Services,” *Procedia Comput. Sci.*, vol. 198, no. 2021, pp. 750–756, 2021, doi: 10.1016/j.procs.2021.12.317.
[26] Z. H. Mir, J. Toutouh, F. Filali, and Y. B. Ko, “Enabling DSRC and c-V2X integrated hybrid vehicular networks: Architecture and protocol,” *IEEE Access*, vol. 8, pp. 180909–180927, 2020, doi: 10.1109/ACCESS.2020.3027074.
[27] A. Rayamajhi, A. Yoseph, A. Balse, Z. Huang, E. M. Leslie, and V. Fessmann, “Preliminary Performance Baseline Testing for Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X),” in *2020 IEEE 92nd Veh. Technol. Confe. (VTC2020-Fall)*, 2020, pp. 1–5. doi: 10.1109/VTC2020-Fall49728.2020.9348708.
[28] S. A. M. Hussain, K. M. Yusof, S. A. M. Hussain, and R. Asuncion, “Performance evaluation of vertical handover in Internet of Vehicles,” *Int. J. Smart Sens. Intell. Syst.*, vol. 14, no. 1, pp. 1–16, 2021, doi: 10.21307/IJSSIS-2021-012.
[29] C. Zoghlami, R. Kacimi, and R. Dhaou, “5G-enabled V2X communications for vulnerable road users safety applications: a review,” *Wirel. Networks*, vol. 29, no. 3, pp. 1237–1267, 2023, doi: 10.1007/s11276-022-03191-7.
[30] T. Yoshizawa *et al.*, “A Survey of Security and Privacy Issues in V2X Communication Systems,” *ACM Comput. Surv.*, vol. 99, no. 9, 2022, doi: 10.1145/3558052.
[31] D. Kanthavel, S. K. B. Sangeetha, and K. P. Keerthana, “An empirical study of vehicle to infrastructure communications - An intense learning of smart infrastructure for safety and mobility,” *Int. J. Intell. Networks*, vol. 2, no. June, pp. 77–82, 2021, doi: 10.1016/j.ijin.2021.06.003.
[32] M. N. Tahir, P. Leviäkangas, and M. Katz, “Communication Using Cellular Technologies,” *Sensors*, pp. 1–14, 2022, doi: 10.3390/s22031142.
[33] R. Pan, L. Jie, X. Zhao, H. Wang, J. Yang, and J. Song, “Active Obstacle Avoidance Trajectory Planning for Vehicles Based on Obstacle Potential Field and MPC in V2P Scenario,” *Sensors*, vol. 23, no. 6, pp. 1–15, 2023, doi: 10.3390/s23063248.
[34] D. Oladimeji, K. Gupta, N. A. Kose, K. Gundogan, L. Ge, and F. Liang, “Smart Transportation: An Overview of Technologies and Applications,” *Sensors*, vol. 23, no. 8, pp. 1–32, 2023, doi: 10.3390/s23083880.
[35] W. M. Jang, “The 5G Cellular Downlink V2X Implementation Using V2N With Spatial Modulation,” *IEEE Access*, vol. 10, no. December, pp. 129105–129115, 2022, doi: 10.1109/ACCESS.2022.3226691.
[36] K. Tan, D. Bremner, J. Le Kernec, Y. A. Sambo, L. Zhang, and M. A. Imran, “Intelligent Handover Algorithm for Vehicle-to-Network Communications With Double-Deep Q-Learning,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 7, pp. 7848–7862, 2022, doi: 10.1109/TVT.2022.3169804.
[37] C. Mahabal, H. Wang, and H. Fang, “Dual Mode Localization Assisted Beamforming for mmWave V2V Communication,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 9, pp. 9450–9459, 2022, doi: 10.1109/TVT.2022.3175165.
[38] C. Kalita, N. Choudhury, A. Misra, and K. K. Sarma, “Design of a Basic Vehicular Communication Network using Radar and Camera Sensor with Enhanced Safety Features,” *Int. J. Circuits, Syst. Signal Process.*, vol. 16, pp. 822–830, 2022, doi: 10.46300/9106.2022.16.101.

[39] J. Brož, T. Tichý, V. Angelakis, and Z. Bělinová, “Usage of V2X Applications in Road Tunnels,” *Appl. Sci.*, vol. 12, no. 9, 2022, doi: 10.3390/app12094624.

[40] M. A. Hathibelagal, R. G. Garroppo, and G. Nencioni, “Experimental comparison of migration strategies for MEC-assisted 5G-V2X applications,” *Comput. Commun.*, vol. 197, pp. 1–11, 2023, doi: 10.1016/j.comcom.2022.10.009.

[41] K. Kiela *et al.*, “Review of V2X-IoT standards and frameworks for ITS applications,” *Appl. Sci.*, vol. 10, no. 12, 2020, doi: 10.3390/app10124314.

