A Novel Solution for Uu Interface Based C-V2X

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Abstract After 20 years of development, V2X has been facing industrialization challenges from DSRC to C-V2X. On the one hand, the new requirements for spectrum, chips, equipment, and networks introduced by the PC5 interface have caused high technical barriers to industrialization. On the other hand, the penetration rate of V2X terminals, application ecology and business models are difficult to implement in industrialization. Aiming at the Uu interface based C-V2X solution (UC-V2X), this paper introduces a risk filtering algorithm through the V2X levels of capability, and proposes a software-defined C-V2X solution (SUC-V2X), which systematically solves the C-V2X problems of industrialization. This paper further preliminarily verifies the performance of SUC-V2X.

Keywords PC5 interface based C-V2X (PC-V2X), Uu interface based C-V2X (UC-V2X), Software defined Uu interface based C-V2X (SUC-V2X), V2X Levels, Risk Filtering Algorithm (RFA).

1. Introduction

V2X is a communication technology developed based on Cooperative Intelligent Transportation System (C-ITS) and Internet of Vehicles (IOV), including vehicle to vehicle (V2V), vehicle to infrastructure (V2I), vehicle to pedestrian (V2P), vehicle to network (V2N), etc. OBU is the V2X terminal device installed on the vehicle, and RSU is the V2X network device installed on the roadside. The interaction between V2X devices supports rich V2X applications [1][2].

V2X applications are usually divided into four categories: info-entertainment, traffic efficiency, traffic safety and cooperative driving. These applications have strict requirements in communication latency and reliability [3]. At present, the performance indicators of V2X application for driving assistance have been basically clear [4][5][6][7]. The V2X application for high-level autonomous driving has been studied successively. 3GPP analyzes the application requirements of platooning, advanced driving, sensor extending and remote driving [8][9]. C-SAE starts and completes the definition of indicators for V2X Day II and advanced cooperative autonomous driving applications [10][11].

Aiming at the communication requirements of low latency and high reliability of V2X applications, 3GPP introduced C-V2X technology based on 4G LTE and 5G NR technology. C-V2X includes LTE-V2X and NR V2X. LTE-V2X is based on LTE enhancement and is mainly aimed at low-level assisted driving applications. NR-V2X is based on 5G uRLLC scenario, supports advanced autonomous driving application, and provides higher reliability and lower latency communication capability [12][13].

Fig. 1. PC-V2X and UC-V2X
Based on 3GPP cellular network architecture, C-V2X forms PC5 interface based C-V2X (PC-V2X) solution and Uu interface based C-V2X (UC-V2X) solution [14][15]. PC-V2X realizes direct communication between V2X devices by introducing a new PC5 interface in the sidelink [16][17]. UC-V2X uses the existing Uu Interface to reuse the mobile network infrastructure and realize the communication between V2X devices. The PC-V2X solution can be converted to the corresponding UC-V2X solution. V2V communication is converted into V2N2V communication by introducing V2X Application Server equipment transfer in cellular network. V2I communication is converted into V2N2I communication by introducing RSU equipment into cellular network (Figure 1).

PC-V2X solution directly inherits the early DSRC. It is easier to support V2V and V2I applications based on broadcast mode, and has become the main solution of C-V2X. Industry practice shows that the solution still faces great challenges.

1) High speed vehicles make the network topology change frequently. Communication is easily blocked by surrounding large vehicles and buildings, and the link life is relatively short. Communication security and reliability become a huge challenge [19].
2) A new radio spectrum needs to be allocated for the PC5 interface. LTE-V2X needs to allocate 10~20 MHz spectrum, and NR-V2X also needs to allocate more than 40 MHz spectrum, which poses a great challenge to scarce spectrum resources [18].
3) It is necessary to develop new C-V2X chip for PC5 interface, as well as new OBU equipment and RSU equipment. This has resulted in the slow development of C-V2X industry and closed application ecology.
4) RSU network needs to be deployed for PC5 interface. In order to meet the V2X communication requirements and provide a communication network with wide coverage and large capacity, the cost of network construction, operation and maintenance cannot be ignored [3][19].
5) Lack of mature business model. A large number of existing vehicles need to install OBU equipment. There is not enough commercial force to drive OBU penetration.

UC-V2X solution completely does not rely on PC5 interface, inherits the mature capabilities and network infrastructure of cellular network, has the capabilities of high rate, large capacity, wide coverage and high penetration, and can reuse the chip, hardware, ecological environment, business model and other achievements of Mobile Internet [20]. After long-term research and verification, UC-V2X also has the following problems [20][21].

