EdgeVCD: Intelligent Algorithm-Inspired Content Distribution in Vehicular Edge Computing Network

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***Abstract*—Vehicular edge computing (VEC), which integrates mobile-edge computing (MEC) into vehicular networks, can provide more capability for executing resource-hungry applications and lower latency for connected vehicles. Distributing the result content to connected vehicles is vital for them to take proper actions based on computing results. However, the increasing number of connected vehicles and the limited communication resources make the content distribution a challenge. Besides, the diversity of connected vehicles and contents makes it more challenging for content distribution. To address this issue, in this article, we propose EdgeVCD, an intelligent algorithm-inspired content distribution scheme. Specifically, we first propose a dual-importance (DI) evaluation approach to reflect the relationship between the Priority of Vehicles (PoV) and the Priority of Contents (PoC). To make use of the limited communication resources, we then formulate an optimization problem to maximize the system utility for content distribution. To solve the complex optimization problem effectively, we first divide the road into small segments. Then, we propose a fuzzy-logic-based method to select the most proper content replica vehicle (CRV) for aiding content distribution and redefine the number of content request vehicles in each segment. Thereafter, the optimization problem is transformed into a nonlinear integer programming problem. Inspired by the artificial immune system, we propose an immune clone-based algorithm to solve it, which has a fast convergence to an optimal solution. Extensive simulations validate the effectiveness of our proposed EdgeVCD in terms of system utility, average utility, and convergence.**

***Index Terms*—Content distribution, dual-importance (DI) evaluation, fuzzy logic, immune clone, intelligent algorithm, vehicular edge computing (VEC) network.**

I. Introduction

As ONE of the most important parts of the Internet of Things (IoT), the vehicular network contributes much to the intelligent transportation system (ITS) in enhancing road safety and improving traffic efficiency. However, the increasing number of connected vehicles and their resource-hungry applications pose new challenges in terms of computation and processing for providing reliable and efficient vehicular services [1]. To tackle this problem, vehicular edge computing (VEC) has been come up as a novel paradigm, in which the computation nodes are moved to a proximity of vehicles and a lower latency is achieved than mobile cloud computing (MCC) [2]–[4].

In a VEC network, computational nodes can be deployed in cell towers, road side units (RSUs), and within connected vehicles. The computation tasks are first offloaded to the computation nodes for processing. After computing the tasks, distributing the result content to vehicles through vehicle-to-infrastructure (V2I) is vital for vehicles to take the correct actions based on the computing results. For example, the computing results for high-precision map content are critical to the connected vehicles for improving the positioning accuracy and thus enhancing the road safety [4].

However, the increasing number of connected vehicles and the limited communication resource poses significant challenges to the cellular network or RSUs for the surging content distribution tasks in the VEC network [5]. Since the connected vehicles themselves can be regarded as edge nodes and have enhanced the caching capability, the cache-enabled connected vehicles can be regarded as a new promising approach to store and disseminate the prefetched content through vehicle-to-vehicle (V2V) communications [6], [7]. Although some cooperative content distribution schemes have been proposed in [8]–[12], where the target vehicles receive content from multiple other content replica vehicles (CRVs) or RSUs when they are out of the communication range of the current content provider, how to select the most proper CRVs as collaborative vehicles is still a challenge. The reason is that many factors have impacts on the selection of collaborative vehicles, such as the moving speed of vehicles, which ensures the mobility of selected CRV is stable; the path similarity, which avoids frequent switching between request vehicles and different CRVs; and the channel condition, which indicates a preference to those CRVs that are able to provide better wireless links to request vehicles. However, it is hard to select the most proper CRV that subject to multiple constraints in polynomial time.

Besides, in the VEC network, different types of vehicles may request the same type of content, or the same type of vehicles may request different types of content. For

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example, private cars, public buses, and emergency cars (e.g., ambulances or police cars) request safety-related and real-time content simultaneously, or some private cars request entertainment content and content with high priority simultaneously. The diversity of vehicles and contents make it difficult to decide whether to distribute content based on the Priority of Vehicles (PoV) or the Priority of Contents (PoC).

New approaches are required to address these challenges in order to provide reliable and efficient content distribution for the connected vehicles in resource-constrained VEC networks. Most of the VEC literature mainly focuses on computation offloading, content caching, security, and privacy [13], very few works have incorporated the selection of CRVs and the diversity of vehicle and contents into VEC networks for content distribution, while the joint allocation of V2I and V2V also have not been fully exploited in VEC networks.

To bridge this gap, in this article, we focus on content distribution in the VEC network. By taking a full consideration of the diversity of vehicles and contents, and the selections of CRVs, we propose EdgeVCD, an intelligent algorithm-inspired content distribution scheme in the VEC network, which maximizes the system utility for content distribution.

The main contributions of this article are as follows.

1) *Dual-Importance (DI) Evaluation:* We divide both contents and vehicles into different categories according to their characteristics. Based on that, we then propose a 2-D DI evaluation method by jointly considering PoV and PoC.
2) *Fuzzy-Logic-Based CRV Selection:* The burden of V2I communication for content distribution can be alleviated through the collaboration of CRVs. However, it is difficult to select the most proper CRV for aiding the content distribution. To this end, we propose a fuzzy-logic-based algorithm to select the most proper CRV.
3) *System Utility Maximization-Oriented Content Distribution:* Since different user gains will be achieved when different communication methods (i.e., V2I or V2V) are utilized for content distribution, and thus resulting in different communication costs, it is hard to develop a tradeoff between them. To address this issue, we develop a utility function by combining the gains from the users and the communication cost from the system and optimize the utility function.
4) *Intelligence Algorithm With Fast Convergence and Validation:* The content distribution issue is formulated as a mixed-integer programming (MIP) problem. After transforming the MIP problem three times, a novel immune clone-based algorithm is proposed to solve it. Compared to the genetic algorithm, the proposed algorithm achieves faster convergence speed. Extensive simulations are conducted for verifying the performance of our proposed EdgeVCD.