[42] E. Cinque, F. Valentini, A. Persia, S. Chiocchio, F. Santucci, and M. Pratesi, “V2X communication technologies and service requirements for connected and autonomous driving,” *2020 AEIT Int. Conf. Electr. Electron. Technol. Automotive, AEIT Automot. 2020*, 2020, doi: 10.23919/aeitautomotive50086.2020.9307388.

[43] S. Gupta, C. Maple and R. Passerone, "An Investigation of Cyber-Attacks and Security Mechanisms for Connected and Autonomous Vehicles," in *IEEE Access*, vol. 11, pp. 90641-90669, 2023, doi: 10.1109/ACCESS.2023.3307473.

[44] I. Soto, M. Calderon, O. Amador, and M. Urueña, “A survey on road safety and traffic efficiency vehicular applications based on C-V2X technologies,” *Veh. Commun.*, vol. 33, p. 100428, 2022, doi: 10.1016/j.vehcom.2021.100428.

[45] P. P. Borthakur, T. Nath, and D. Hatibaruah, “Study and analysis of A Vehicular Traffic Intersection Point , For Traffic and Congestion Control in Amolapatty, Dibrugarh, Assam,” *Eur. Chem. Bull.*, vol. 12, no. 10, pp. 2103–2120, 2023.

[46] H. Pourrahmani *et al.*, “The applications of Internet of Things in the automotive industry: A review of the batteries, fuel cells, and engines,” *Internet of Things (Netherlands)*, vol. 19, no. July, p. 100579, 2022, doi: 10.1016/j.iot.2022.100579.

[47] B. W. Duan, B. Gu, and A. B. Whinston, “on the I Nternet : a N E Mpirical I Nvestigation,” *MIS Q.*, vol. 33, no. 1, pp. 23–48, 2009.

[48] J. Alonso-zarate, “A Comprehensive Survey of V2X Cybersecurity Mechanisms and Future Research Paths,” in *IEEE Open J. Commun. Soc.*, pp. 1–69, 2023, doi: 10.1109/OJCOMS.2023.3239115.

[49] S. Chen *et al.*, “The Requirements of V2X Applications BT - Cellular Vehicle-to-Everything (C-V2X),” S. Chen, J. Hu, L. Zhao, R. Zhao, J. Fang, Y. Shi, and H. Xu, Eds. Singapore: Springer Nature Singapore, 2023, pp. 49–79. doi: 10.1007/978-981-19-5130-5_2.

[50] M. Murtaza, C.-T. Cheng, M. Fard, and J. Zeleznikow, “The importance of transparency in naming conventions, designs, and operations of safety features: from modern ADAS to fully autonomous driving functions,” *AI Soc.*, vol. 38, no. 2, pp. 983–993, 2023, doi: 10.1007/s00146-022-01442-x.

[51] A. Chalvatzaras, I. Pratikakis, and A. A. Amanatiadis, “A Survey on Map-Based Localization Techniques for Autonomous Vehicles,” *IEEE Trans. Intell. Veh.*, vol. 8, no. 2, pp. 1574–1596, 2023, doi: 10.1109/TIV.2022.3192102.

[52] A. Jospine, L. H. M. Audah, A. Hamzah, and H. Qasim, “Vehicle monitoring system with geofencing capability,” *J. Electron. Volt. Appl.*, vol. 1, no. 2, pp. 1–13, 2020, doi: /10.30880/jeva.2020.01.02.001.

[53] K. Ahmad, H. Khujamatov, A. Lazarev, N. Usmanova, M. Alduailij, and M. Alduailij, “Internet of Things-Aided Intelligent Transport Systems in Smart Cities: Challenges, Opportunities, and Future,” *Wirel. Commun. Mob. Comput.*, vol. 2023, 2023, doi: 10.1155/2023/7989079.

[54] S. Caputo, L. Mucchi, M. A. Umair, M. Meucci, M. Seminara, and J. Catani, “The Role of Bidirectional VLC Systems in Low-Latency 6G Vehicular Networks and Comparison with IEEE802.11p and LTE/5G C-V2X,” *Sensors*, vol. 22, no. 22, 2022, doi: 10.3390/s22228618.

[55] E. Moradi-Pari, D. Tian, M. Bahramgiri, S. Rajab, and S. Bai, “DSRC Versus LTE-V2X: Empirical Performance Analysis of Direct Vehicular Communication Technologies,” *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 5, pp. 4889–4903, 2023, doi: 10.1109/TITS.2023.3247339.

[56] S. Lahdya and T. Mazri, “Data Security Challenges in Self-Driving Car,” *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch.*, vol. 48, no. 4/W3-2022, pp. 61–66, 2022, doi: 10.5194/isprs-archives-XLVIII-4-W3-2022-61-2022.

[57] M. J. Khan *et al.*, “Advancing C-V2X for Level 5 Autonomous Driving from the Perspective of 3GPP Standards,” *Sensors*, vol. 23, no. 4, pp. 1–26, 2023, doi: 10.3390/s23042261.