1) The problem of low latency: The V2V communication based on PC5 interface has only one hop, while the V2N2V communication based on Uu interface has multi hops including includes uplink and downlink. It is a challenge to support the ultra-low latency requirements of V2X.
2) The problem of message congestion: When transmitting beacon messages (CAM, BSM, etc.) based on Uu interface, messages send to all vehicles in the broadcast area in downlink, resulting in a sharp increase in bandwidth and message congestion.
3) The problem of system architecture: V2N2V communication processes messages by introducing V2X Application Server equipment on the network side. V2N2I communication processes messages by introducing RSU equipment on the network side. The combination of two communications need further study.

This paper presents a systematic solution to the problems existing in UC-V2X solution. The main original contributions are as follows:

1) According to V2X low latency and high reliability, V2X applications and C-V2X networks are graded to support the hierarchical development and deployment of C-V2X networks.
2) Based on MEC, the integration solution of RSU and V2X Application Server is proposed, and the Software defined UC-V2X (SUC-V2X) architecture is given.
3) V2X application mode and collision avoidance method are proposed, and a risk filtering algorithm is proposed to solve the downlink bandwidth problem of unicast transmission.

The organizational structure of this paper is as follows: the second section introduces the current situation and progress of relevant research work. The third section introduces V2X levels based on URLL capability. The fourth section introduces the SUC-V2X solution. The fifth section introduces the system verification. The sixth section summarizes the full text and looks forward to the future work and direction.

2. Related Work

UC-V2X solution has been studied in the early stage of LTE and has received continuous attention in the NR stage [20][21]. The research progress of the main problems is as follows:
2.1 The problem of low latency

LTE is a wireless technology for mobile broadband (MBB) applications proposed by 3GPP. LTE can provide high rate (peak uplink up to 50 Mbps and downlink up to 100 Mbps), low latency (user plane latency less than 5 ms), high density (a single cell supports more than 400 active users), high mobility (speed 350 km / h), etc. LTE-Advanced and LTE-Advanced Pro versions further improve the rate (peak uplink up to 500 Mbps and downlink up to 1 Gbps) and reduce the latency, which has become the main technology for LTE commercial deployment [3][22].

The actual performance of LTE network has also been studied and verified in many aspects. For throughput, Sevindik et al. measured the commercial network of LTE version R8. UE runs at the speed of 40 to 50 km / h, with an average throughput of 10 Mbps [23][24]. For large capacity, Zhang et al. designed six scenarios based on the Internet of Things data load mode to verify that when 300 uses are connected to eNodeB, the average throughput is greater than 2.4 Mbps when the bandwidth is from 10 MHz to 20 MHz [25]. For latency, LTE combined with mobile edge computing (MEC) can significantly shorten E2E communication latency. Emara et al. studied the MEC based LTE network, and the simulation verified that the average E2E latency can be reduced from about 110 milliseconds to about 25 milliseconds [28]. Based on the Car2MEC project, Deutsche Telekom, Nokia and Continental jointly carried out V2X field test on A9 highway. The E2E latency of MEC based LTE network can be reduced to less than 30 milliseconds [29][30].

NR technology supports three application scenarios: enhanced mobile broadband (eMBB), mass machine type communications (mMTC) and ultra-reliability and low latency communications (uRLLC). NR fully provides high speed (peak uplink 10 Gbps, downlink 20 Gbps), low latency (for uRLLC, user plane latency UL is 0.5 ms, DL is 0.5 ms) and high reliability for V2X and other IOT requirements (the general reliability requirements of uRLLC transmission are 32 B packet latency of 1 ms, reliability of 99.999%). For V2X, PC5 interface and Uu Interface, the reliability is 300 B packet latency of 3~10 ms, reliability of 99.9999%), high mobility (mobility of 500 km/h) [3][26].

The NR R15 version has been commercially available on a large scale. Speedtest Global Index gives real indicators for 5G business network. For example, in Q2 of 2021, the median downlink throughput of 5G network of China Telecom is 304 Mbps and the median latency is 24 ms [27]. Srinivasa et al. studied the feasibility of co-locating MEC and 5G base stations, and combined with V2X use case to evaluate the latency of 3~5 ms [31]. Ma et al. proposed a MEC assisted 5G-V2X prototype system for cooperative autopilot. The autonomous driving vehicle runs at the speed of 30-60 km/h. The average round-trip time (RTT) between UE and MEC servers is 3.5ms, the minimum value is 2.4ms, and the data receiving rate is 14.7 Mbps. It is proved that the system can meet the requirements of V2N and V2V low latency (3ms) and high reliability (99.999%) [32].

Based on the development of 3GPP technology and the introduction of MEC and other new technologies, we can see that UC-V2X solution has the ability to support V2X high reliability and low latency requirements.

2.2 The problem of message congestion

V2X application message sets can be divided into two categories. One is BSM based message set defined by SAE, C- SAE and other standards [7][10][33]; The other is the message set based on CAM and DENM in ETSI standards[3][34][35]. CAM and BSM messages are beacon messages continuously broadcast by each vehicle. DENM message is an event message continuously broadcast and sent by a few vehicles within a limited time. Due to the centralized architecture of LTE and NR networks, V2N2V communication in UC-V2X solution is transmitted upstream through Uu interface unicast link and downstream to all target vehicles through Uu interface unicast or multicast link.

