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Fuzzy Logic-based Resource Allocation Algorithm for V2X Communications in 5G Cellular Networks

Minglong Zhang, Yi Dou, Peter Han Joo Chong, Henry C. B. Chan and Boon-Chong Seet

***Abstract*—In this paper, we spotlight vehicle-to-everything (V2X) communications in 5G cellular networks. Cellular V2X (C-V2X) communications in 5G enable more advanced services with requirements of ultra-low latency and ultra-high reliability. How to make full use of the limited physical-layer resources is a key determinant to guarantee the quality of service (QoS). Therefore, resource allocation plays an essential role in exchanging information between vehicles, infrastructure, and other devices. In order to intelligently and reasonably allocate resources, a self-adaptive fuzzy logic-based strategy is developed in this paper. To evaluate the network performance for this adaptive strategy, a system model for V2X communications is built for urban areas, and typical safety and non-safety services are deployed in the network. Simulation results reveal that the proposed fuzzy logic-based algorithm can substantially improve resource utilization and satisfy the requirements of V2X services, compared with prior counterparts, which cannot provide guaranteed services due to low resource utilization.**

***Index Terms*—5G, resource allocation, V2X communications, fuzzy logic, vehicular networks.**

I. INTRODUCTION

Vehicle-to-everything (V2X) communications in 5G cellular networks have drawn considerable attention in recent years. Differing from V2X communications supported in dedicated short range communications (DSRC), cellular V2X (C-V2X) communications in 5G enables more advanced services as defined in the latest specification of the Third Generation Partnership Project (3GPP). Those services, on the one hand, fulfil more useful functions visualized in intelligent transportation systems (ITS); on the other hand, however, consume considerably more spectrum and time resources, as well as having more stringent requirements. The latest Release 16, published by 3GPP, has specified four types of enhanced V2X (eV2X) services [1], including extended sensors, vehicle platooning, advanced driving and remote driving. In conjunction with the 27 basic use cases as specified in Release 14 [2], the enhanced use cases seek to minimize traffic accidents, improve road and vehicle utilization and provide infotainment in ITS.

At the physical layer, C-V2X in 5G adopts single-carrier frequency-division multiple access (SC-FDMA) and supports 20 MHz or 10 MHz channel width at the 5.9 GHz band. A channel is divided into subframes in the time dimension and into subchannels in the frequency dimension. A subchannel comprises multiple consecutive resource blocks (RBs) in the same subframe. Each RB is 180 KHz wide in frequency and is made up of 12 subcarriers of 15 KHz each. One RB is the smallest unit of frequency resources that can be assigned to vehicles. The number of RBs in a subchannel is configurable. Data are transmitted over a certain number of subchannels in the physical sidelink shared channel (PSSCH), while the sidelink control information (SCI) that stores the modulation and coding scheme (MCS) used for decoding at the receivers is sent over the physical sidelink control channel (PSCCH). The number of engaged subchannels for transmission is set up by the size of data to be transmitted. Fig. 1 shows the structure of two-dimensional time-frequency resource pool.

The 5G V2X (i.e., similar to cellular V2X, or C-V2X) has two separate radio interfaces. The *uU* interface is a cellular interface for supporting vehicle-to-infrastructure (i.e., vehicle to a base station or eNB) communications via uplink/downlink, while the other one called *PC5* interface is for providing direct V2X communications between vehicles and other user equipment (UEs) via sidelink. Four different work modes are specified for C-V2X in the 5G standard [3]. However, only mode 3 and mode 4 can support Ultra-Reliable Low-Latency Communications (URLLC), according to their different resource reservation approaches. When vehicles are out of the coverage of base stations, they usually switch to mode 4 and select time and spectrum resources autonomously using a sensing-based semipersistent scheduling (SPS) scheme. In contrast, if vehicles fall into the communication range of base stations, they work in mode 3, where there are two options for resource allocation. The resources are either managed and allocated dynamically by base stations or reserved via the SPS scheme.

Many prior studies involving physical resource allocation focus on transmission scheduling and resource reservation for mode 4, and the significance of the dynamic resource allocation method in mode 3 is underestimated. However, the vast majority of vehicles are used in urban areas, where a huge amount of information is exchanged among different UEs. Although the SPS-based scheme shows flexibility due to its distributed working manner, dynamic resource allocation, as one of the candidates in mode 3, also has great potential to exploit resources more effectively and ensure QoS, especially when confronting the stringent requirements of the eV2X services. In this paper, we explore using fuzzy logic, which is one of the important components in machine learning, to deal with the problems arising in dynamic resource allocation in mode 3, as well as to enhance network performance in 5G C-V2X.

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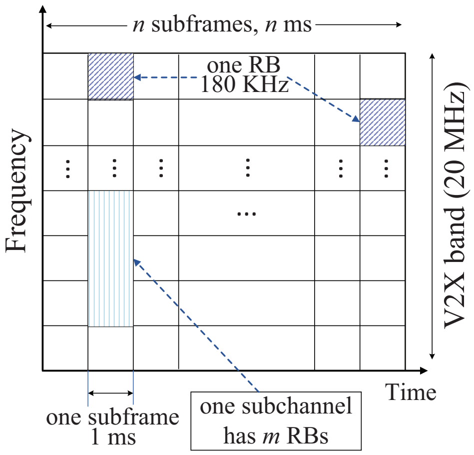


Fig. 1: Two-dimensional (time and frequency) resource pool for 5G sidelink

Since the working mechanism of fuzzy logic resembles the human brain, it plays an important role in machine learning. Recent advances show the adoption of fuzzy logic in machine learning. The study in [4] proposed a protocol for data storage in vehicular networks. The protocol employs fuzzy logic to make decisions on carrier node selection and uses Q-learning to evaluate long-term efficiency. In paper [5], fuzzy logic and machine learning interwork for the Internet of things (IoT) resource ranking. Fuzzy logic is applied to address uncertainties in the definition of ideal weights for QoS attributes, while supervised machine learning is responsible for the classification of resources.

This study is an extension work of [6]. The key contributions are as follows: 1) A fuzzy logic-based resources allocation algorithm, named FUZZRA, is proposed to fully utilize the physical-layer resources and maximize the reuse of limited resources without causing evident interference; 2) The FUZZRA is a self-adaptive scheme, meaning it can automatically adjust the parameters in the process of fuzzification by tracking the instantaneous status of the network, thereby maintaining the best possible performance at all times; 3) A cellular V2X network in urban areas is studied and a network-level simulation model is built using NS-3 based on a traffic and road model in SUMO [7]; 4) Typical basic V2X and eV2X services, including both safety and non-safety services, are deployed in the network and the network performance is evaluated.

The remainder of this paper is organized as follows. Section II reviews the related works on resource allocation in C-V2X. Section III elaborates on the system model and the typical services deployed in the model. Section IV proposes a resource allocation scheme based on fuzzy logic. Section V evaluates the network performance and compares its performance with some benchmarks. Finally, Section VI concludes the paper and outlines the future work.

II. RELATED WORK

[**Response 7**] Two resource allocation schemes have been proposed in [6]. The first one is a simple dynamic allocation scheme (i.e., the naive scheme) based on a random selection of subchannels and subframes for each request. The other one is a location-aware resource allocation scheme (LARA). The key idea of the LARA is to allow limited number of concurrent links in the network while avoiding much interference at recipients. These two schemes can achieve an almost 100% packet delivery ratio, when inter-cell interference is not considered, because the intra-cell interference is diminished as much as possible. For example, in the randomly assigning method, two or more simultaneous broadcasts are not allowed, while in the LARA, the distance between any two concurrent transmitting nodes is far enough, thus not causing too much interference. However, the two approaches are not able to guarantee the QoS, because a considerable portion of requests has been declined (especially in a dense network), which implies those UEs cannot exchange information with their peers.

