Applicants and Prospects of Uplink/Downlink Decoupled Access Cellular Vehicle-to-Everything (C-V2X) in B5G/6G

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Abstract. The cellular vehicle-to-everything (C-V2X) is an important information technology solution to address the low-latency and high-reliability communication demands of current vehicle users in beyond 5th generation (B5G) and 6th generation (6G) wireless communications. However, existing C-V2X frameworks suffer from frequent handovers, insufficient data rates, and imbalanced base station loads due to the smaller coverage range of base stations. To address these challenges, it becomes imperative to introduce uplink/downlink decoupled access (DUDe) into the preexisting coupled access framework. This article analyzes the core challenges of C-V2X, summarizes the development background and advantages of DUDe, examines the feasibility of applying DUDe in C-V2X, explores various application directions related to uplink/downlink decoupled access C-V2X, and finally concludes with the development of uplink/downlink decoupled access C-V2X.

Keywords: C-V2X, B5G/6G, stochastic geometry, uplink/downlink decoupled access..

1. Introduction

The European Automobile Manufacturers Association (ACEA) reports that the number of registered passenger vehicles in the European Union reached 253 million in 2021, with over 1.9 million of them being pure electric vehicles [1]. Meanwhile, based on CEIC data, the full sum of registered vehicles in the United States was 282, 366, 285 vehicles as of December 2021, showing a growth of 2.34% compared to the same period in 2020 [2]. With the advancement of communication technologies, the user base of connected vehicles has been expanding. In this context, in-vehicle communication has gained significant attention, leading to various demands related to in-vehicle entertainment, gaming, and autonomous driving. Thus, the concept of the V2X has emerged as a pivotal technology to address these demands [3]. V2X technology pertains to the use of the most recent information and communication technologies for establishing connections within the transport system, linking pedestrians, vehicles, roads, and the cloud. This connectivity encompasses vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), vehicle-to-cloud (V2C), and vehicle-to-road (V2B) communications. V2X communication technology has the potential to enhance traffic efficiency, boost vehicle intelligence, and facilitate advanced capabilities in autonomous driving, thus contributing to the development of intelligent, effective, and secure communication services.

At present, there exist two potential implementation options for V2X communication: Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X) technology. DSRC is a wireless technology developed based on the IEEE 802.11p standard, enabling short-range data exchange between DSRC devices. It is widely used in vehicles and intelligent transportation systems (ITS), incorporating devices like on-board units (OBUs) within vehicles, handheld devices carried by pedestrians, and roadside units (RSUs) positioned alongside the roads. Nevertheless, DSRC faces certain limitations that impede its extensive use in V2X communication. It performs inadequately in densely populated scenarios, and its radio spectrum falls short of meeting the projected high data traffic demands for in-vehicle communication [4]. These performance challenges, combined with its restricted scalability, contribute to the limited adoption of DSRC in V2X.

C-V2X is a V2X communication technology based on cellular systems. It utilizes and enhances the functionalities and elements of cellular networks, enabling low latency and highly reliable communication among nodes in V2X. C-V2X enriches driving and communication modes, contributing to better realization of V2P, V2I, and V2C, among others. Compared to DSRC, C-V2X offers faster link rates, higher interference resistance, a larger coverage range, and non-line-of-sight (NLOS) capabilities. Furthermore, as communication technology updates and evolves, cellular networks transition from 4G (the 4th generation mobile communication technology) to 5G (the 5th generation mobile communication technology), leading to the evolution of C-V2X into LTE-V2X and the development of 5G-NR-V2X technologies. It is foreseeable that future C-V2X will continue to evolve within the framework of beyond 5th generation and 6th generation wireless communications (B5G/6G).

There remain several challenges to be addressed in the context of C-V2X. In the existing user connectivity and access methods, to guarantee the quality of service (QoS) amidst users irregular mobility, the communication signal needs to be maintained at a certain strength. Continuous base station (BS) signal monitoring, along with cell selection and reselection, is essential for user equipments (UEs). Such frequent handovers contribute to excessive switching and lower network throughput [3]. The concentrated implementation of C-V2X somewhat restricts its capacity to facilitate low-latency V2V communication, which undermines the effectiveness of safety applications [4].