When unicast technology is used for downlink transmission, the target vehicle is addressed separately, and the same message is sent to all target vehicles at the same time. Network congestion is mainly limited by the PDSCH capacity of downlink channel [36]. For CAM and BSM messages, ETSI evaluated the LTE network based on the CoCarX project. It shows that under the condition that each vehicle sends cam messages at 10 Hz and 10 neighbors, a cell can support 57 vehicles to meet the communication latency requirement of 100 ms[36][37]. Kim et al. studied that the end-to-end performance decreased exponentially after the number of vehicles exceeded 100 [38]. Calabuig et al. simulated and evaluated that a LTE cell can retain an acceptable low latency for up to 150 on-board users broadcast at 10 Hz [39][40]. At present, there are many methods to solve the congestion problem, including reducing the message frequency [41], clustering vehicles [42], scheduling optimization, etc. Relevant results show that the existing solution cannot completely solve the overload problem of LTE network [20][38][41][45]. For DENM messages, because DENM messages are a few senders and last for a limited time, the downlink channel is only temporarily and partially used. Research shows that LTE transmission of event messages is feasible [20][36][45].
When the downlink adopts broadcast technology transmission, the whole broadcast area is addressed at the same time, allowing single cell transmission or multi cell simultaneous transmission. Calabuig et al. researched shows that at CAM 10 Hz, when the number of vehicles in a single cell increases to more than 60, the broadcast mode begins to be better than the unicast mode [43]. Kato et al. researched shows that LTE networks can support the requirements of up to 300 vehicles using eMBMS broadcasting [3][44]. However, there are several problems with the downlink broadcast technology. Due to the high latency of eMBMS joining and leaving multicast services, the latency is difficult to meet the requirements of V2X applications [45]; Because the V2V broadcast area of the vehicle is small, variable and overlapping, while the eMBMS broadcast area is a large and fixed broadcast area, the two broadcast areas do not match [3][21][38]. A number of research programs have been carried out to solve the broadcasting problem. ETSI solves the problem of large-area broadcasting area with the help of a dedicated back-end server supporting geographic broadcasting [21]. Through mobile edge computing, the core network function of eMBMS can be closer to or even juxtaposed in the base station, or the user plane of the core network function of eMBMS can be closer to or even juxtaposed in the base station to reduce the broadcast latency [45][46]. However, these solutions have great changes to the existing wireless network technology and are difficult to implement. On the other hand, there are few commercial deployments of eMBMS, and the implementation cost of V2X is high.

Based on the existing research, although some progress has been made in congestion, the problem has not been solved.

### 3.3 The problem of system architecture

3GPP defines C-V2X architecture based on LTE and NR architecture, and adds functional entities such as V2X Application Server. For RSU, 3GPP further gives two implementation options. The first is UE-type RSU. UE-type RSU equipment includes UE and V2X application function logic, and communicates with V2X on-board terminal based on PC5 interface. This is the mainstream type of RSU. The other is NB-type RSU. NB-type RSU has two types: eNB-type RSU including eNodeB, shared L-GW and V2X Application Server defined based on LTE network and gNB-type RSU (including gNodeB, shared UPF and V2X Application Server) defined based on NR network (Figure 2) [14][15].

For V2X Application Server, Wang et al. proposed a four layer architecture based on MEC to support C-V2X system, including central cloud layer, edge computing platform layer, roadside equipment layer and user equipment layer. The edge computing platform collects vehicle, pedestrian and other related information through roadside devices such as RSU and base station, and provides the operating environment and core capabilities for V2X Application server and edge applications deployed on it [47]. Moubayed et al. studied the optimal V2X Service Placement Based on MEC and node computing resource availability [48]. Li et al. proposed a Cloud Control System (CCS) based on Intelligent Connected Vehicle (ICV) and V2X, and introduced edge cloud. Edge cloud collects the status information of roads and participating objects from roadside communication devices and sensing devices, and is responsible for providing basic services to enhance safety and energy efficiency [49].

For RSU, Liu et al. studied to add RSU function to 5G gNodeB based on the requirements of 3GPP gNB-type RSU, so that gNodeB supports both Uu interface and PC5 interface, so as to realize the functional integration of 5G gNodeB and RSU, common site deployment and unified operation and maintenance [50].