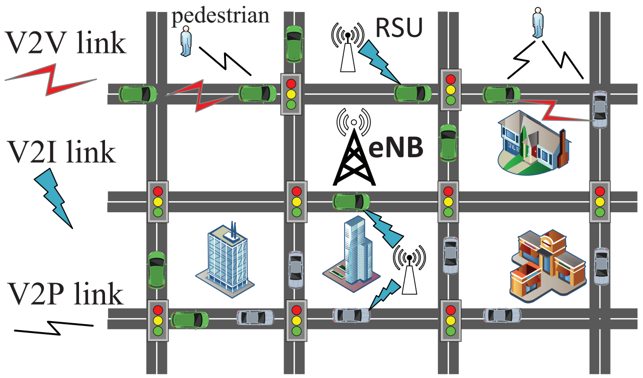


Fig. 2: [**Response 15**] V2X communications in a 5G cellular network in urban areas: the eNB communicates with different UEs (e.g., vehicles, RSUs and pedestrians) via uplink/downlink. The V2X communications contains V2V link, V2I link (vehicle or pedestrian to RSU) and V2P link. Safety services can be provided via V2V and V2P link, while infotainment and traffic status updating can be carried out via V2I link.

The study in [8] identified the inefficiency of the SPS scheme in subchannel reselection due to the size difference between two packets in two consecutive selections. Based on the findings, a modification to the original SPS was proposed to make full use of subchannels. Nardini *et. al* [9] considered feasibility and evaluated the system-level performance of two dynamic scheduling schemes: a sequential scheme resembling TDMA and a simultaneous transmission scheme with frequency reuse for a platooning application, which is a typical cooperative driving use case envisioned in C-V2X. However, the authors only considered the platooning application in their simulations, and network-level performance is unknown if more applications are employed in networks. Through extensive simulations, the study revealed how the resource allocation in mode 4 affects key performance indicators, such as latency and packet delivery rate in high-density vehicular networks [10]. Modeling C-V2X was also provided mathematically. As a case in point, the authors of [11] quantified four transmission errors and provided packet delivery ratio (PDR) against distance in mode 4. To maximize the number of concurrent V2V links, a belief propagation-based algorithm was developed to allocate RBs for vehicles [12]. Unfortunately, the algorithm only works for a simplified situation of V2V using the unicast case.

[**Response 8**] Nonorthogonal multiple access is introduced in V2X networks where unicast V2V, multicast V2V and V2I communications are considered and spectrum resources are reused [13]. In the paper, an interference hypergraph to model the complicated interference is constructed and a resource block assignment method is obtained using a cluster coloring algorithm. The paper [14] proposes a resource scheduling for platooning in a multi-cell system, but its performance for other V2X scenarios other than platooning is unknown. Based upon an assumption that both cellular users and vehicular users share the same RBs, two different schemes are presented in [15] and [16]. In [15], dynamic resource pricing is made, and a cooperative resource sharing algorithm makes two user groups jointly purchase and share resources. In [16], a joint solution to power control and sub-carrier assignment is proposed for uplink, downlink and vehicular link. The solution can maximize the number of vehicular links while satisfying the QoS for cellular users. However, the latest standard allows V2X via sidelink to utilize a separate frequency band rather than sharing the same frequency with cellular users. Paper [17] studied V2X at smart intersections, and a semi-persistent-based scheduling method is proposed to avoid resource collision by using RSU's sensing information. However, the scheduling only works in mode 4 rather than mode 3. In [18], the authors considered how to determine V2V links and to allocate suitable channels to minimize total delivery latency. A greedy cellular-based V2V link selection algorithm is proposed to solve the problem. However, this work only suits the overlay scheme where the V2V links share the same resources with uplink/downlink, and may not work well for eV2X cases due to limited bandwidth.

Fuzzy logic was also employed for resource allocation in cellular networks. In [19], network resources, such as connections between Fog Computing-Zone Controllers and Fog Computing BBU Controllers in 5G VANETs are allocated in a flexible and scalable way. However, the fuzzy-logic-based strategy in this work cannot solve the problems in resource allocation in 5G C-V2X networks, because the research in [19] focuses on link connectivity between vehicles in the networks, rather than on allocation of spectrum and time resources. Wu *et. al* [20] proposed a fuzzy logic method to address the issues of interference coordination among cells, as well as resource allocation among the users served by the same cell. In the proposed fuzzy logic method, four factors are considered and fuzzified as inputs. These are required data rate, signal strength at reception, interference level and fading level. The outcome of the fuzzy system includes a three-state judgment (i.e., positive, neutral, and negative) for allocability and transmission power. Finally, a decision-making algorithm was used to allocate RBs to mobile stations (MSs) in the same cell in accord with the suitability scores obtained from the defuzzification. The proposed algorithm can improve the system throughput and allow the base stations of different small cells to work autonomously. However, the authors did not consider the interference between MSs associated with the pico-base station and MSs associated with the macro-base station. In addition, the algorithm cannot work on resource allocation in the circumstance of 5G C-V2X, where many services are based on broadcast rather than on the unicast communications between BS and mobile stations via downlink and uplink.

The authors in [21] investigated how to guarantee the quality of service in cellular V2X. A joint consideration of transmission mode selection (e.g., V2V or V2I communications), RB allocation and power control is undertaken. A deep reinforcement learning (DRL) algorithm is proposed to maximize the capacity of V2I (i.e., vehicle-to-base station) links. However, its model adopts a shared resource pool between V2I and V2V links, which is evidently different with 5G V2X communications, where V2V and V2I have separate spectrum bands and each VUE has two independent radio interfaces. The work in [22] tries to allocate resources to different UEs in 5G cellular networks through the advantage of a DRL-based algorithm. However, the research work considers time slots in uplink/downlink rather than two-dimensional time-frequency resources of sidelink. Therefore, the strategies for RA in the above studies are not suitable for allocating resources in 5G V2X communications.

III. System Model

A. System Model

In 5G vehicular networks, various UEs (e.g., vehicles, RSUs, smart devices and other smart devices) are provided with basic safety services, eV2X services and entertainment-related services at the same time. Our goal is to allocate resources for those UEs and satisfy the requirements, such as delivery latency, data rate and packet delivery rate.

Fig. 2 depicts the system model considered in this paper. In the model, different kinds of UEs associate with an eNB, and all of them form a cellular network in an urban area. Note that RSU can be viewed as a static UE. All UEs are within the coverage area of the eNB. Each RSU covers a region where it can communicate with other mobile UEs. UEs working in mode 3 are able to exchange information via sidelinks that consist of V2V, V2P and V2I links. The eNB, on the other hand, dynamically manages the resources. Whenever a UE disseminates a message, it should first apply for permission and physical resources by sending a request to the eNB via the uplink. When it receives a reply that indicates which physical resources (including both subframes and subchannels) in the pool have been reserved for the UE from the eNB via a downlink, the UE can commence transmission based on the resources dedicated by the eNB. In opposition, if the eNB cannot allocate resources for a request, the request will be rejected and the UE will terminate the transmission accordingly. In addition, for the sidelink radio interface PC5, we assume that it operates in a half-duplex mode, which means that UEs cannot send and receive data simultaneously via the sidelink due to high interference.

In the system model, we consider six typical services. To clearly reflect how various applications influence the performance of the C-V2X network, the elected services include

TABLE I: Type of services implemented in the V2X communications.