In the context of V2X applications, new challenges are being placed on various aspects of cellular network systems. According to the report by 5GAA [5], the spectrum requirement for basic safety needs in direct communication is 10-20 MHz below 5.9 GHz, while advanced driving requires an additional 40 MHz or more. In addition to the basic road safety spectrum requirements, the 3GPP Service and system aspects (SA) working group has studied four categories of V2X enhanced applications, including platooning, advanced driving, sensor augmentation, and remote driving, along with their corresponding communication requirements [6]. As shown in Table 1, in V2X-enhanced applications, the maximum end-to-end latency is 100 ms, with support for the utmost reliability of 99.999%, a peak data rate of 1000 Mbps, and a maximum communication range of 1000 meters. These impose greater technological requirements on the development of C-V2X.

Table 1: V2X Enhanced Application Performance Summary

Application type	Payload (Bytes)	Maximum end-to-end latency (ms)	Reliability (%)	Data rate (Mbps)	Minimum communication range (m)
Platooning	50~650	10~25	90%~99.99%	≤65	80~350
Autonomous driving	300~12000	3~100	90%~99.999 %	10~53	360~700
Sensor information exchange	1600	3	99.999%	≤1000	50~1000
Remote driving		5	99.999%	25	

To meet the increasing demand for mobile data, cellular networks are progressively shifting towards multi-tier heterogeneous networks (HetNets). In the B5G/6G era, these HetNets comprise macro base stations (MBS) offering broad coverage and a plethora of small base stations (SBS). With the network densification and the explosive growth in mobile data usage, user association poses a significant challenge in HetNet topology, especially for C-V2X users with high mobility and stringent communication requirements [7]. At the same time, a promising emerging technology called DUDe has received significant attention. This technology allows the uplink (UL) and downlink (DL) of user links to connect to the optimal BSs separately, breaking the traditional cellular network limitation of coupled UL and DL communication links to the same BS. DUDe separates UL and DL by connecting UEs to the nearest BS in UL. This reduces the transmit power of UL, thereby improving the signal-to-interference and noise ratio (SINR) and rate of UL while improving interference conditions.

DUDe has shown strong feasibility in the context of V2X and has the potential to improve coverage probability, rates, spectral efficiency, and other performance indicators [8]. In [9], C-V2X was modeled as a Cox process, and V. Vardhan Chetlur et al. analyzed DL coverage probability and rate performance, proposing a method equivalent to increasing the density of MBS to improve rate coverage. DUDe enhances UL SINR and reduces transmit power. S. Singh et al. introduced a new generative model to analyze UL performance [10], providing formulas for calculating UL SINR and rate distribution, and they proved that DUDe significantly improves the UL/DL coverage range. J. Wu et al. used modeling and data analysis to demonstrate that DUDe helps improve interference conditions [11].

In recent research, researchers have begun to apply DUDe to C-V2X and have studied the enhancements it brings to C-V2X, confirming the feasibility and reliability of DUDe in C-V2X applications. In an article[12], a stochastic geometry-based shared channel V2X model was proposed. In [13], DUDe was first introduced into C-V2X, showing that it can enhance UL throughput and load balancing in C-V2X. DUDe was introduced into C-V2X networks by L. Jiao et al [14]. to better support V2X applications. It underwent in-depth theoretical analysis using stochastic geometry and experimental results to demonstrate the feasibility of their approach. K. Yu et al. examined the potential of UL/DL decoupled access RAN framework in V2X [7], introduced QoS metrics for C-V2V, and demonstrated that DUDe can substantially enhance load balancing and lower transmission power in C-V2X.

This article aims to confront a series of challenges currently posed by CV2X such as frequent user handovers, low network throughput, and inadequate latency for practical application requirements. The goal is to promote the application and widespread adoption of decoupled access in both UL and DL within C-V2X networks, particularly in the context of B5G/6G.

The main contributions of this paper are as follows:

- We conducted a comparative analysis between C-V2X and DSRC, provided an in-depth overview of the development context of DUDe, and underscored the advantages inherent to the implementation of DUDe.
- To address challenges such as UL/DL load imbalance and frequent UE handovers, we delved into the viability of integrating DUDe into the realm of C-V2X. In doing so, we put forth a series of implementation methodologies, encompassing resource management, mobility management, and load balancing strategies.
- Taking practical applications into consideration, we are committed to introducing a spectrum of technologies into the domain of C-V2X and outlining multifaceted development pathways.

The structure of the paper is arranged as follows. Section 2 provides an overview of the development background and benefits of DUDe. Section 3 analyzes DUDe in C-V2X. Section 4 offers prospects for the application directions associated with DUDe in C-V2X. Finally, Section 5 provides a summary of the paper.