Based on the existing research, V2X Application Server has been fully studied on reducing communication latency and providing V2X applications based on MEC platform. The integration of RSU and NodeB based on Uu Interface can realize the sharing of resources between RSU and NodeB and reduce the cost. However, NodeB supports PC5 interface and V2X application layer functions, which has a great impact on the system architecture and is difficult to implement. The architecture of UC-V2X solution needs to be further studied.
3. System Design

3.1 V2X Levels of Capability

SAE divided autonomous driving into six levels based on automation capability [51], which grade autonomous driving applications and autonomous driving vehicles. V2X is a similar complex systems. We use a similar method to divide V2X into six levels based on core capability of ultra-reliability and low latency (URLL).

| V2X Level | E2E Latency (ms) | Reliability (%) | Typical V2X Application |
|-----------|-----------------|-----------------|-------------------------|
| L0        | > 100           | < 90%           | Speed Limit Warning     |
| L1        | ≤ 100           | ≥ 90%           | Forward Collision Warning|
| L2        | ≤ 50            | ≥ 99%           | Cooperative Vehicle Merge|
| L3        | ≤ 20            | ≥ 99.9%         | Autonomous parking      |
| L4        | ≤ 10            | ≥ 99.99%        | Cooperative collision avoidance|
| L5        | ≤ 3             | ≥ 99.999%       | Emergency trajectory alignment|

The development of V2X applications can be roughly divided into two stages. In the first stage, V2X application is mainly for auxiliary driving scenarios, and provides various auxiliary warning applications for drivers through broadcasting. The URLL requirements of V2X applications in the first stage are basically same [4][5][6][7]. Levels of typical V2X applications are as follows.

| Application | Type          | E2E latency (ms) | Reliability (%) | V2X Level |
|-------------|---------------|-----------------|-----------------|-----------|
| Speed Limit Warning | I2V            | 500             | 90%             | L0        |
| In-Vehicle Signage   | I2V            | 500             | 90%             | L0        |
| Green Light Optimal Speed Advisory | I2V            | 200             | 90%             | L0        |
| Lane Change Warning | V2V            | 100             | 90%             | L1        |
| Do Not Pass Warning  | V2V            | 100             | 90%             | L1        |
| Intersection Collision Warning | V2V/I2V | 100             | 90%             | L1        |
| Left Turn Assistant  | V2V/I2V       | 100             | 90%             | L1        |
| Emergency Vehicle Warning | V2V/I2V | 100             | 90%             | L1        |
| VRU Collision Warning | V2P/I2V | 100             | 90%             | L1        |
| Emergency Brake Warning | V2V            | 100             | 90%             | L1        |
| Control Lost Warning  | V2V            | 100             | 90%             | L1        |
| Abnormal Vehicle Warning | V2V            | 100             | 90%             | L1        |
| Red Light Violation Warning | I2V | 100             | 90%             | L1        |
| Hazardous Location Warning | I2V | 100             | 90%             | L1        |
| Forward Collision Warning | V2V | 100             | 90%             | L1        |
| Pre-crash sensing warning (ETSI) | V2V | 50              | 90%             | L2        |
| Pre-crash Sensing Warning (DOT) | V2V  | 20              | 95%             | L3        |

It can be seen that the V2X application in the first stage mainly belongs to L1. In particular, for pre-crash sensing warning applications, the latency defined in ETSI standard is 50 ms [5], which belongs to L2. The latency defined by the U.S. Department of Transportation is 20 ms [4], which belongs to L3. However, the C-SAE standard is not defined and can be replaced by a similar forward collision warning application (L1).

The V2X application in the second stage is mainly for autonomous driving scenarios, providing collaborative perception, planning and control capabilities for advanced autonomous driving. Since the V2X application in the second stage is still developing, there are differences in the definition of URLL indicators in various standards. Levels of typical V2X applications are as follows [9][10][11].

| Application | Type          | E2E latency (ms) | Reliability (%) | V2X Level |
|-------------|---------------|-----------------|-----------------|-----------|
| Information sharing for automated driving[9] | V2V/V2I | 100             |                | L1        |
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Sensor Data Sharing[10] V2V/V2I 100 L1
Collaborative perception[11] V2V/I2V 100 L1
Cooperative Vehicle Merge[10] I2V 50 L2
Cooperative Intersection Passing[10] I2V 50 L2
Cooperative Lane Change[10] V2V/V2I 50 L2
Sensor information sharing[9] V2V 50 99 L2
Video sharing (Extended Sensors) [9] V2V 50 90 L2
Cooperative Platooning Management[10] V2V/V2I 50 L2
Cooperative lane change[9] V2V 25 90 L3
Platooning information sharing[9] V2V/V2I 20 L3
Cooperative signal-less intersection[11] I2V 20 L3
Self-driving vehicle "out of trouble"[11] I2V 20 L3
Autonomous parking[11] I2V 20 L3
Cooperative lane change[9] V2V 10 99.99 L4
Cooperative collision avoidance[9] V2V 10 99.99 L4
Video sharing (Extended Sensors) [9] V2V 10 99.99 L4
Sensor information sharing[9] V2V 10 99.99 L4
Platooning information sharing[9] V2V 10 99.99 L4
Remote driving information exchange[9] V2V, V2S 5 99.999 L5
Emergency trajectory alignment[9] V2V 3 99.999 L5
Sensor information sharing[9] V2V 3 99.999 L5

It can be seen that V2X applications in the second stage mainly belong to L2 ~ L3 levels. Some V2X applications belong to L4 ~ L5 levels. For V2X applications of L4 ~ L5 levels, it has the following characteristics.