V2X Services	Message Type	Beacon Frequency	End-to-End Delay	Data Rate
Cooperative awareness (CAT1)	Periodic broadcast	100 ms	100 ms	5-100 Kbps
Cooperative manoeuvre (CAT2)	Periodic broadcast	10 ms	10 ms	2-5 Mbps
Cooperative sensing (CAT3)	Event-driven Broadcast	N/A	10 ms	10-25 Mbps
Dynamic traffic control and warning (CAT4)	Periodic broadcast	500 ms	500 ms	0.5-2 Mbps
Nonsafety non-real-time content (CAT5)	Non-periodic unicast	N/A	300-65535 ms	1-5 Mbps
Nonsafety real-time content (CAT6)	Non-periodic unicast	N/A	20 ms	5-10 Mbps

both safety as well as non-safety related services with distinct features among them. Table I shows their features and requirements.

As defined by the European Telecommunications Standards Institution (ETSI) [23], Cooperative Awareness Message (CAM) is a periodical message broadcast by all vehicles. Its main purpose is to create mutual awareness among vehicles in the same vicinity by interchanging their instant status information. It shares the same functionality of the basic safety message (BSM) in DSRC. The service of cooperative maneuver is for coordination in advanced driving, such as automatic platooning and assisted lane changing. Since it relates to the process of exchanging information in a fast-moving environment, a higher data rate and beacon frequency are required, compared with the CAM. Distinguished from the CAM and cooperative maneuvering, cooperative sensing refers to the extended sensors in eV2X. Vehicles start to transmit the data generated by the sensors rigged in them only when certain triggering events take place. In this case, a colossal amount of data is exchanged within a short time interval to prevent accidents. In our system model, we make a reasonable assumption that vehicles broadcast such types of data to prevent crashes only when they arrive at a junction, because the complicated traffic situations that can arise at intersections may result in latent hazards.

As far as dynamic traffic control and warning, messages are periodically broadcast by RSUs to notify vehicles of the current road conditions and traffic situations. Regarding the last two use cases, which are both non-safety related services, real-time content is widely used in applications of social media and entertainment, such as audio-visual online chat and video streaming via the Internet, while non-real-time content is demanded by data downloading and uploading, such as sending/receiving emails, and advertisement broadcasting. For ease of discussion in the following sections, we use CAT1, CAT2, ... , CAT6 to denote six services that will be deployed in our system model, as marked in Table I.

B. *Performance Metrics*

[Response 1]

1) Successful transmission ratio (STR)

Successful transmission ratio is a ratio between the total number of transmissions and the total number of transmission requests over a period of time. Since every UE may send transmission requests to the eNB during this period, the eNB either allocates physical resources to the UE or declines the requests, depending on whether resources can be found by the allocation strategy. Therefore, it indicates how many transmissions can be accommodated by the network. Let N_{UE} denote the total number of UEs in the cellular network, $N_{rq}(i)$ denotes the total number of requests made by UE(i), and $N_{tx}(i)$ denotes the number of transmissions from UE(i), then the STR is defined as follows

$$STR = \frac{\Sigma_{i=1}^{N_{UE}} N_{tx}(i)}{\Sigma_{i=1}^{N_{UE}} N_{rq}(i)} \tag{1}$$

2) Packet delivery ratio (PDR)

Usually packet reception within the transmission range of a transmitter is guaranteed. However, due to cochannel interference caused by subchannel reuse, the PDR may be affected. For a recipient UE i that associates with a transmission j, we define

$$I_{UE}(i,j) = \begin{cases} 1, & \text{if the UE } i \text{ receives the packet,} \\ 0, & \text{others.} \end{cases} \tag{2}$$

Assuming that there are N_{tx_bt} broadcast transmissions and N_{tx_ut} unicast transmissions, the packet delivery ratio is defined as

$$PDR = \frac{\Sigma_{j=1}^{N_{tx\_bt}} \Sigma_{i=1}^{R_{UE}(j)} I_{UE}(i,j) + \Sigma_{i=1}^{N_{tx\_ut}} I_{UE}(i)}{\Sigma_{j=1}^{N_{tx\_bt}} R_{UE}(j) + N_{tx\_ut}} \tag{3}$$

where $R_{UE}(j)$ means the number of the recipients within the range of a broadcast transmission j. The number of recipients for a unicast transmission is always one.

3) Network throughput

Regarding network throughput, it is the sum of each UE's throughput over all UEs in the network. Let $\chi(i)$ denote total number of packets received by UE i, and $L_p(k)$ denote the length of packet k in bits, we have

$$TH_N = \frac{\Sigma_i \Sigma_{k=1}^{\chi(i)} L_p(k)}{T} \tag{4}$$

where T is the consumed time for accomplishing all scheduled transmissions and receptions.

IV. A FUZZY LOGIC-BASED RESOURCE ALLOCATION SCHEME FOR 5G V2X

A. *A self-adaptive fuzzy logic-based algorithm for Resource Allocation*

1) *Overview of the algorithm*

The proposed fuzzy-logic based resource allocation (FUZZRA) specifies the best choice of resources for sidelink transmissions in a cellular network and maximizes the reuse of resources, thus improving network performance. Fig. 3 presents the schematic diagram of the algorithm.

The core of the algorithm is the *fuzzy logic modules* that process the input information and output crisp values

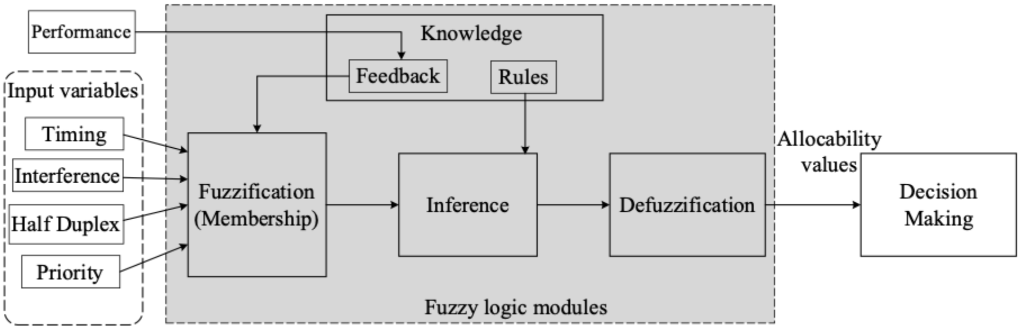


Fig. 3: Diagram of FUZZRA algorithm.

indicating allocability of certain resources. The input variables are actually four factors (i.e., timing, interference, half-duplex and service priority) that will assess the suitability of the resources for a transmitter. The definition of those factors will be discussed as follows. Upon reception of a request from a UE, the four corresponding factors will be fuzzified by the membership functions that convert single-valued inputs into the values of a fuzzy set. The fuzzy values will be judged in the inference module according to predefined rules. Finally, the judgment that stands for the extent of a verdict will be defuzzified and numerical values showing allocability will be yielded for decision making. Furthermore, the real-time network performance, which also acts as knowledge, is fed back to the fuzzification module as a critical principle in adjusting the parameters of the membership functions. In this study, according to the feature of the inputs, the coefficients of the membership functions of the interference factor and the half-duplex factor can be adjusted, while the priority of provided services in the network can also be reconfigured accordingly. Noticeably, before each sidelink transmission, the sender should first send a request message that contains the information on its current location and packet reception during the last transmission period.

2) *Considered factors*

I. Timing factor

This factor shows how urgently a message will be sent. The higher the value, the less the time left for transmission. Different types of messages have different requirements on data rate, i.e., transmission period. This factor is defined based on the observation that different applications in V2X have different requirements for data rate. A message can be transmitted at any subframe (i.e., time) but should be within the right transmission period, in order to obviate a large delay.

Assume the transmission period for a certain type of message is P (i.e., P milliseconds or P subframes), the timing factor is calculated by:

$$T(w) = \frac{w}{P}, 1 \leq w \leq P \tag{5}$$

where w is the sequential number of the current subframe in the whole transmission period P and it must be a positive integer. For example, if a transmission being currently scheduled situates in the i^{th} subframe, then we let $w = i$. The w can only increase one at a time if the current subframe does not work for the transmission. This can be deemed as an adjournment. The values of P for different services can be obtained according to beacon frequency in Table I.