[58] J. Choi, V. Marojevic, C. B. Dietrich, J. H. Reed, and S. Ahn, “Survey of Spectrum Regulation for Intelligent Transportation Systems,” *IEEE Access*, vol. 8, pp. 140145–140160, 2020, doi: 10.1109/ACCESS.2020.3012788.

[59] F. Arena, G. Pau, and A. Severino, “A review on IEEE 802.11p for intelligent transportation systems,” *J. Sens. Actuator Networks*, vol. 9, no. 2, pp. 1–11, 2020, doi: 10.3390/jsan9020022.

[60] J. Cassou-Mounat, H. Labiod, and R. Khatoun, “Simulation of Cyberattacks in ITS-G5 Systems,” *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 12574 LNCS, pp. 3–14, 2020, doi: 10.1007/978-3-030-66030-7_1.

[61] N. F. Binti Abdul Rahim *et al.*, “Channel Congestion Control in VANET for Safety and Non-Safety Communication: A Review,” *2021 6th IEEE Int. Conf. Recent Adv. Innov. Eng. ICRAIE 2021*, no. August 2022, 2022, doi: 10.1109/ICRAIE52900.2021.9704017.

[62] T. Shimizu, B. Cheng, H. Lu, and J. Kenney, “Comparative Analysis of DSRC and LTE-V2X PC5 Mode 4 with SAE Congestion Control,” *IEEE Veh. Netw. Conf. VNC*, vol. 2020-Decem, 2020, doi: 10.1109/VNC51378.2020.9318353.

[63] A. Chehri, H. Chehri, N. Hakim, and R. Saadane, “Realistic 5.9 GHz DSRC Vehicle-to-Vehicle Wireless Communication Protocols for Cooperative Collision Warning in Underground Mining,” *Smart Innov. Syst. Technol.*, vol. 185, no. June, pp. 133–141, 2020, doi: 10.1007/978-981-15-5270-0_12.

[64] M. Hoffmann, P. Kryszkiewicz, and A. Kliks, “Frequency Selection for Platoon Communications in Secondary Spectrum Using Radio Environment Maps,” *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 3, pp. 2637–2650, 2022, doi: 10.1109/TITS.2021.3136681.

[65] Q. Ding and Y. Lv, “Research on Resource Scheduling Method Based on LTE-V2X Direct Connect Communication,” *Int. Conf. Signal Process. Proceedings, ICSP*, vol. 2020-Decem, pp. 679–683, 2020, doi: 10.1109/ICSP48669.2020.9321062.

[66] L. M. Lopez, C. F. Mendoza, J. Casademont, and D. Camps-Mur, “Understanding the Impact of the PC5 Resource Grid Design on the Capacity and Efficiency of LTE-V2X in Vehicular Networks,” *Wirel. Commun. Mob. Comput.*, vol. 2020, 2020, doi: 10.1155/2020/8156908.

[67] M. Karoui, A. Freitas, and G. Chalhoub, “Performance comparison between LTE-V2X and ITS-G5 under realistic urban scenarios,” *IEEE Veh. Technol. Conf.*, vol. 2020-May, 2020, doi: 10.1109/VTC2020-Spring48590.2020.9129423.

[68] D. Mishra, A. Trotta, E. Traversi, M. Di Felice, and E. Natalizio, “Cooperative Cellular UAV-to-Everything (C-U2X) communication based on 5G sidelink for UAV swarms,” *Comput. Commun.*, vol. 192, no. June, pp. 173–184, 2022, doi: 10.1016/j.comcom.2022.06.001.

[69] J. Huang, D. Fang, Y. Qian, and R. Q. Hu, “Recent advances and challenges in security and privacy for V2X communications,” *IEEE Open J. Veh. Technol.*, vol. 1, no. June, pp. 244–266, 2020, doi: 10.1109/OJVT.2020.2999885.

[70] A. Hegde and A. Festag, “Mode Switching Performance in Cellular-V2X,” *IEEE Veh. Netw. Conf. VNC*, vol. 2020-Decem, 2020,