- Existing low-level implementations: For example, "Cooperative lane change", "Sensor information sharing", "Video sharing (Extended Sensors)" are defined by 3GPP. C-SAE standard has similar low-level implementations.
- Specifications under special conditions: For example, the "Remote driving information exchange" application defined by 3GPP is an index introduced at a speed of 250 km/h. In fact, "Remote driving information exchange" is mainly a low-speed scenario. If we reduce the speed (e.g. less than 80 km/h), we can reduce the level to L3. "Platooning information sharing" is an index when the headway of vehicles is 1 m and the speed is 100 km/h. From the existing research and verification, the headway can be increased by more than 4 m, and the level can be reduced to below L3.
- Specific application capabilities: For example, "emergency trajectory alignment" defined in 3GPP belongs to a special capability that is not applied

The latency and reliability indexes of different versions of 3GPP standard are different. We can grade the capability according to the indicators that UC-V2X network meets V2X applications. The following table is our recommended minimum requirements for UC-V2X network levels (PC-V2X network can be treated similarly).

**TABLE VI: V2X LEVEL OF UC-V2X NETWORK**

| V2X Level | Minimum Requirements of UC-V2X |
|-----------|------------------------------|
| L0        | LTE                          |
| L1        | LTE-A                        |
| L2        | LTE-A with MEC or 5G NR eMBB |
| L3        | 5G NR eMBB with MEC          |
| L4        | 5G NR uRLLC (UL and DL: 6 ms) with MEC(4 ms) |
| L5        | 5G NR uRLLC (UL and DL: 2 ms) with Embedded MEC(1 ms) |

Based on the above V2X application and UC-V2X network levels, we can see:

- L2 UC-V2X network can meet the requirements of V2X assisted driving.
- L3 UC-V2X network can meet the basic requirements of autonomous driving.
- L4 UC-V2X network can meet the needs of enhanced autonomous driving.
L5 UC-V2X network can meet the requirements of autonomous driving in special scenarios.

To sum up, UC-V2X network can be planned and implemented in stages in combination with 3GPP version evolution, deployment cost and other factors, as well as the progress of autonomous driving and V2X application requirements. This is a long-term development process. Therefore, UC-V2X can support URLL requirements of V2X applications.

### 3.2 System Architecture

For the V2N2V communication, considering the low latency capability of MEC, V2X Application Server is divided into two parts: real-time functions such as forwarding are deployed on the MEC platform, and non-real-time functions are deployed on the external cloud platform.

For V2N2I communication, we adopt NB-type RSU architecture. Since NB-type RSU provides RSU functions through L-GW/ UPF and V2X Application Server [14] [15], we can smoothly migrate L-GW/ UPF and V2X Application Server to MEC platform to form MEC based NB-type RSU. NB-type RSU communicates with on-board terminal through Uu interface, no longer retains PC5 interface. RSU becomes a software module deployed on MEC (Fig. 3).

![Fig. 3 MEC Based NB-Type RSU](image)

To sum up, the UC-V2X system architecture is adjusted as follows:

- The NB-type RSU based on MEC is integrated with the edge function of V2X Application Server to become a software V2X function deployed on the MEC platform. We call it ESU (Edge Side Unit).
- The cloud function part of V2X Application Server becomes the software V2X function deployed on the cloud platform. We call it CSU (Cloud Side Unit).
- V2X terminal (including vehicle terminal, pedestrian terminal, etc.) becomes a software V2X functional deployed on the UE platform. We call it USU (User Side Unit). The on-board soft terminal is USU-V; The pedestrian soft terminal is USU-P.
- CSU, ESU and USU are interconnected through open protocols such as TCP / IP. V2N2I application is completed through USU-ESU communication process; V2N2V application is completed through the communication process of USU-ESU-USU.

![Fig. 4 Architecture of SUC-V2X](image)
Since each V2X functional unit of the above UC-V2X system is a software module deployed on general computing platforms such as UE, MEC and cloud, we call it software defined UC-V2X (SUC-V2X) (Fig. 4). As a pure application system, SUC-V2X can directly inherit the development achievements of Mobile Internet.

3.3 Application Modes

V2V broadcast communication is the basic requirement of V2X applications. In the PC-V2X solution, each vehicle periodically broadcasts beacon messages to the surrounding within the wireless signal coverage (hundreds of meters). V2V receiver needs to filter out a large number of spam messages, which not only wastes a lot of wireless bandwidth, but also a lot of computing power.