II. Interference factor

Identical subchannels may be dedicated to multiple UEs at the same time, in order to improve spectrum efficiency. This will surely cause interference to the recipient nodes due to simultaneous transmissions. To accurately assess the influence on a scheduling transmission, real-time SINR should be considered. However, among all service types, a substantial proportion are involved in broadcasting, according to our system model and the reality of C-V2X networks. Apparently, a real-time update of SINR would pose a great network burden. Fortunately, by adopting the fuzzy concept, we can estimate the interference level according to the distance between transmitters without feeding back the SINR.

Typically, the received power P_r for the unobstructed scenario is

$$P_r = P_t \left(\frac{\sqrt{G_l}\lambda}{4\pi d} \right)^2 \tag{6}$$

where P_t is the transmitted power, G_l is the antenna gain, λ is the wave length, and d is the distance between transmitter and receiver, according to Friis path loss model. The Friis model is restricted to an unobstructed clear path between the transmitter and receiver. To encompass random shadowing effects due to signal blockage by objects such as vehicles, trees, buildings, etc., we usually adopt a logarithmic-distance path loss model where the path loss PL is $PL = PL_0 + 10\gamma log_{10}(d/d_0) + \chi$. In the equation, PL_0 is the path loss at the reference distance d_0, γ is the path loss exponent, χ is a zero-mean Gaussian distributed random variable. The equivalent non-logarithmic gain model is

$$\frac{P_r}{P_t} = d_0^{\gamma} 10^{-\frac{PL_0+\chi}{10}} \frac{1}{d^{\gamma}} \tag{7}$$

Assuming that all vehicle UEs have the same transmission power, the received power is inversely proportional to the distance. That is, $P_r \propto d^{-\gamma}$ and γ depends on channel model. According to [23], the value of γ should range from 2.7 to 3.5 in urban areas, so we take $\gamma = 3$ in the definition of the interference factor.

Let R denote the transmission radius of the vehicle and d_i is the distance between a transmitter and the i^{th} interfering node, if there are m transmitters that can cause interference, the interference factor can be defined as follows:

$$I(d_1, d_2, ..., d_m) = \begin{cases} +\infty, \forall d_i \leq R \\ \frac{\Sigma_{i=1}^{m} \frac{1}{(d_i-R)^3}}{\frac{1}{R^3}} = \Sigma_{i=1}^{m} \frac{R^3}{(d_i-R)^3}, d_i > R \end{cases} \tag{8}$$

The above formula reflects the relative strength between the interference and the receiving signal. A larger value of $I(d_1, d_2, ..., d_m)$ suggests stronger interference is impacting the receivers. For instance, if there is an interfering node within the transmission range of a node (i.e., $d_i \leq R$) that is broadcasting, a considerable percentage of the receiving nodes may experience failure in reception due to high interference levels. In contrast, if the interfering node is far away from the sender, only the nodes located within the overlapped area (if applicable) cannot receive the data.

III. Half-duplex radio factor

The half-duplex problem means a UE cannot receive data while transmitting at the same time, even via different channels. This is confined by the attribute of the half-duplex radio. In V2X communications, if two UEs within each other's communication range broadcast concurrently in different subchannels, vehicles around them can receive information from both, as the interference between two subchannels is negligible. However, in this situation the two sending nodes cannot have mutual reception. We call this a half-duplex problem, or mutual reception problem. Such a situation diverges from the original desire of certain applications, such as mutual awareness in CAM. On the other hand, if one vehicle lies outside the broadcast range of another vehicle and they don't share the same resources, vehicles located in the overlapped area of two vehicles can receive messages from both vehicles, which in turn enhances road safety. Like interference factors, the mutual reception factor is up to the received power and the distance between transmitters. Its definition is

$$M(d_{min}) = \begin{cases} 1, \forall d_{min} \leq R \\ \frac{\frac{1}{d_{min}^3}}{\frac{1}{R^3}} = \frac{R^3}{d_{min}^3}, d_{min} > R \end{cases} \tag{9}$$

where $d_{min} = min(d_1, d_2, ..., d_n)$ represents the smallest distance between one currently sending node and n other sending nodes. From 0 to 1, the closer the value of $M(d_{min})$ to 1, the larger the probability of suffering the half-duplex problem will be.

IV. Service priority factor

[**Response 2**] As described in the 5G standard, different types of services have different priority levels. According to [24], safety-related services have higher priority than non-safety related services, because the foremost and most important purpose of ITS is to ensure road safety. In addition, the two eV2X services (cooperative maneuver and cooperative sensing) have higher reliability requirements than that of the two basic safety services. Thus, we prioritize the two eV2X services at the highest level, and non-safety services at the lowest level. When resources are limited and excessive UEs contend for transmission, high-priority services are superior to low-priority ones and are supposed to take priority, to obtain resources. In our system model, there is a total of six types of services coexisting in the network. The priority factor is demonstrated in Table II.

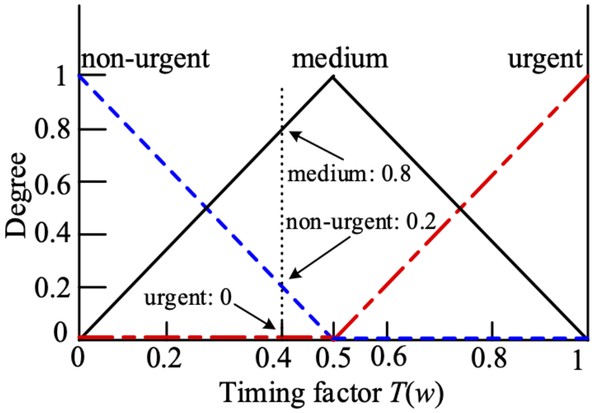


Fig. 4: Timing membership function and a fuzzification example.

TABLE II: Priority factor.

Service Type	Priority
Cooperative manoeuvre (CAT2) Cooperative sensing (CAT3)	High
Cooperative awareness (CAT1) Dynamic traffic Control and warning (CAT4)	Medium
Non-safety non-real-time content (CAT5) Non-safety real-time content (CAT6)	Low

Remarkably, the above specification is not always fixed. The FUZZRA can adjust the priority of a service according to the dynamics of a network. When the transmission requests for a certain service with lower priority are largely more than those of another service with higher priority, its original priority can be promoted, for the purpose of avoiding resource waste. Such an adaptive strategy is based on the observation that transmissions for certain services, such as CAT3 and CAT6, take place intermittently, or some services can even be disabled temporarily. In such a situation, a dogmatic prioritization could incur large delays and low efficiency.

3) *Fuzzification*

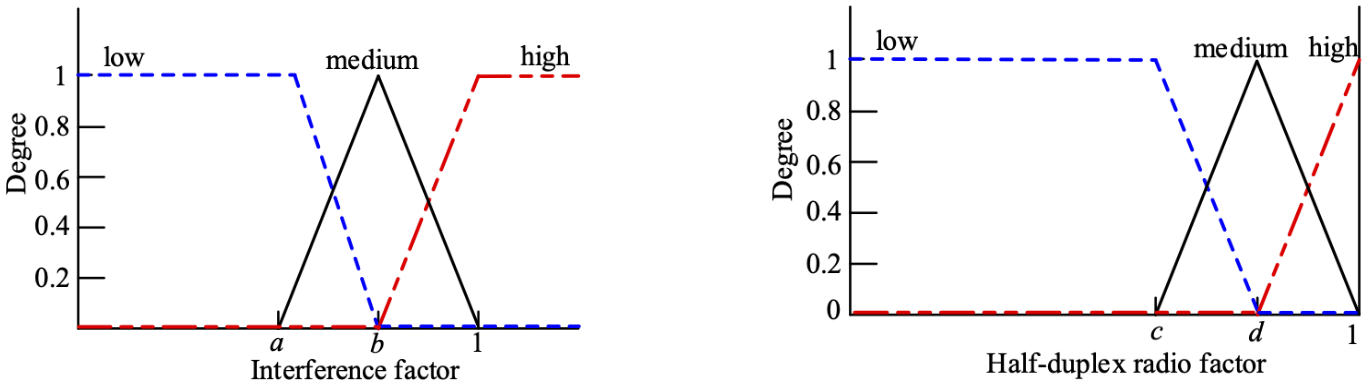
In the fuzzification module, numerical values of input factors are converted to fuzzy values using fuzzy membership functions.