doi: 10.1109/VNC51378.2020.9318394.
[71] A. Dayal, V. K. Shah, B. Choudhury, V. Marojevic, C. DIetrich, and J. H. Reed, "Adaptive Semi-Persistent Scheduling for Enhanced On-road Safety in Decentralized V2X Networks," *2021 IFIP Netw. Conf. IFIP Netw. 2021*, 2021, doi: 10.23919/IFIPNetworking52078.2021.9472822.
[72] K. Sehla, T. M. T. Nguyen, G. Pujolle, and P. B. Velloso, "Resource Allocation Modes in C-V2X: From LTE-V2X to 5G-V2X," *IEEE Internet Things J.*, vol. 9, no. 11, pp. 8291–8314, 2022, doi: 10.1109/JIOT.2022.3159591.
[73] J. Hu, L. Zhao, Y. Feng, Y. Liu, and M. Gao, "Research, Implementation and Practice of Congestion Control Mechanism in LTE-V2X," *IEEE Veh. Technol. Conf.*, vol. 2022-Septe, pp. 1–5, 2022, doi: 10.1109/VTC2022-Fall57202.2022.10012979.
[74] A. Abou El Hassan, I. Kerrakchou, A. El Mehdi, and M. Saber, "Road Safety Enhancement of Intelligent Transportation Systems: From Cellular LTE-V2X Toward 5G-V2X," *Digital Technologies and Applications*, 2022, pp. 745–754.
[75] J. Hu *et al.*, "Off-Network Communications for Future Railway Mobile Communication Systems: Challenges and Opportunities," *IEEE Commun. Mag.*, vol. 60, no. 10, pp. 64–70, 2022, doi: 10.1109/MCOM.001.2101081.
[76] H. Bagheri *et al.*, "5G NR-V2X: Toward Connected and Cooperative Autonomous Driving," in *IEEE Commun. Stand. Mag.*, vol. 5, no. 1, pp. 48-54, March 2021, doi: 10.1109/MCOMSTD.001.2000069.
[77] M. Harounabadi, D. M. Soleymani, S. Bhadauria, M. Leyh, and E. Roth-Mandutz, "V2X in 3GPP Standardization: NR Sidelink in Release-16 and beyond," *IEEE Commun. Stand. Mag.*, vol. 5, no. 1, pp. 12–21, 2021, doi: 10.1109/MCOMSTD.001.2000070.
[78] A. Mamane, F. Fattah, M. El Ghazi, Y. Balboul, M. El Bekkali, and S. Mazer, "Proportional fair buffer scheduling algorithm for 5G enhanced mobile broadband," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 5, pp. 4165–4173, 2021, doi: 10.11591/ijece.v11i5.pp4165-4173.
[79] T. K. Le, U. Salim, and F. Kaltenberger, "An Overview of Physical Layer Design for Ultra-Reliable Low-Latency Communications in 3GPP Releases 15, 16, and 17," *IEEE Access*, vol. 9, pp. 433–444, 2021, doi: 10.1109/ACCESS.2020.3046773.
[80] B. S. Khan, S. Jangsher, A. Ahmed, and A. Al-Dweik, "URLLC and eMBB in 5G Industrial IoT: A Survey," *IEEE Open J. Commun. Soc.*, vol. 3, no. May, pp. 1134–1163, 2022, doi: 10.1109/OJCOMS.2022.3189013.
[81] Á. Knapp, A. Wippelhauser, D. Magyar, and G. Gódor, "An overview of current and future vehicular communication technologies," *Period. Polytech. Transp. Eng.*, vol. 48, no. 4, pp. 341–348, 2020, doi: 10.3311/PPTR.15922.
[82] D. Garcia-Roger, E. E. González, D. Martín-Sacristán, and J. F. Monserrat, "V2X Support in 3GPP Specifications: From 4G to 5G and beyond," *IEEE Access*, vol. 8, pp. 190946–190963, 2020, doi: 10.1109/ACCESS.2020.3028621.
[83] J. Mei, X. Wang, and K. Zheng, "An intelligent self-sustained RAN slicing framework for diverse service provisioning in 5G-beyond and 6G networks," *Intell. Converg. Networks*, vol. 1, no. 3, pp. 281–294, 2021, doi: 10.23919/icn.2020.0019.
[84] S. Zeadally, M. A. Javed, and E. Ben Hamida, "Vehicular Communications for ITS: Standardization and Challenges," *IEEE Commun. Stand. Mag.*, vol. 4, no. 1, pp. 11–17, 2020, doi: 10.1109/MCOMSTD.001.1900044.
[85] X. Lin *et al.*, "5G New radio evolution meets satellite communications: Opportunities, challenges, and solutions," *5G Beyond Fundam. Stand.*, pp. 517–531, 2021, doi: 10.1007/978-3-030-58197-8_18.
[86] M. Alrabeiah and A. Alkhateeb, "Deep Learning for mmWave Beam and Blockage Prediction Using Sub-6 GHz Channels," *IEEE Trans. Commun.*, vol. 68, no. 9, pp. 5504–5518, 2020, doi: 10.1109/TCOMM.2020.3003670.
[87] A. Nauman, T. N. Nguyen, Y. A. Qadri, Z. Nain, K. Cengiz, and S. W. Kim, "Artificial Intelligence in Beyond 5G and 6G Reliable Communications," *IEEE Internet Things Mag.*, vol. 5, no. 1, pp. 73–78, 2022, doi: 10.1109/iotm.001.2100140.