In the SUC-V2X solution, based on the wireless base station, ESU collects more comprehensive traffic data in real time from vehicles, pedestrians, roadside infrastructure, etc. Relying on the powerful storage and computing capacity of the edge computing platform, ESU can make more detailed analysis. Therefore, ESU is the data aggregation and application control center of V2X, which brings new changes to V2X application.

V2X application is a service provided for vehicles and pedestrians in a specific area at a specific time through data transmission, which has obvious regionality and effectiveness. Different types of V2X applications have different transmission requirements, resulting in different traffic requirements. Combined with V2X application scenarios, V2X application modes can be divided into the following categories:

1) Event mode
V2X events refer to abnormal traffic objects (vehicles, roads, pedestrians, etc.) or traffic behaviors (low speed, retrograde, congestion, etc.), which have an impact on safety, efficiency, driving conditions, etc. Each event includes event type, event source, event location, event level, duration, propagation area and other information. Typical events include vehicle events (e.g. emergency brake, abnormal vehicle, and stationary vehicle), road events (e.g. hazard location, speed limit, and signal violation), etc.

There are two ways to generate V2X events: one is that the event is generated in the event source and then sent through DENM message in broadcasting (such as events: emergency brake, stationary vehicle, etc. [35]); One is that the CAM/BSM receiver generates local events according to the received message (such as emergency vehicle, slow vehicle, etc. [34]). For the first way, ESU analyzes the propagation area and duration of events according to received DENM messages, and then sends events to receivers. For the second way, ESU analyzes events according to received CAM/BSM messages, and then processes them according to the DENM event mode.

Based on data analysis capability in ESU, event filtering algorithm is introduced to filter a large number of unnecessary receivers according to the propagation area and duration of events. Because the event is targeted at specific traffic objects and lasts for a limited time, and is filtered based on ESU traffic, based on the existing research results, it is feasible for SUC-V2X solution to support V2X events.

2) Beacon mode
When the vehicle is driving, the local sensor generates a large amount of sensing data and operation data. V2X can only share part of the data. Based on the requirements of data integrity and real-time, collision avoidance (CA) applications need real-time analysis at vehicles. This category includes collision warning for assisted driving (e.g. forward collision warning, intersection collision warning, VRU collision warning, lane change warning, do not pass warning, left turn assistant) and awareness sharing for autonomous driving (for example: sensor data sharing, sensor information sharing, collaborative perception, planning information sharing).

According to the received CAM / BSM messages, ESU needs to send the received messages to vehicles that may cause collision except events. Collision risk is mainly caused by adjacent vehicles and decreases rapidly with distance. Therefore, ESU introduces a Risk Filtering Algorithm (RFA) to filter unnecessary receivers and reduce downlink traffic according to the propagation area and duration of risk. Based on the existing research results, ESU RFA algorithm is the key to support V2X beacon transmission in SUC-V2X solution.

3) Interactive mode
The application of intention negotiation and cooperative control between traffic objects requires point-to-point or point-to-multipoint interaction. This includes advanced autonomous driving applications such as remote driving, platooning and autonomous parking.

Such advanced autonomous driving applications often have fewer participants and short duration. Based on NR technology, SUC-V2X solution can effectively support interaction mode [54][55][56].

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3.4 Risk Filtering Algorithm

The research results of collision risk are relatively rich. Research methods include trajectory prediction, collision probability, collision time (time to x indicator), safety field and other methods [57][58][59][60][61][62][63]. These methods are mainly used to estimate whether potential collisions will occur or the probability of occurrence in certain scenarios. The problem to be solved is that ESU reduces unnecessary receivers to filter the downlink traffic by evaluating the collision risk for the specified vehicle under the condition that the data is incomplete and the scenario is uncertain. We first build the model for ESU collision risk.

In order to avoid collision risk omission as much as possible, we divide the collision risk into direct collision risk and indirect collision risk. Assuming that the host vehicle $h$ travels at speed $v$, and there is a risk space with radius $R$ centered on $h$ in the surrounding. The traffic objects set $O$ is composed of other vehicles, pedestrians, etc. in the risk space. Safety distance is a widely used method to measure the risk of vehicle collision. We call the collision between traffic objects around the host vehicle $h$ and the host vehicle $h$ as the direct collision of the host vehicle $h$. These traffic objects of the direct collision risk of the host vehicle $h$ are described by the set $S$:

$$S := \left\{ D_{ho}(t) < D_c \right\}$$

(1)

Here $D_{ho}(t)$ is the distance between $h$ and $o$ at time $t$; $T$ is the time range of collision risk investigation; $D_c$ is the critical safety distance of vehicle $h$, which is related to driver’s reaction time, vehicle state (speed, acceleration, etc.), vehicle behavior (following, lane changing, etc.), Lane state, weather and other factors.