By using predefined linguistic variables of non-urgent, medium and urgent, and their respective membership functions, the timing factor can be transformed into fuzzy value, as shown in Fig. 4 and equations from (10) to (11). For instance, when the timing factor is 0.4, a vertical line representing this timing factor meets with curves of "non-urgent", "medium" and "urgent" at (0.4, 0.2), (0.4, 0.8) and (0.4, 0), respectively. Therefore, the fuzzy values we obtained are {non-urgent: 0.2, medium: 0.8, urgent: 0}.

The mathematical expressions of the three membership functions for the timing factor are

- the non-urgent:

$$f_{tn}(x) = \begin{cases} -2x + 1, & x \in [0, 0.5], \\ 0, & x \in (0.5, 1] \end{cases} \tag{10}$$



(a)

(b)

Fig. 5: The membership functions for (a) the interference factor and (b) the half-duplex radio factor.

- the medium:

$$f_{tm}(x) = \begin{cases} 2x & x \in [0, 0.5], \\ -2x+2, & x \in (0.5, 1] \end{cases} \tag{11}$$

- and the urgent:

$$f_{tu}(x) = \begin{cases} 0 & x \in [0, 0.5], \\ 2x-1, & x \in (0.5, 1] \end{cases} \tag{12}$$

The membership function of the interference factor is illustrated in Fig. 5 (a). The functions of the curves in the figure are:

- the low interference:

$$f_{IL}(x) = \begin{cases} 1 & x \in [0, a], \\ \frac{x-b}{a-b}, & x \in (a, b] \\ 0, & x > b \end{cases} \tag{13}$$

- the medium interference:

$$f_{IM}(x) = \begin{cases} \frac{x-a}{b-a} & x \in (a, b], \\ \frac{x-1}{b-1}, & x \in (b, 1] \\ 0, & other, \end{cases} \tag{14}$$

- the high interference:

$$f_{IH}(x) = \begin{cases} 0 & x \in [0, b], \\ \frac{x-b}{1-b}, & x \in (b, 1] \\ 1, & x > 1 \end{cases} \tag{15}$$

In the above functions, the two parameters a and b are adjustable, in order to maximize the network throughput. More specifically, if a and b are tuned to be smaller, the degree of the interference factor will be inclined to enlarge the value of medium and high fuzzy values, thereby suppressing concurrent transmissions as well as alleviating interference. In opposition, a larger a and b can encourage more nodes to transmit simultaneously via the same resources, but making the network subject to higher interference levels. By making use of feedback from nodes in the cellular network, the FUZZRA can adjust both parameters to improve the spectrum efficiency and network throughput. The variables a and b are initialized to 0.4 and 0.7, respectively.

Similarly, the membership function for the half-duplex factor is defined in Fig. 5 (b), and the curves for low, medium and high cases are represented by (16), (17) and (18), respectively.

TABLE III: Rule base.

Rule	Timing	Interference /Half-duplex	Priority	Verdict
1	Non-urgent	Low	Low	Not Acceptable
2			Medium	Acceptable
3			High	Good
4	Non-urgent	Medium	Low	Bad
5			Medium	Not Acceptable
6			High	Acceptable
7	Non-urgent	High	Low	Bad
8			Medium	Bad
9			High	Not Acceptable
10	Medium	Low	Low	Acceptable
11			Medium	Good
12			High	Perfect
13	Medium	Medium	Low	Not Acceptable
14			Medium	Acceptable
15			High	Acceptable
16	Medium	High	Low	Bad
17			Medium	Bad
18			High	Not Acceptable
19	Urgent	Low	Low	Acceptable
20			Medium	Good
21			High	Perfect
22	Urgent	Medium	Low	Not Acceptable
23			Medium	Acceptable
24			High	Good
25	Urgent	High	Low	Bad
26			Medium	Bad
27			High	Not Acceptable

Again, both c and d can be adjusted, and their initial values are 0.5 and 0.7, respectively.

$$f_{ML}(x) = \begin{cases} 1 & x \in [0, c], \\ \frac{x-b}{c-b}, & x \in (c, d] \\ 0, & x > d \end{cases} \tag{16}$$

$$f_{MM}(x) = \begin{cases} \frac{x-c}{d-c}, & x \in (c, d], \\ \frac{x-1}{d-1}, & x \in (d, 1] \\ 0, & x \in [0, c], \end{cases} \tag{17}$$

$$f_{MH}(x) = \begin{cases} 0, & x \in [0, d], \\ \frac{x-d}{1-d}, & x \in (d, 1], \end{cases} \tag{18}$$

4) *Inference*

Once the fuzzy values of the factors are determined, the inference module will use IF/THEN rules to induce the verdict. The linguistic variables of the verdict are defined as {Perfect, Good, Acceptable, Not Acceptable, Bad}. The rules are listed

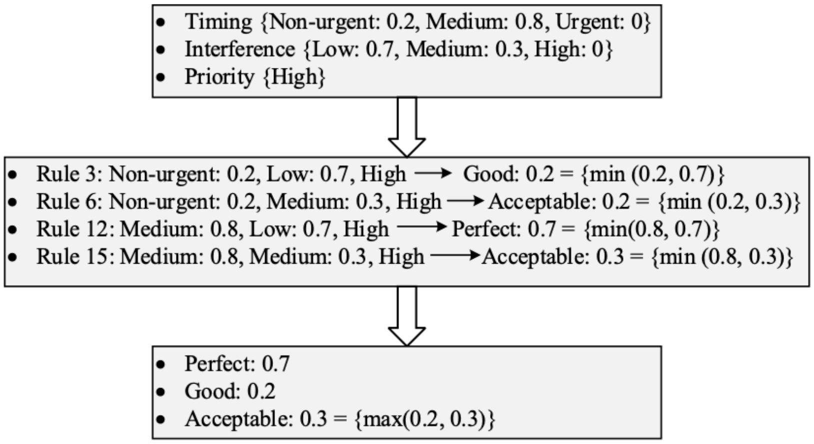


Fig. 6: An example of application of Min-Max principle in fuzzy rule evaluation.

in Table III. For example, in the table, Rule 5 can be expressed as follows.

IF *Timing* is Non-urgent, *Interference/Half-duplex* is Low, and *Priority* is High, **THEN** *Verdict* is Good.

In the table, interference and half-duplex radio factor are listed in the same column, because only one of them can appear at a time. That is, for resources being assigned to the current scheduling of transmission, those scheduled resources can cause either interference (i.e., with overlapped subchannels) or half-duplex radio (i.e., totally different subchannels) effect on the current ones.

Since there could be multiple rules being applied at the same time, the inference system adopts an unweighted Min-Max principle [1] to obtain the results. In principle, for each applied rule, the minimal value of the antecedent (i.e., the IF part) turns to be the final degree, while the maximal value of the consequent (i.e., the THEN part) is finally accepted when combining different rules.