2. Overview of DUDe

In this section, we primarily discuss the development background of DUDe, which involves the separation of UL and DL, allowing a UE to connect to different service nodes in UL and DL. We elaborate on the advantages of DUDe in detail from various perspectives, including SINR, interference conditions, spectrum efficiency, coverage, throughput, and load balancing.

2.1 Development Background of DUDe

As shown in Fig. 1, the number of small cells globally is steadily on the rise alongside the progress of communication technologies like 4G and 5G. According to the market forecast survey report by the Small Cell Forum (SCF) in 2022, the compound annual growth rate (CAGR) of small cell deployments is projected to reach 15% over the next five years. It is estimated that by 2027, there will be a cumulative deployment of nearly 36 million small cell radio frequency systems [15]. In the past, MBS served as the primary provider of services in the cellular system cell structure under the traditional coupled user association approach. Due to their large coverage range, MBSs were typically positioned at a distance from UEs, posing challenges for users seeking to connect to nearby BSs in UL. This limitation hindered the enhancement of UL network performance, especially for time-critical and data-intensive applications. Nevertheless, the widespread deployment of small cells has transformed this landscape, granting users the flexibility to establish connections with closer BSs in UL. This advancement simplifies users' ability to fulfill their specific requirements by selecting and connecting to nearby BSs. It has created favorable conditions for the rapid advancement of HetNets and DUDe.

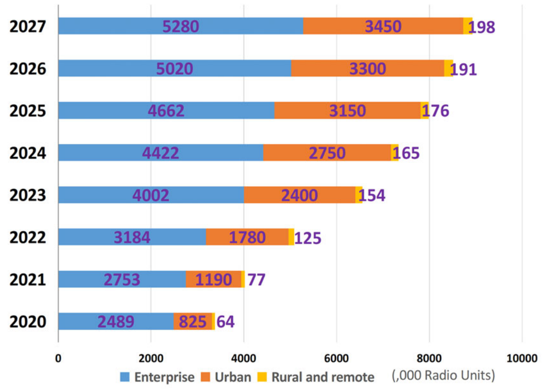

Fig. 1: The development of the number of SBSs worldwide.

3GPP is an international standards organization responsible for developing and defining global standards for mobile communication technologies. In 3GPP Release 4 and Release 5, High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) technologies were introduced to enhance the data rates of DL and UL respectively. In 3GPP Release 8 and Release 9, long-term evolution (LTE) technology was introduced, marking the advent of 4G networks. LTE utilized technologies such as Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) to provide higher data rates, lower latency, and improved spectral efficiency, further enhancing DUDe. In 3GPP Release 10 [16] and subsequent versions, the emergence and development of 5G networks brought advanced beamforming techniques, broader spectrum resources, flexible spectrum management, and the introduction of network slicing, enabling greater decoupling and improved performance to meet the performance and service requirements of different applications.

2.2 Benefits of DUDe

The rise of heterogeneous networks, featuring smaller cells within macro cell coverage areas operating at higher carrier frequencies and reduced transmit power, demands a reconsideration of the coupling and association strategies between UEs and BSs. Decoupling UL and DL separates the UL and DL transmissions, originating from a holistic perspective on bidirectional (DL/UL) traffic and UE association, rather than optimizing DL and UL transmissions separately under coupled access.

2.2.1 Improved UL SINR and Reduced Transmit Power

In the context of HetNets, macro cells usually exhibit a considerably broader DL coverage range compared to small cells, primarily due to variations in DL transmit power, BS height, and antenna gain.However, in UL, the transmit power among different transmitters is roughly the same. Therefore, by applying DUDe, the transmit power can be alternately reduced, while maintaining a fixed SINR, to minimize the path loss during propagation [8]. Additionally, when a UE transmits at maximum power, connecting to a closer BS can also improve the UL SINR.

2.2.2 Improved Interference Conditions

In HetNets, different transmit power levels among BSs at different tiers result in varying interference levels, while DUDe helps improve the interference conditions. Under coupled access, UL is tied to DL, leading to suboptimal UL performance. This means that the selection of BSs is not necessarily optimal, causing UEs to increase their transmit power and thus increase interference on other devices' links. By applying DUDe, UL can choose to connect to a closer BS with better signal quality, reducing the required transmit power for UEs and consequently lowering the interference level on other links [11].