We further investigate the collision of the traffic object $s \in S$ itself, which may cause risk to the host vehicle $h$. If the traffic object $s \in S$ collides with the traffic object in its surrounding, it is called the indirect collision of the host vehicle $h$. These traffic objects of the indirect collision risk of the host vehicle $h$ are described by the set $Q$:

$$Q := \bigcup_{s \in S} \left\{ D_{so}(t) < D_c \right\}$$

(2)

Considering the direct and indirect collision risks of the host vehicle $h$, the traffic object set $P$ with collision risk of the host vehicle $h$ can be described as

$$P = (S \cup Q)$$

(3)

It is difficult to accurately calculate the collision risk of each vehicle. In order to simplify the calculation, combined with the safety distance and lane isolation effect, the area formed by the driving lane of the host vehicle $h$ and the left and right adjacent lanes within the forward and backward critical safety distance is called the direct collision area of host vehicle $h$. We divide the risk space of host vehicle $h$ into three areas to describe (Figure 5):

- **Red Area**: the risk area of direct collision with the host vehicle $h$. We regard the collision area of the host vehicle $h$ as red area $A_R$. Based on the location of the traffic object, traffic objects in the Red Area are recognized as the set $O_R$. It can be proved that $S \equiv O_R$. We can use the set $O_R$ to replace the set $S$.
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- **Yellow Area**: the risk area of the indirect collision with the host vehicle $h$. After the collision areas of all traffic objects in the red area are superimposed, the yellow area $A_Y$ is formed after the Red Area is removed. Based on the location of the traffic object, traffic objects in the Yellow Area are recognized as the set $O_Y$. Similarly, we can use set $O_Y$ replaces set $Q$.
- **Green Area**: other risk area $A_G$ located outside the Yellow Area.

The traffic object set $P$ with collision risk of the host vehicle $h$ can be simplified as

$$P = (O_R \cup O_Y)$$  \hspace{1cm} (4)

We can quickly judge the collision risk by detecting whether the vehicle is in the collision area in combination with the HD map. The pseudo code of RFA algorithm is as follows.

**Algorithm 1. Pseudo-code of RFA**

Input: Host Vehicle: $V$, Set of Traffic Object: $O$, HD Map: $M$

Output: Objects in Red Area: $O_R$, Objects in Red Area: $O_Y$

1: function RiskFilterAlgo ($V, O, M, O_R, O_Y$)
2:     $A_R = \text{GetArea}(\text{GetPosition}(V), M)$
3:     $A_Y = \text{GetArea}(\text{GetPosition}(V), M)$
4:     for each $O_i$ in $O$
5:         if (LocationIn($\text{GetPosition}(O_i), A_R$))
6:             AddObjectToSet($O_i$, $O_R$)
7:         endif
8:     if (LocationIn($\text{GetPosition}(O_i), A_Y$))
9:         AddObjectToSet($O_i$, $O_Y$)
10:    endif
11: endfor
12: return $O_R$, $O_Y$
13: end function

Under normal network conditions, ESU sends all objects status in Red Area set $O_R$ and Yellow Area set $O_Y$ in downlink to meet various requirements of collision avoidance application. Under the condition of network congestion, ESU only sends all objects status in Red Area set $O_R$ to support the basic requirements of collision avoidance application.

Based on the above risk filtering algorithm, we roughly evaluate the maximum downlink traffic of ESU. In order to simplify, we use TTC and THW to judge the driving risk. Here we take $\text{TTC} = 3$ s and $\text{THW} = 1$ s. Take the critical safety distance $D$ for straight travel and lane change $D_c = vt_{TTC}$. Car following spacing $D_f = vt_{THW}$. Assuming that the beacon message size is $M = 300$ bytes, it is sent at the frequency of $f = 10$ Hz [64].

![Through Road Scenario for RFA](image)

**Fig. 6 Through Road Scenario for RFA**
1) Through lane driving scenario:
As shown in Figure 6, in the through lane, vehicles drive according to the maximum traffic density. Then Vehicles in the Red Area $N_R = 20$, Vehicles in Yellow Area $N_Y = 64$. Then the corresponding downlink flow of the Red Area: $8 \times N_R \times M \times f = 0.5$ Mbps; Combined flow in Red Area and Yellow Area: $8 \times (N_R + N_Y) \times M \times f = 1.5$ Mbps.

2) Intersection driving scenario:
As shown in Figure 7, at a two-way 10 Lane intersection, the host vehicle goes straight from north to south through the intersection. The driving of the host vehicle is processed according to the through lane driving scenario, while the vehicles is entering or has entered the intersection area are regarded as the Red Area in other directions. Due to the slow speed at the intersection, the scope of the Yellow Area has been appropriately reduced.