To articulate how the Min-Max principle works, an example is included in Fig. 6. Suppose the degree of timing, interference and priority for a potential transmission are {Non-urgent: 0.2, Medium: 0.8, Urgent: 0}, {Low: 0.7, Medium: 0.3, High: 0} and {High}, respectively. In this case, these fuzzy values match the condition of rule 3, rule 6, rule 12 and rule 15. In rule 3, the degree for non-urgent timing is 0.2, for low interference, 0.7 and for service priority, high. According to the minimal principle, we take 0.2 for the final verdict of Good. Similarly, the fuzzy value of final verdicts from rule 6, rule 12 and rule 15 are 0.2 for Acceptable, 0.7 for Perfect and 0.3 for Acceptable, respectively. In the last stage, as both rule 6 and rule 15 lead to the verdict of Acceptable, according to the maximal principle, the largest value between the two consequents is confirmed as the final value for Acceptable.

5) *Defuzzification and Decision Making*

In defuzzification, the fuzzy values of verdicts are processed, and crisp values are produced based on an output membership function. There are different defuzzification methods with diverse characteristics and computation complexities. For example, according to the work [25], they are mainly categorized into two groups: maxima methods and distribution methods. In this study, we select the centroid method that calculates the center of the area or the center of gravity (COG), which belongs to the latter. The output membership function is defined in Fig. 7. To compute the output value, we first use output values from fuzzification to truncate the defuzzification functions in the figure, and then apply the disjunction principle to merge shapes and form a new shape. Finally, the following formula is utilized to calculate the x coordinate of the centroid of the shape, which is also the output of the entire fuzzification system.

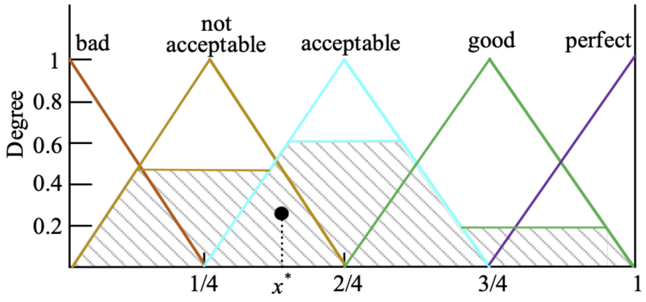


Fig. 7: Output membership function and the defuzzification method of COG.

$$x^* = \frac{\int x\mu_{\tilde{A}}(x)dx}{\int \mu_{\tilde{A}}(x)dx} \tag{19}$$

where $\mu_{\tilde{A}}(x)$ is the output membership function. In Fig. 7, an example is provided to show the mechanism of COG. Assume the degree for the verdict "bad" and "perfect" is zero, and for "not acceptable", "acceptable" and "good" it is 0.5, 0.6 and 0.2, respectively. After truncating the output membership function and applying disjunction on trapezoids, the geometric shape we obtained is the shadowed shape. By applying the equation (19), the final results of defuzzification can be obtained.

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[1] **[Response 11]** The unweighted principle means that the inference system treats all input factors fairly when inferring a verdict. However, in some systems, if one or more factors have a larger influence on the final decision, the weighted method may be adopted.

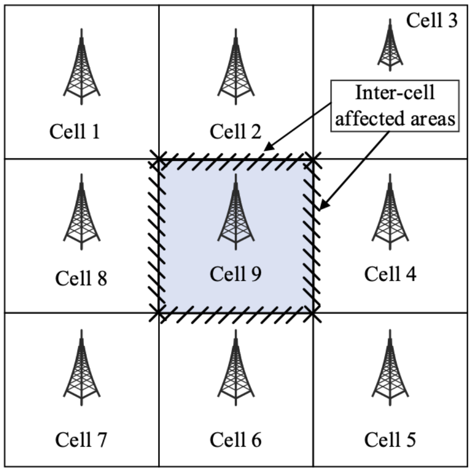


Fig. 8: Nine adjacent cells in the simulation model.

The *decision-making* module compares the output of the fuzzy system with a predefined threshold value. If it is larger than the threshold, resources will be dedicated to the requesting UE. Otherwise, other resources will be considered. If the FUZZRA cannot find appropriate resources for a request after searching the entire resource pool and the transmission time has expired, the eNB would decline the request and the transmission will not take place. As aforementioned, both the interference issue and the half-duplex issue are considered in the fuzzy system, two thresholds are predefined, and they correspond to the application of a different combination of antecedents in the rule base, i.e., applying timing factor, interference factor and priority factor or timing factor, half-duplex radio factor and priority factor.

6) *Key Features of the FUZZRA*

In order to improve the STR yet keep a high reception ratio, resources should be optimally dedicated to UEs in the cellular network. To achieve this aim, multiple factors should be considered at the same time in a resource allocation method. Otherwise, the allocation method cannot yield the best results. For example, channels are reused by multiple users in some wireless networks. That is, concurrent links are allowed. Notwithstanding, concurrent transmissions may cause severe interference, if not well arranged. As we know, the probability of the packet reception depends on the signal-to-interference-plus-noise ratio (SINR). In wireless channels, the factors that contribute to the SINR are often random (or appear random), including the signal propagation and the situation around transmitters and receivers. Therefore, although interference can sometimes be theoretically formulated, it is rather difficult to predict and track the SINR precisely, especially in highly mobile vehicular networks. Based on such an observation, adopting fuzzy values for SINR seems to be more reasonable to model network performance. Compared with some heuristic algorithms [26], [27] in resource allocation, the proposed FUZZRA does not need accurate channel state information, which is nearly impossible to acquire in a highly dynamic and complicated environment, such as urban areas. In addition, another advantage of fuzzy logic is that there is no training process before deploying it in a C-V2X network, compared with machine learning-based algorithms, such as [21].

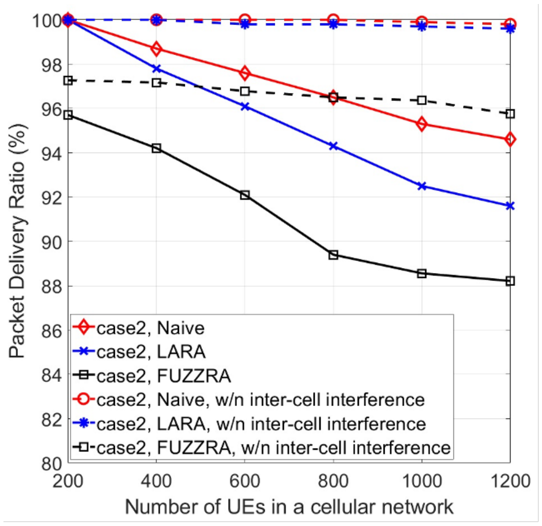


Fig. 9: PDR performance comparison among three allocation strategies for packet delivery ratio.

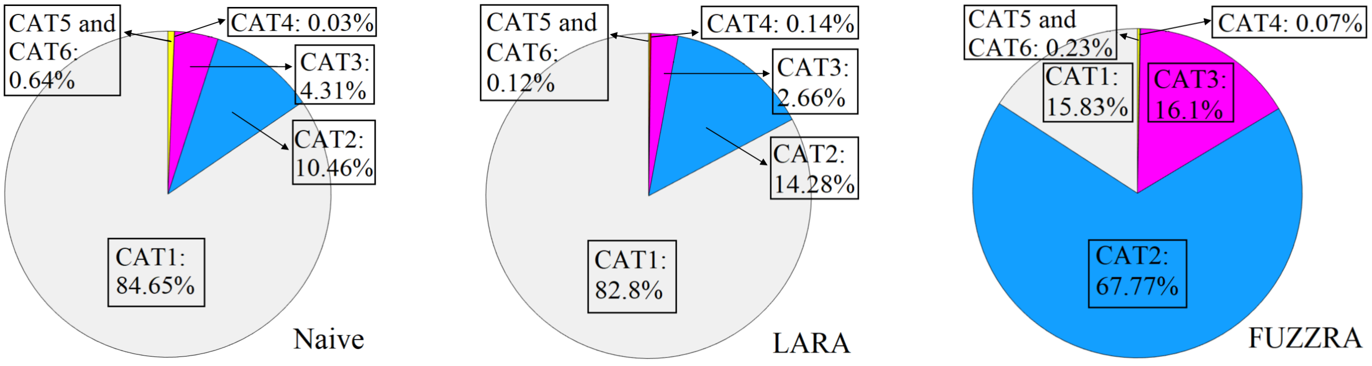
On the other hand, aside from interference, other factors also play a part in determining network performance. Those factors also possess fuzzy attributes, to a certain extent. For example, different types of applications coexisting in the network may have different priorities, which should be considered at the same time. However, crispy-value based functions/algorithms cannot handle such factors effectively. To comprehensively take into account factor randomness and fuzziness, we develop a fuzzy-logic based algorithm to allocate time resources and frequency resources more wisely.