2.2.3 Enhancing UL Spectrum Efficiency and Coverage

In the process of building the 5G enhanced Mobile Broadband (eMBB), the CBand with its large bandwidth has become the preferred frequency range for most operators worldwide. However, due to the uneven UL-DL slot ratio in New Radio (NR) and the significantly higher DL power of gNodeBs compared to UE power, there are challenges of imbalanced UL-DL coverage and limited UL coverage in the C-Band. Additionally, with the introduction of technologies such as massive MIMO beamforming and CRS-Free, the DL interference is reduced, further exacerbating the UL-DL coverage gap in the C-Band and becoming a bottleneck for 5G development and deployment. DUDe has redefined the spectrum pairing scheme to address these challenges. In one proposed scheme, sub-3G transmission is used for UL data in the UL-limited area, while DL data is transmitted in the C-Band, thereby improving UL coverage and spectrum efficiency. In principle, applying DUDe improves the interference conditions, resulting in reduced interference and increased SINR for a given signal. Consequently, the spectral efficiency of the UL channel is also improved. Moreover, coverage probability refers to the probability of the SINR of a signal exceeding a certain threshold. Therefore, as the SINR increases [8], the coverage probability also improves.

2.2.4 Increasing UL Data Rates or Throughput

Increasing the desired received power and reducing interference are beneficial for achieving higher SINR and spectral efficiency in the network, thereby improving data rates [10]. Additionally, DL bias can also contribute to increased data rates. This is because DL bias can expand the coverage range of DL small cells, allowing more UEs to connect to nearby small cells in UL. As a result, UEs at the cell edge and in the middle obtain more resources, leading to higher UL rates. Of course, rate gains can also be attributed to the improved channel quality brought about by DUDe.

2.2.5 Load Balancing in UL and DL

In the conventional coupled access framework, UL load on the MBS is multiple times greater than that on the SBS. Owing to the substantially higher transmit power of the MBS, even in situations with a limited number of MBSs, a greater number of UEs are inclined to establish DL connections with the MBS in order to receive stronger signals. As a result, in this framework, UEs choose to connect to the same BS, the MBS, in both UL and DL, leading to a higher load on the MBS compared to the SBS. This load imbalance becomes more pronounced when the links connected to the MBS have lower path loss. Furthermore, in situations where SBSs are densely deployed, and the MBS density remains constant, the SBS load diminishes as the number of SBSs rises, owing to competition for access among SBSs. This intensifies the existing disparity in UL-DL load.

To confront these challenges, DUDe can establish more UL connections between UEs and SBSs while maintaining DL connections with the MBSs. This improves the utilization of SBSs, reduces the load on the MBSs, and achieves UL/DL load balancing. Therefore, in the next-generation communication networks characterized by heterogeneity and densification, it is crucial to introduce the DUDe framework to improve the load distribution among BSs [17].

3. UL/DL decoupled access C-V2X

This section introduces the UL/DL decoupled access C-V2X system framework and analyzes the UL/DL decoupled access C-V2X from various aspects, including the reasons why DUDe can be applied to C-V2X and the management methods for UL/DL decoupled access C-V2X.

3.1 The Framework of C-V2X

As shown in Fig. 2, the framework of C-V2X can be divided into three layers based on the network structure: the application layer, the network layer, and the perception layer.

•Perception Layer: This layer is primarily responsible for environment perception to support functions such as perception data-assisted driving. It collects vehicle operating conditions and surrounding environmental information through onboard sensors, radar, and positioning systems, providing feedback to the driver.

•Network Layer: This layer is primarily used for vehicle network access, data analysis, and node management. It processes and analyzes the data collected by the perception layer through access networks and core networks, enabling resource allocation and information load balancing.

•Application Layer: This is the top layer of the C-V2X framework, where data generated by the perception and network layers is analyzed and processed. It provides personalized services to users, such as autonomous driving, multimedia entertainment, and emergency assistance.

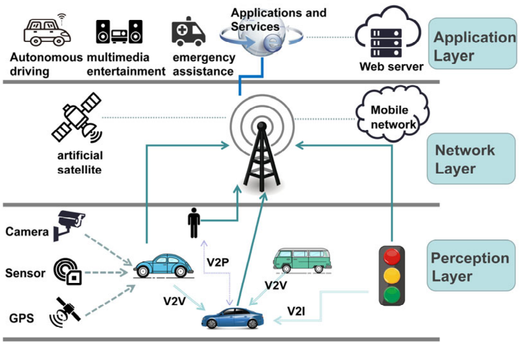

Fig. 2: The framework of C-V2X.