Then vehicle in the Red Area $N_R = 54$, vehicles in Yellow area $N_Y = 40$. Then downlink Red Area flow: $8 \times N_R \times M \times f = 1.3$ Mbps; Flow in Red Area and Yellow Area: $8 \times (N_R + N_Y) \times M \times f = 2.3$ Mbps.

Referring to the bandwidth performance indicators of LTE and NR networks, we believe that SUC-V2X can support beacon communication. For V2X events, a similar filtering algorithm can be constructed according to the propagation range and duration.

4. System Verification
There have been many verifications on the performance (latency, capacity, etc.) of LET and NR networks [25][30][31][32]. In order to verify the performance indicators of the SUC-V2X system based on LET and NR, we designed and developed a prototype system. The prototype system is installed in Upper Campus of the Chinese University of Hong Kong (Shenzhen). The system includes two intelligent and connected vehicles, two smart phones, LTE and NR wireless networks, as well as ESU and CSU servers (Fig. 8). Autonomous driving systems are installed on industrial computers of vehicles, connected through the USU-V terminal and CPE to the wireless network. The smartphone is based on Android, and the USU-P terminal is installed. The wireless network selects 4G and 5G eMBB commercial networks of operator A (China Unicom) and operator B (China Mobile). 4G network is LTE-A network. 5G network adopts 5G NSA network of R15 version. Due to the limitation of commercial network security, the edge computing platform cannot be used and the capacity limit cannot be tested. We deployed ESU and CSU on two Dell servers in the campus data center for latency test.
The verification site is a ring road of the campus. The total length of the ring road is about 1 km, with four intersections, two of which are equipped with signal lights. We deployed some typical V2X scenarios based on scenarios (Figure 9).

The verification scenario is that the intelligent and connected vehicle drives along the test route at the speed of 30 km/h. V2X terminals (USU-V and USU-P) connect to ESU through Uu interface and transmit messages based on COAP over UDP protocol. V2X terminal sends BSM or PSM messages periodically according to 10 Hz. After receiving the message, ESU selects the receiving terminal based on the risk filtering algorithm, combines the status of multiple terminals, and sends through RSM message (Figure 10).
Latency test includes RTT latency between USU and ESU through Ping, and E2E latency of message transmission based on USU-ESU-USU application layer. We tested the latency of LTE and NR commercial networks respectively.

The LTE network latency verification result based on operator A is shown in Figure 11. The average latency of Ping based RTT of ESU is 15.15 ms, and the end-to-end latency of V2X application layer is 76.08 ms. The latency occasionally exceeds 100 ms. Considering the V2X application reliability of L1 level, the requirement is not high (90%). Therefore, the LTE-A network of operator A can meet the requirements of V2X L1.

The NR network latency verification results based on operator A are shown in Figure 12. The average latency of Ping based RTT of ESU is 11 ms, and the end-to-end latency of V2X application layer is 36.34 ms. Therefore, the NR network of operator A can meet the requirements of V2X L2.
The NR network latency verification results based on operator B are shown in Figure 13. The average latency of Ping based RTT of ESU is 11.89 ms, and the end-to-end latency of V2X application layer is 40.2 ms. Since the ESU of the network is connected to the 5G core network through a dedicated line, the latency is more stable. It can be seen that the NR network of operator B can meet the requirements of V2X L2.

![Fig. 13 Latency of NR Network](image)

The field test results show that the commercial networks of operator A and operator B can meet the requirements of SUC-V2X system and support L1 and L2 V2X applications. If edge calculation is introduced, V2X level can be further improved.

5. Conclusions and Future Work

The development of V2X has been facing the challenge of industrialization. Based on the new opportunities brought by the development of 5G and autonomous driving, we need to re-examine C-V2X. Aiming at the problems of the UC-V2X solution, this paper sorts out the V2X application communication mode through the V2X levels, introduces the risk filtering algorithm, and proposes the SUC-V2X solution, which opens up a new path for the development of V2X. The SUC-V2X solution brings the following values:

- Reuse the existing wireless spectrum and chips, reuse the existing Mobile Internet industry ecology, and lower the technical threshold of industrialization.
- Reuse existing wireless network infrastructure, reduce network deployment costs, and support rapid implementation of V2X.
- Reuse existing mobile terminals and application ecosystems, and rapidly increase V2X penetration through software upgrades and other methods.
- Reuse the existing mature business model of the mobile Internet.
- Quickly support the development of existing L2/L3 autonomous driving, and provide a foundation for the development of NR networks and the deployment of uRLL networks.

SUC-V2X is a complex system. This paper preliminarily analyzes and constructs the risk filtering algorithm. More efficient and comprehensive risk filtering algorithm and event filtering algorithm need to be further studied. The performance and scenario verification of SUC-V2X is a long-term process. This paper only gives preliminary verification, and more scenarios need to be launched to promote the implementation of V2X industrialization.

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