[88] L. Miao, J. J. Virtusio, and K. L. Hua, "Pc5-based cellular-v2x evolution and deployment," *Sensors (Switzerland)*, vol. 21, no. 3, pp. 1–14, 2021, doi: 10.3390/s21030843.
[89] D. Sabella *et al.*, "Global MEC supporting automotive services: From multi-operator live trials to standardization," *2021 IEEE Conf. Stand. Commun. Networking, CSCN 2021*, pp. 7–13, 2021, doi: 10.1109/CSCN53733.2021.9686115.
[90] S. Bartoletti *et al.*, "Positioning and Sensing for Vehicular Safety Applications in 5G and beyond," *IEEE Commun. Mag.*, vol. 59, no. 11, pp. 15–21, 2021, doi: 10.1109/MCOM.011.2100339.
[91] K. Z. Ghafoor, M. Guizani, L. Kong, H. S. Maghdid, and K. F. Jasim, "Enabling Efficient Coexistence of DSRC and C-V2X in Vehicular Networks," *IEEE Wirel. Commun.*, vol. 27, no. 2, pp. 134–140, 2020, doi: 10.1109/MWC.001.1900219.
[92] K. Ansari, "Joint use of DSRC and C-V2X for V2X communications in the 5.9 GHz ITS band," *IET Intell. Transp. Syst.*, vol. 15, no. 2, pp. 213–224, 2021, doi: 10.1049/itr2.12015.
[93] Z. Ur R. Zia, H. Ur Rahman, M. H. Malik, and A. Jahngir, "Technical Challenges in Achieving Ultra-Reliable & Low Latency Communication in 5G Cellular-V2X Systems," *LC Int. J. STEM*, pp. 2708–7123, 2020, doi: 10.47150.
[94] A. Ghosal and M. Conti, "Security issues and challenges in V2X: A Survey," *Comput. Networks*, vol. 169, no. March 2019, 2020, doi: 10.1016/j.comnet.2019.107093.
[95] H. Zhou, W. Xu, J. Chen, and W. Wang, "Evolutionary V2X Technologies Toward the Internet of Vehicles: Challenges and Opportunities," *Proc. IEEE*, vol. 108, no. 2, pp. 308–323, 2020, doi: 10.1109/JPROC.2019.2961937.
[96] Y. Qian, F. Ye, and H.-H. Chen, "Security in V2X Communications," in *Security in Wireless Communication Networks*, IEEE, 2022, pp. 311–331. doi: 10.1002/9781119244400.ch15.
[97] H. H. Qasim, A. M. Jasim, and K. A. Hashim, "Real-time monitoring system based on integration of internet of things and global system of mobile using Raspberry Pi," vol. 12, no. 3, pp. 1418–1426, 2023, doi: 10.11591/eei.v12i3.4699.
[98] R. Shrestha, S. Y. Nam, R. Bajracharya, and S. Kim, "Evolution of v2x communication and integration of blockchain for security enhancements," *Electron.*, vol. 9, no. 9, pp. 1–33, 2020, doi: 10.3390/electronics9091338.
[99] G. Nencioni, R. G. Garroppo, and R. F. Olimid, "5G Multi-access Edge Computing: a Survey on Security, Dependability, and Performance," *IEEE Access*, vol. 11, no. June, 2023, doi: 10.1109/ACCESS.2023.3288334.
[100] R. Pavithra, V. kumar Kaliappan, and S. Rajendar, "Security Algorithm for Intelligent Transport System in Cyber-Physical Systems Perceptive: Attacks, Vulnerabilities, and Countermeasures," *SN Comput. Sci.*, vol. 4, no. 5, p. 544, 2023, doi: 10.1007/s42979-023-01897-9.
[101] S. A. Abdel Hakeem, A. A. Hady, and H. Kim, "Current and future developments to improve 5G-NewRadio performance in vehicle-to-everything communications," *Telecommun. Syst.*, vol. 75, no. 3, pp. 331–353, 2020, doi: 10.1007/s11235-020-00704-7.
[102] M. M. Elsayed, K. M. Hosny, M. M. Fouda, and M. M. Khashaba, "Vehicles communications handover in 5G: A survey," *ICT Express*, 2022. doi: 10.1016/j.icte.2022.01.005.
[103] S. K and C. chinnasamy, "Efficient VANET handover scheme using SSDN by incorporating media independent handover framework," *Meas. Sensors*, vol. 26, no. November 2022, p. 100684, 2023, doi: 10.1016/j.measen.2023.100684.
[104] M. Noor-A-Rahim *et al.*, "6G for Vehicle-to-Everything (V2X) Communications: Enabling Technologies, Challenges, and Opportunities," *Proc. IEEE*, vol. 110, no. 6, pp. 712–734, 2022, doi: 10.1109/JPROC.2022.3173031.
[105] T. Ojanper *et al.*, "Piloting and Evaluation of 5G-Enabled Road Safety and Cybersecurity Services," pp. 669–674, 2023, doi:

10.1109/EuCNC/6GSummit58263.2023.10188301.
[106] P. Pramod Kumar and K. Sagar, "A Proficient Vertical Handover Decision Making Algorithm in Internet of Vehicles with 5G," *Proc. Int. Conf. Electron. Renew. Syst. ICEARS 2022*, vol. 3, no. Icears, pp. 456–462, 2022, doi: 10.1109/ICEARS53579.2022.9751892.
[107] P. Thakur and A. Ganpati, "Vertical handover techniques in VANETs," *Int. J. Veh. Inf. Commun. Syst.*, vol. 6, no. 2, pp. 185–216, 2021, doi: 10.1504/IJVICS.2021.115263.
[108] C. R. Storck, E. E. d. O. Lousada, G. G. d. O. Silva, R. A. F. Mini, and F. Duarte-Figueiredo, "FiVH: A solution of inter-V-Cell handover decision for connected vehicles in ultra-dense 5G networks," *Veh. Commun.*, vol. 28, Apr. 2021, doi: 10.1016/j.vehcom.2020.100307.
[109] Z. Haider *et al.*, "A Novel Cooperative Relaying-Based Vertical Handover Technique for Unmanned Aerial Vehicles," *Secur. Commun. Networks*, vol. 2022, 2022, doi: 10.1155/2022/5702529.
[110] P. Elechi, S. Orike, and E. C. Akujobi, "Minimization of Handoff Failure in a Heterogeneous Network Environment using Multi Criteria Fuzzy System," *J. Telecommun. Electron. Comput. Eng.*, vol. 13, no. 2, pp. 17–22, 2021.
[111] H. E. I. Jubara, "An efficient handover procedure in vehicular communication," in *2020 2nd International Conference on Computer and Information Sciences, ICCIS 2020*, Oct. 2020. doi: 10.1109/ICCIS49240.2020.9257665.
[112] J. Kim *et al.*, "A Formally Verified Security Scheme for Inter-gNB-DU Handover in 5G Vehicle-to-Everything," *IEEE Access*, vol. 9, pp. 119100–119117, 2021, doi: 10.1109/ACCESS.2021.3107308.
[113] E. Ndashimye, N. I. Sarkar, and S. K. Ray, "A Multi-criteria based handover algorithm for vehicle-to-infrastructure communications," *Comput. Networks*, vol. 185, Feb. 2021, doi: 10.1016/j.comnet.2020.107652.
[114] E. Ndashimye, N. I. Sarkar, and S. K. Ray, "A network selection method for handover in vehicle-to-infrastructure communications in multi-tier networks," *Wirel. Networks*, vol. 26, no. 1, pp. 387–401, 2020, doi: 10.1007/s11276-018-1817-x.
[115] S. Khalid, A. Alam, and M. Ilyas, "Optimized security context switching with low latency in vertical handover," *Proc. Pakistan Acad. Sci. Part A*, vol. 57, no. 1, pp. 37–44, 2020.
[116] M. Naresh, D. V. Reddy, and K. R. Reddy, "Multi-objective emperor penguin handover optimisation for IEEE 802.21 in heterogeneous networks," *IET Commun.*, vol. 14, no. 18, pp. 3239–3246, 2020, doi: 10.1049/iet-com.2019.1228.
[117] Usman I. H., Omizegba E. E., Jiya J. D., Bakare G. A., and Godwin S, "Review of Handover Decision Algorithms in Wireless Communication Networks," *Int. J. Adv. Res. Sci. Commun. Technol.*, vol. 18, no. 9, pp. 271–278, 2023, doi: 10.48175/ijarsct-11345.
[118] W. T. Alshaibani, I. Shayea, R. Caglar, J. Din, and Y. I. Daradkeh, "Mobility Management of Unmanned Aerial Vehicles in Ultra–Dense Heterogeneous Networks," *Sensors*, vol. 22, no. 16, 2022, doi: 10.3390/s22166013.
[119] J. Sultan, M. S. Mohsen, N. S. G. Al-Thobhani, and W. A. Jabbar, "Performance of hard handover in 5G heterogeneous networks," *2021 1st Int. Conf. Emerg. Smart Technol. Appl. eSmarTA 2021*, pp. 1–8, 2021, doi: 10.1109/eSmarTA52612.2021.9515745.
[120] N. Aljeri and A. Boukerche, "Fog-enabled vehicular networks: A new challenge for mobility management," *Internet Technol. Lett.*, vol. 3, no. 6, 2020, doi: 10.1002/itl2.141.
[121] L. Tuyisenge, M. Ayaida, S. Tohme, and L. E. Afilal, "A mobile internal vertical handover mechanism for distributed mobility management in VANETs," *Veh. Commun.*, vol. 26, Dec. 2020, doi: 10.1016/j.vehcom.2020.100277.