7) *Computational Complexity*

[**Response 9**] The computational complexity of the FUZZRA is $O(N)$.

Proof: Assuming that there are N_{req} transmission requests from all of the UEs, the algorithm will assign resources for each request. For $\forall\ \lambda \in N_{req}$, a value of suitability η for pre-assigned subchannels at each subframe is calculated. A request will be refused if no allocable resources are found before reaching its transmission period, so the worst case will be 500 subframes (among all six types of services, CAT4 has the largest transmission period of 500 ms). At each subframe, the calculation of the suitability value will be carried out n_{cal} times, which is determined by the number of pre-assigned subchannels c_{req}. That is, $n_{cal} = 22/c_{req}$. To calculate η, four factors are calculated at first according to equations from eqn. (5) to (9), and then fuzzification, inference and defuzzification are conducted respectively. Evidently, the computing time for arithmetic operation from eqn. (5) to (19) and the comparison in inference are constants. Suppose the running time for computing timing factor, interference factor, priority factor is T_1, T_2, T_3, respectively, and for conducting fuzzification, inference and defuzzification is T_4, T_5, T_6, respectively, then the total computing time would be:

$$\begin{aligned} f(N_{req}) &= 2N_{req} + 1000N_{req} + 1000N_{req}n_{cal}\sum_{i=1} T_i \\ &< KN_{req} \end{aligned} \tag{20}$$



(a) (b) (c)

Fig. 10: Constituent of different types of packets in V2X communications applying different algorithms of resource allocation for: (a) Naive; (b) LARA; and (c) FUZZRA.

where K is a large constant and $K > 1002 + 1000 n_{cal} \sum_{i=1} T_i$. Therefore, the FUZZRA has a linear computational complexity of $O(N)$.

V. PERFORMANCE EVALUATION

A. Simulation Setup

In order to evaluate the performance of the proposed FUZZRA described above, a cellular V2X network is simulated in NS-3 [28] based on the system model in Section III. It comprises one eNB, a number of pedestrians as cellular UEs (CUEs), vehicular UEs (VUEs) and RSUs. In order to reflect traffic in urban regions, a Manhattan grid network of roads is built in SUMO [7]. The traffic model is linked with the V2X network model to form a realistic system shown by Fig. 2. VUEs and CUEs are mobile UEs, while RSUs are static UEs. All of the UEs fall into the coverage of the eNB. In addition, taking into account the existence in reality of both inter-cell interference and intra-cell interference, we simulate nine independent cells at the same time and measure the performance of the middle one (cell 9), as shown in Fig. 8.

Traditionally, the covered area of a cellular network is drawn as a hexagon. However, the hexagon shape is far from the actual circumstance. In reality, the network of roads/streets forms a grid, like a typical Manhattan district. The roads in the adjacent cell may connect to one another. However, a hexagon cell means some of the roads may not be connected. Moreover, in the conducted simulations, inter-cell interference is considered. Inter-cell interference usually significantly affects vehicles moving on roads on the borders of two cells. Hexagon cells make it difficult to simulate interference and reflect its influence. Therefore, for both reasons of reality and simulations, a square cell is more suitable to reveal the actual performance of C-V2X networks.

Vehicles broadcast the messages of the first two services specified in Table I at all times in order to prevent accidents. The event-driven messages (CAT3) are only sent when VUEs passing an interception and each vehicle broadcasts 200 packets per time unit. Pedestrians (i.e., as vulnerable road users) enable the CAM application to alert vehicles and ensure road safety via smart devices. The CAT4 information is disseminated by RSUs every 500 milliseconds. Regarding the last two non-safety cases, we assume that they are primarily completed by communication between RSUs and VUEs or CUEs. Those moving UEs can access the Internet directly via RSU when they are within RSU coverage. Actually, UEs should get/send data from/to the Internet only when there is a demand. To simulate it, we let P_{CAT5} and P_{CAT6} denote the probability of a UE exchanging data through the Internet by means of the services of CAT5 and CAT6, respectively. Apart from CAT1, CUEs can also access the services of CAT5 and CAT6, but do not include services in CAT2, CAT3 or CAT4.

TABLE IV: Key Parameters in simulation.

Parameter	Value
Frequency/Band width	5.9 GHz/20 MHz
Number of VUEs in one cell	200 to 1200/50/4
Number of CUEs/RSUs in one cell	50/4
Transmission range	RSU: 200 m CUEs and VUEs: 100 m
Coding rate/Number of cells	0.5/9
Travel velocity	Vehicle: 0 to 50 km/h Pedestrian: 0 to 10 km/h
Area size/Grid size	1000 m x 1000 m/10x10
Channel fading model	Nakagami fading
Path loss exponent	3
Number of RBs per subchannel / Number of subchannels in PSSCH	5/22
Supported modulations	16QAM: safety services 64QAM: non-safety services

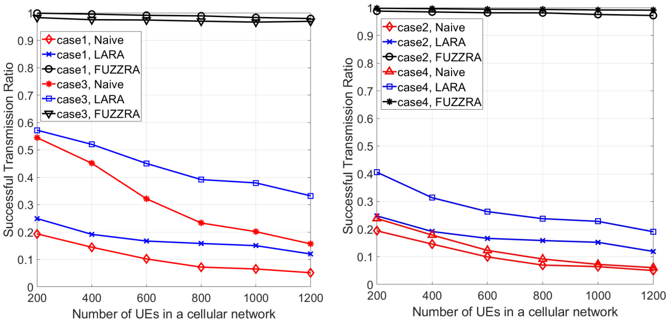
TABLE V: Packet size in simulation.

Service Type	Packet Size (bytes)
CAT1	300
CAT2, CAT5 and CAT6	1500
CAT3	3000
CAT4	1200

The Nakagami fading model has been widely adopted in many vehicular environments due to its realistic characteristic. We assume that all V2X channels in our system model experience Nakagami fading and the channel gain keeps unchanged during the entire duration of a packet. For reception power Y, the probability density function is given as follows:

$$f_Y(y) = \frac{m^m y^{m-1}}{\Gamma(m)\omega^m} e^{\frac{-my}{\omega}} \tag{21}$$

where ω and m denote the mean received power and fading exponent, respectively. We let m to be 1.5 if the distance



(a) (b)

Fig. 11: Successful transmission ratio for V2X communications applying various resource allocation schemes.

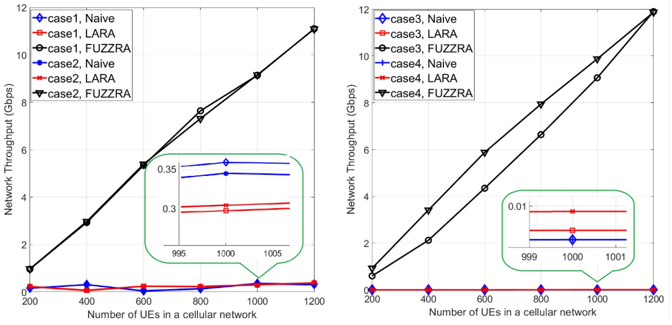
between a sender and a receiver is less than 80 m or 0.8 for any other cases with a larger distance, according to an empirical study [29].