C-V2X, based on cellular communication, possesses V2X communication capabilities and offers benefits like easy deployment and dependable transmission. C-V2X leverages the existing mobile network infrastructure for information services. By facilitating extensive connectivity and efficient data exchange among vehicles, pedestrians, roads, and the cloud, it fosters the advancement and implementation of autonomous driving technology and intelligent transportation systems. C-V2X can address the varied service needs of future vehicular communication applications. Additionally, driven by progress in B5G/6G technologies, C-V2X will be integrated with DUDe, further enhancing link security and flexibility, thus bolstering the convergence of autonomous driving and cellular networks.

3.2 UL/DL Decoupled Access Association Policy

In the UL/DL decoupled C-V2X, UEs employ 2 association strategies: maximize received power and SINR. When BSs have equal transmit power, choosing max received power means the nearest BS with the least path loss. Yet, higher received power may mean more interference and not always maximum SINR. UEs adapt strategies to varied situations, selecting MBS/SBS access based on requirements.

The connection between vehicles and BSs depends on factors such as transmit power, received power, and antenna gain. In DL, vehicles will associate with the one offering the highest maximum received power between MBS and SBS. In UL, the vehicle's connection with a BS is influenced by factors such as the transmit power of the vehicle towards the MBS/SBS and the antenna gains.

Therefore, UL/DL independently accessing MBS/SBS based on association strategies will result in four cases.

3.3 How to Implement DUDe in C-V2X

3.3.1 Mobility Management: Coverage, Handover, and Relay

As mentioned above, DUDe can significantly improve the coverage of UL by reducing the transmit power of UEs in UL [8]. This means that in C-V2X scenarios with larger coverage, users can maintain their connection to a BS for a longer time, reducing the probability of BS handover. Additionally, the need for relaying is also reduced, leading to improved reliability, stability, and security of communication.

DUDe can also be applied in relay technology. Within the framework of decoupling rules, UL and DL users have the autonomy to access both MBS and SBS independently and without restrictions. As shown in Fig. 3, there are three different UL/DL association scenarios. In some cases, due to factors such as signal strength and interference conditions, users need to rely on one or two BSs for V2V communication. In Cases 2 and 3, relaying can be achieved through a single BS. However, in Case 1, where UL/DL links are established through two BSs, an interface between BSs is needed to support the relaying [7]. The application of DUDe in relaying improves network capacity and enhances the stability of data transmission.

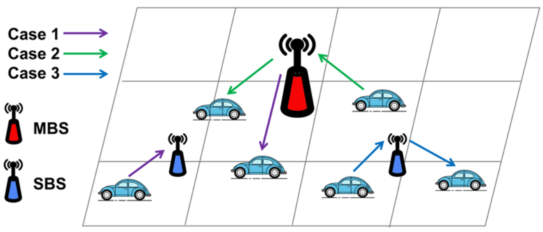

Fig. 3: Three different UL/DL association scenarios.

3.3.2 Resource Management

In the existing cellular networks, BSs continue to serve new UEs even when they exceed their capacity, resulting in service continuation under high load conditions. However, the allocation of spectrum resources and service time per user device may decrease accordingly. Power can be efficiently managed as a valuable resource for BSs in the DUDe framework of C-V2X networks. The objective of resource management is to achieve maximum user rates while utilizing minimal resources.

DUDe treats UL and DL as two separate links, decoupling the dependency of UL on DL. It enables independent management of UL and DL, allowing for separate allocation of power resources to each link, thereby aiming to maximize user rates [10].

3.3.3 Load Balancing

In the same BS, the load in UL and the load in DL may not be equivalent. This means that connecting the same set of UE to the same BS in both UL and DL is not always the optimal solution [14]. To confront this challenge, a solution is to employ decoupled access for at least some UEs. As shown in Fig 4, DUDe divides the cellular network into "balanced regions" (Region A, C) and "imbalanced regions" (Region B). In relatively balanced regions, traditional access strategies can be used. However, in the imbalanced regions, the UL and DL of UEs are decoupled. In DL, UEs are connected to the BS with the strongest received signal, following traditional methods. In UL, the access decision is based on the performance after the signal traverses the UL.