[122] W. S. Hwang, T. Y. Cheng, Y. J. Wu, and M. H. Cheng, "Adaptive Handover Decision Using Fuzzy Logic for 5G Ultra-Dense Networks," *Electron.*, vol. 11, no. 20, pp. 1–15, 2022, doi: 10.3390/electronics11203278.
[123] A. U. Rehman, M. Bin Roslee, and T. Jun Jiat, "A Survey of Handover Management in Mobile HetNets: Current Challenges and Future Directions," *Appl. Sci.*, vol. 13, no. 5, pp. 1–43, 2023, doi: 10.3390/app13053367.
[124] A. K. Gupta, V. Goel, R. R. Garg, D. R. Thirupurasundari, A. Verma, and M. Sain, "A fuzzy based handover decision scheme for mobile devices using predictive model," *Electron.*, vol. 10, no. 16, 2021, doi: 10.3390/electronics10162016.
[125] S. Alraih, R. Nordin, I. Shayea, N. F. Abdullah, and A. Alhammadi, "Ping-Pong Handover Effect Reduction in 5G and beyond Networks," *Proc. 2021 IEEE Work. Microw. Theory Tech. Wirel. Commun. MTTW 2021*, pp. 97–101, 2021, doi: 10.1109/MTTW53539.2021.9607205.
[126] S. Sonmez, I. Shayea, S. A. Khan, and A. Alhammadi, "Handover Management for Next-Generation Wireless Networks: A Brief Overview," *Proc. 2020 IEEE Work. Microw. Theory Tech. Wirel. Commun. MTTW 2020*, pp. 35–40, 2020, doi: 10.1109/MTTW51045.2020.9245065.
[127] Y. Li, W. Zhou, and S. Zhou, "Forecast Based Handover in an Extensible Multi-Layer LEO Mobile Satellite System," *IEEE Access*, vol. 8, pp. 42768–42783, 2020, doi: 10.1109/ACCESS.2020.2977831.
[128] N. M. Kibinda and X. Ge, "User-Centric Cooperative Transmissions-Enabled Handover for Ultra-Dense Networks," *IEEE Trans. Veh. Technol.*, vol. 71, no. 4, pp. 4184–4197, Apr. 2022, doi: 10.1109/TVT.2022.3141455.
[129] M. B. Patil and L. Math, "A novel approach for optimization of handover mechanism using metaheuristics algorithms," *Meas. Sensors*, vol. 24, no. September, p. 100467, 2022, doi: 10.1016/j.measen.2022.100467.
[130] H. Zhu and Y. Peng, "Research on Adaptive Handover Scheme Based on Improved Genetic Algorithm," *Procedia Comput. Sci.*, vol. 166, pp. 557–562, 2020, doi: https://doi.org/10.1016/j.procs.2020.02.022.
[131] A. Kose, H. Lee, C. H. Foh, and M. Dianati, "Beam-based mobility management in 5G millimetre wave V2X communications: A survey and outlook," *IEEE Open J. Intell. Transp. Syst.*, vol. 2, no. September, pp. 347–363, 2021, doi: 10.1109/OJITS.2021.3112533.
[132] J. Tanveer, A. Haider, R. Ali, and A. Kim, "An Overview of Reinforcement Learning Algorithms for Handover Management in 5G Ultra-Dense Small Cell Networks," *Appl. Sci.*, vol. 12, no. 1, 2022, doi: 10.3390/app12010426.
[133] Y. Ullah, M. Bin Roslee, S. M. Mitani, S. A. Khan, and M. H. Jusoh, "A Survey on Handover and Mobility Management in 5G HetNets: Current State, Challenges, and Future Directions," *Sensors*, vol. 23, no. 11, pp. 1–36, 2023, doi: 10.3390/s23115081.
[134] S. A. Khan, I. Shayea, M. Ergen, and H. Mohamad, "Handover management over dual connectivity in 5G technology with future ultra-dense mobile heterogeneous networks: A review," *Eng. Sci. Technol. Int. J.*, vol. 35, 2022, p. 101172. doi: 10.1016/j.jestch.2022.101172.
[135] C. Wang, J. Shen, J. F. Lai, and J. Liu, "B-TSCA: Blockchain Assisted Trustworthiness Scalable Computation for V2I Authentication in VANETs," *IEEE Trans. Emerg. Top. Comput.*, vol. 9, no. 3, pp. 1386–1396, 2021, doi: 10.1109/TETC.2020.2978866.
[136] N. Aljeri and A. Boukerche, "A two-tier machine learning-based handover management scheme for intelligent vehicular networks," *Ad Hoc Networks*, vol. 94, Nov. 2019, doi: 10.1016/j.adhoc.2019.101930.
[137] Y. Lin, Z. Zhang, Y. Huang, J. Li, F. Shu, and L. Hanzo, "Heterogeneous User-Centric Cluster Migration Improves the Connectivity-Handover Trade-Off in Vehicular Networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 16027–16043, 2020, doi: 10.1109/TVT.2020.3041521.