Table IV illustrates chief parameters in simulation. In the resource pool, there are 100 subframes and 22 subchannels. To avoid large delays, a transmission request should be approved in the next T_{sf} subframes if suitable resources can be located. The value of T_{sf} depends on different services. For transmissions of CAT5, the variable T_{sf} equals 100 ms. Otherwise, it would be the corresponding end-to-end delay. In addition, successful packet reception can be guaranteed within a sender's transmission range, but UEs that are out of the range may still have a lower probability (the probability depends on channel conditions) to receive the transmitted information. Table V lists packet sizes of all services in the simulations.

[**Response 4**] To better evaluate how different V2X services affect the network performance, various combinations of services have been considered in the simulations (see Table VI). According to [24], 5G V2X has as many as 31 safety services (4 eV2X and 27 basic services). To test the performance of the proposed allocation algorithm, we take two typical basic safety services, two eV2X services and two infotainment services. Among all six services, CAT3 has the most stringent requirement and consumes the largest bandwidth. Moreover, both CAT3 and CAT6 require a very short delay of 10 ms and 20 ms respectively. By selecting these different service types, we want to test if the proposed FUZZRA can satisfy the requirements of multiple services, especially for the URLLC.

B. Simulation results and discussions

Extensive simulations have been implemented to evaluate network performance with respect to packet delivery ratio, successful transmission ratio, and network throughput for the FUZZRA scheme in comparison with the naive and LARA schemes [6].



(a) (b)

Fig. 12: Network throughput for C-V2X applying four different resource allocation algorithms.

TABLE VI: Services in different simulation cases.

Simulation Case	Included Services
Case 1	CAT1, CAT2, CAT3, CAT4, only safety-related Services
Case 2	All services, $P_{CAT5} = P_{CAT6} = 0.1$
Case 3	CAT1, CAT3, CAT4, $P_{CAT5} = P_{CAT6} = 0.1$
Case 4	CAT1, CAT2, CAT4, $P_{CAT5} = P_{CAT6} = 0.1$

In Fig. 9, the PDR performance is presented for all three schemes in case 2. The naive scheme has the highest PDR and it is followed by the LARA and the FUZZRA. The naive and the LARA have better PDR, because the former does not have intra-cell interference, and the latter has very limited intra-cell interference, so the corresponding two dashed curves are very close to 100%. This is determined by their characteristic of avoiding concurrent transmissions as much as possible in the same cell. However, the FUZZRA allows as many concurrent links as possible, in order to satisfy more requests from VUEs. Therefore, intra-cell interference inevitably appears, and will lower the PDR. In addition, inter-cell interference negatively causes almost the same effect on PDR for all three schemes, because the resource allocation in all of the adjacent cells works independently and the interference mainly affects VUEs that are close to the boundaries.

[**Response 3**] Fig. 10 further shows the constituent of transmitted packets of different services listed in Table II. The results are obtained based on the circumstance of case 2. The naive and LARA treat all types of requests equally, so applications with higher request frequency yet less resource consumption account for the majority, which can be validated by the proportions represented in (a) and (b). Therefore, the CAT1 transmissions dominate all transmissions in the naive and the LARA, in contrast to CAT2 taking up the most part and CAT3 taking up the second most part in (c), as both CAT2 and CAT3 have the highest priority in FUZZRA. The priority of CAT1 and CAT4 is moderate, so the CAT1 has the third largest proportion. CAT4 occupies the smallest proportion, as its transmission frequency is the lowest, although it has higher priority than the non-safety related categories of CAT5 and CAT6.

Fig. 11 shows *STR* against the quantity of UEs in a C-V2X network. With the increase in vehicle volume in a cellular network, it is more difficult for the eNB to find available resources for excessive transmission requests due to the increasing competition. Therefore, from the figure, the *STR* descends significantly for both the naive and LARA schemes in all cases when the volume of UEs goes up in the network.

Moreover, the worst case scenario is that even if there are only 200 VUEs spreading over an area of 1 km^2, the *STR* turns to be at a rather low level of 0.2 if all six services are enabled (case 2) and the naive method is applied, not to mention the case with more VUEs. That is, more than 80% of the requests are rejected, which makes it hard to fulfill the requirements of many V2X applications. Although the LARA scheme can somehow boost the *STR*, compared with the naive, it is still far from satisfactory. However, the FUZZRA can maintain the *STR* at least 98% for all four cases and vehicle volumes. On the other hand, FUZZRA shows more robustness than the other two methods, when enabling or disabling the two eV2X services (cooperative maneuver and cooperative sensing). This is based on the observations that for the same resource allocation scheme, the gaps between case 2 and case 3 or case 4 are different for three schemes but the smallest one is the FUZZRA.

Fig. 12 shows the network throughput. [**Response 6**] In case 1 and case 2, the throughput of the naive and the LARA are not sensitive to the number of UEs, because the network is already saturated and no more resources can be allocated to UEs. In contrast, the network throughput obtained from fuzzy logic grows steadily from 1 Gbps to 11 Gbps, significantly outperforming its counterparts - more than 10 times. For each scheme in Fig. 12a, its relevant curves for case 1 and case 2 are very close, because case 1 only involves four safety V2X services, while case 2 includes all services. However, the probability of transmitting two non-safety services is only 0.1, and both have the lowest priority. Therefore, they cannot contribute too much to network throughput.

On the other hand, for the naive and the LARA, the two eV2X services have a more considerable impact on throughput than the FUZZRA, which can be observed based on the comparison between the bottom curves in (a) and (b). Eliminating any one of the eV2X services will significantly reduce the throughput from 350 Mbps to 10 Mbps. However, such changes in provided services do not incur so large a difference in throughput if FUZZRA is adopted in the network. The benefit stems from the adaptiveness of the FUZZRA, which can dynamically promote the priority of a service to a higher priority in accord with network status (say raise the priority of CAT1 from medium to high if there are fewer requests for highpriority messages). However, the naive and the LARA always treat different types of services equally and work in a first-come-first-serve mode, which may be affected by the proportion among the requests with a different priority.

VI. CONCLUSION

In conclusion, we have investigated the strategy of resource allocation for 5G V2X communications. We first introduce the two types of resource allocation in mode 3. Since vehicles and other UEs are within the coverage of the base station, we focus on dynamic resource allocation, in which the base station manages all two-dimensional time-frequency resources. However, the V2X standard proposed by 3GPP does not mandate any dynamic resource allocation for mode 3. Motivated by this, a fuzzy logic-based resource allocation algorithm (i.e., FUZZRA) is proposed in the paper. The FUZZRA takes multiple variables as input factors and comprehensively considers how to allocate appropriate resources to various UEs using the advantage of fuzzy logic. It can also dynamically adjust the parameters in the fuzzy system according to the network status, in order to ensure the full utilization of resources and QoS. A simulation model is then developed in NS-3 and SUMO to simulate V2X communications in cellular networks, in which both inter-cell and intra-cell interference exist. Simulation results demonstrate that compared with prior schemes, the FUZZRA can greatly boost resource utilization, improve information dissemination among various UEs and promote network throughput.

[**Response 12**] The FUZZRA provides a good solution for resource allocation and at the same time maintains low complexity. Moving forward, motivated by an explosive increase in smartphone users, which results in challenges such as bandwidth utilization, spectrum crisis and high energy consumption , we plan to work on how to improve resource utilization for device-to-device (D2D) communications [30] in 5G cellular networks, taking advantages of fuzzy logic.

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