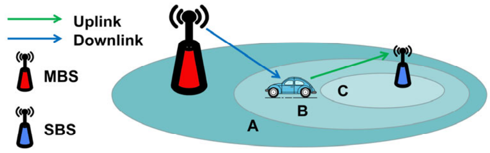

Fig. 4: The balanced region and imbalanced region in the cellular network

4. Prospects for Decoupled C-V2X Development

In the practical application of UL/DL decoupled access C-V2X, several factors need to be considered, including the system decision-making approach, security performance, capacity, and path loss. This section introduces various technologies such as reinforcement learning, blockchain, MIMO, SAGIN, and RIS. These technologies can be seamlessly integrated into the UL/DL decoupled access C-V2X framework to meet the challenges mentioned above.

4.1 Task Offloading and Resource Management Based on Reinforcement Learning

In a UL/DL decoupled access C-V2X network for computational offloading, the challenge lies in making optimal decisions based on evolving wireless channels and edge server resources, while meeting real-time application requirements. This requires an adaptable, long-term efficient decision-making process [18]. In C-V2X and DUDe scenarios with limited resources and network instability, offloading decisions become significantly challenging. Here, reinforcement learning-based algorithms have proven superior [13]. These algorithms efficiently determine the best offloading choices and allocate resources by learning channel data and adapting to dynamic V2X changes and various offloading modes [7].

4.2 Security Management Based on Blockchain

In C-V2X, the large number of vehicles poses challenges in synchronizing vehicle information. Moreover, due to sensor data exchange over public channels, the security performance of C-V2X networks is relatively low, making them susceptible to threats such as eavesdropping attacks and message tampering. Consequently, security assurances for aspects like message authentication, data management, and privacy protection in V2X are insufficient. Blockchain, as a next-generation security technology, can offer distributed storage for vehicle access requests, facilitating data storage [19]. Simultaneously, by leveraging blockchain consensus mechanisms, smart contracts, and other algorithms and technologies, it becomes possible to enhance the security of V2X and improve traffic management efficiency.

4.3 Channel Enhancement Based on MIMO

In UL/DL decoupled access C-V2X, poor single-link efficiency due to environmental variations and millimeter-wave attenuation requires the adoption of Multiple-Input Multiple-Output (MIMO) wireless technology. MIMO exponentially increases capacity and spectral efficiency without added bandwidth. Modern MIMO, like Massive MIMO, provides reuse gain, diversity gain, and power gain. Implementing MIMO-equipped antennas and BSs enhances data rates, capacity, and channel stability [20], improving the communication efficiency of UL/DL decoupled access C-V2X.

4.4 Framework Based on SAGIN

In certain C-V2X application scenarios, remote areas with limited BSs can hinder essential communications. The Space-Air-Ground Integrated Information Network (SAGIN) has emerged as a solution, connecting vehicles, aircraft, and various platforms on land, sea, and air via satellite links [21]. Satellites offer broad coverage, reducing handovers and improving QoS. Yet, satellite altitude increases latency and energy loss. Introducing DUDe in SAGIN helps mitigate this issue. Ground-based BSs handle UL and some DL, while satellites manage most DL. UEs establish UL connections with nearby BSs, and satellites act as relays for DL between BSs and vehicles. This approach optimizes UL/DL load balancing, reduces high-speed UE handovers, and enhances overall throughput.

4.5 Reliable Relay Based on RIS

In urban areas, complex terrain scatters signals, degrading communication quality. Reconfigurable intelligent surfaces (RIS) are deployed at the edges of cell in UL/DL decoupled access C-V2X to improve signal quality. RIS-equipped BSs reflect and aggregate scattered beams, directing signals in the specified direction and reducing power and path loss. This boosts channel quality and allows BSs to serve vehicles inside and outside cell boundaries simultaneously, enhancing coverage range and minimizing interference without additional spectrum use [22]. RIS also enhances security, sensing, positioning, and cost efficiency in UL/DL decoupled access C-V2X deployment.

5. Summary

In this article, we have provided a thorough analysis of DUDe's development, highlighting its five key advantages including improving interference conditions, load balancing in UL/DL and so on. We have also explored its feasibility in C-V2X, considering aspects like mobility and resource management. Additionally, we have discussed potential applications, including reinforcement learning and blockchain, within UL/DL decoupled access C-V2X. However, it's essential to acknowledge the practical challenges DUDe faces in C-V2X applications. Our paper aims to promote DUDe's utilization in C-V2X, expand the theoretical framework, and offer insights for strategic deployment in the global V2X industry.

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