[138] S. Khosravi, H. Shokri-Ghadikolaei, and M. Petrova, "Learning-Based Handover in Mobile Millimeter-Wave Networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 7, no. 2, pp. 663–674, 2021, doi: 10.1109/TCCN.2020.3030964.

[139] Q. Liu, C. F. Kwong, S. Zhou, T. Ye, L. Li, and S. P. Ardakani, "Autonomous Mobility Management for 5G Ultra-Dense HetNets via Reinforcement Learning with Tile Coding Function Approximation," *IEEE Access*, vol. 9, pp. 97942–97952, 2021, doi: 10.1109/ACCESS.2021.3095555.

[140] C. Lee, J. Jung, and J. M. Chung, "Intelligent Dual Active Protocol Stack Handover Based on Double DQN Deep Reinforcement Learning for 5G mmWave Networks," *IEEE Trans. Veh. Technol.*, vol. 71, no. 7, pp. 7572–7584, 2022, doi: 10.1109/TVT.2022.3170420.

[141] A. Arwa, T. Alaa, and Z. Faouzi, "Deep Reinforcement Learning Based Handover management for Vehicular Platoon," *2023 Int. Wirel. Commun. Mob. Comput.*, pp. 61–66, 2023, doi: 10.1109/IWCMC58020.2023.10183146.

[142] V. B. Souza, M. H. Pereira, L. H. S. Lelis, and X. Masip-Bruin, "Enhancing resource availability in vehicular fog computing through smart inter-domain handover," *2020 IEEE Glob. Commun. Conf. GLOBECOM 2020 - Proc.*, no. Ml, 2020, doi: 10.1109/GLOBECOM42002.2020.9322238.

[143] M. S. Mollel *et al.*, "Intelligent handover decision scheme using double deep reinforcement learning," *Phys. Commun.*, vol. 42, Oct. 2020, doi: 10.1016/j.phycom.2020.101133.

[144] K. M. Awan, M. Nadeem, A. S. Sadiq, A. Alghushami, I. Khan, and K. Rabie, "Smart handoff technique for internet of vehicles communication using dynamic edge-backup node," *Electron.*, vol. 9, no. 3, pp. 1–20, 2020, doi: 10.3390/electronics9030524.

[145] K. Qi, T. Liu, and C. Yang, "Federated Learning Based Proactive Handover in Millimeter-wave Vehicular Networks," *Int. Conf. Signal Process. Proceedings, ICSP*, vol. 2020-Decem, pp. 401–406, Jan. 2020, doi: 10.1109/ICSP48669.2020.9320974.

[146] H. Tong, T. Wang, Y. Zhu, X. Liu, S. Wang, and C. Yin, "Mobility-Aware Seamless Handover with MPTCP in Software-Defined HetNets," *IEEE Trans. Netw. Serv. Manag.*, vol. 18, no. 1, pp. 498–510, Mar. 2021, doi: 10.1109/TNSM.2021.3050627.

BIOGRAPHIES OF AUTHORS

Hamzah Hadi Qasim obtained a Bachelor of Science degree in Communication Engineering from Iraq University College (IUC), Iraq, in the year 2015. He obtained a Master of Science degree in Electrical Engineering from Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia, in 2018. Currently, he is a Ph.D. candidate in the College of Engineering at Universiti Teknologi MARA (UiTM), Malaysia, in the year 2021. Currently he is work lecturer in Basra University for oil and gas enginerring. Moreover, the researcher's current areas of interest encompass the internet of things (IoT), wireless sensor networks (WSN), vehicle-to-everything (V2X) communication, deep reinforcement learning (DRL), and mobility management for handover management in cellular communication. He can be contacted at email: Enghamza.iq@gmail.com or 2021293252@student.uitm.edu.my.

Husna Zainol Abidin is an Associate Professor at School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), Malaysia. She received her Bachelor of Engineering (B.Eng.) in Electrical from the University of Wollongong, Australia in 2001. She continued her postgraduate study in Universiti Tenaga Nasional and received her Master of Engineering (M.Eng.) in Electrical and Ph.D. in Engineering in 2006 and 2015 respectively. Husna research area includes wireless networking which wireless sensor networks (WSN), internet of things (IoT) and vehicle-to-everything (V2X). She is currently a fellow at the school Industrial Research Laboratory known as Vehicle Intelligence and Telematics Lab (VITAL) in collaboration with the Amtel Cellular Sdn. Bhd. under the UiTM Micro Industrial Hub (MIH) initiative. She has published more than 60 papers in indexed journals and conference proceedings. Currently, she is an editorial member of the School of Electrical Engineering Journal of Electrical and Electronic Systems Research (JEESR) since 2015 which successfully indexed by Malaysian Citation Index (MyCite) in 2016. She can be contacted at email: husnaza@uitm.edu.my.

Syahrul Afzal Che Abdullah obtained B.Eng degree in Electronic Engineering from University of Southampton, UK, M.Sc. in Real Time Software Engineering from Universiti Teknologi Malaysia (UTM), MY, and Ph.D. in Software Engineering from Universiti Sains Malaysia (USM), MY. Currently, he is a senior lecturer at the Centre for Computer Engineering Studies, School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), MY. His research interests include artificial intelligence, autonomous vehicle, internet of things, software engineering and software testing. He is recognized as a Professional Engineer by the Board of Engineers Malaysia, a corporate member of the Institution of Engineers Malaysia (IEM), and a senior member of Institute of Electrical and Electronics Engineers (IEEE), US. He is recognized as Graduate Technologist and Professional Technologist by the Malaysia Board of Technologists (MBOT). He can be contacted at email: bekabox181343@uitm.edu.my.