The remainder of this article is organized as follows. Related works are reviewed in Section II. The system model is presented in Section III. In Section IV, we describe the DI evaluation and problem formulation. The fuzzy-logic-based CRV selection and the immune clone-based optimal link selection are presented in Sections V and VI, respectively. Section VII presents the evaluation results. Section VIII concludes this article.

II. Related Work

The content distribution of vehicular networks can be generally divided into three types: 1) V2I-based content distribution, where vehicles achieve content retrievals through the road communication infrastructure [14]–[18]; 2) V2V-based content distribution, where content distributions are achieved through the V2V communications among vehicles [19]–[25]; and 3) hybrid content distribution (i.e., combine V2V and V2I communications) [8], [10], where the cooperative V2V communications are utilized when the content deliver process has not been finished after V2I communication.

As for the V2I-based system, Liang and Zhuang [14] utilized the RS-WLANs to disseminate data. A network-level and packet-level-based two-level data dissemination method is proposed in this article. The resources in the RS-WLANs are used to facilitate the data dissemination services for the nomadic users with the network level. The packet-level cooperation is exploited to improve the packet transmission rate to a nomadic user. Specific to urban vehicular environment, Trullols-Cruces *et al.* [16] proposed a chunk scheduling algorithm for cooperative downloading for the purpose of achieving a tradeoff between the reliability and the redundancy of data transfer. An enhanced cooperative load balancing (ECLB) method was proposed by Ali *et al.* [17]. The ECLB balances the overload of junction-RSUs and edge-RSUs more freely and can maximize the overall system performance during data dissemination. Luan *et al.* [18] proposed a cost effective and practical method for the purpose of facilitating localized content dissemination from the distributed roadside infrastructure to the vehicles in the urban area. In the proposed method, the content replication in a roadside buffer is formulated as an optimization issue to seek optimal system utility, which accounts for the download demands of files and the integrated download experience of users.

In terms of V2V-based content distribution, Nandan *et al.* [19] proposed a swarming protocol for vehicular *ad hoc* networks (SPAWN), where a file is first chopped into multiple pieces and then swapped among vehicles in a BitTorrent style to facilitate the collaborative download. Most of the other literature is based on network coding. For example, based on network coding, Lee *et al.* [20], [21] proposed the CodeTorrent for the purpose of maximizing the mutual differences of content pieces stored in the nearby vehicles and accordingly reduces the search delay and coordination of piece transmissions; Ye *et al.* [22] developed an analytical model to evaluate the completion probability of content dissemination for the highway scenario; Yan *et al.* [23] developed an analytical model to evaluate the multihop transmission rate of content distribution; and Li *et al.* [24] proposed the CodeOn for efficient content distribution in the highway scenario. In addition to the network coding-based approach, Zhang and Cao [25] proposed a platoon-based protocol, where the content is optimally replicated in a vehicle platoon.

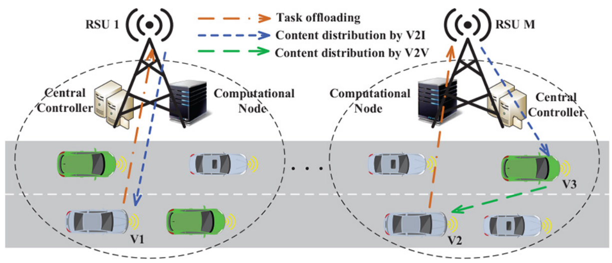

Fig. 1. Content distribution in the VEC network.

As for the hybrid systems, Su *et al.* [26] proposed a game-theoretic approach to parked vehicle-assisted content delivery (GTA-PVACD) in vehicular *ad hoc* networks. Sardari *et al.* [10] proposed a new paradigm for collaborative content distribution from RSUs to vehicular networks, where vehicles are categorized to collector and carrier nodes. The carrier nodes receive the content from RSUs, and the collector nodes recover the source message through the carrier nodes from a far distance. A cooperative Drive-thru Internet method, named ChainCluster was proposed by Zhou *et al.* [8] where the content distribution process is divided into the V2R and V2V phases. In the V2R phase, vehicles forming a linear cluster cooperatively download the content file from the roadside infrastructure and exchange file portions in the V2V phase.

Moreover, some content distribution schemes focus more on the selection of replicas. Silva *et al.* [27] proposed an origin-destination-based content replication (ODCRep) solution for content distribution, where three metrics (i.e., the departure and arrival locations of vehicles, the lifetime of content, and the travel time of vehicles) are considered to select the appropriate vehicles as replicas. Many literature study the selection issue of vehicles by utilizing the fuzzy-logic-based method. Jointly considering three parameters (i.e., buffer occupancy, stability, and energy), Kots and Kumar [28] utilized the fuzzy-logic-based method to efficiently select multipoint relays in the OLSR protocol. Jointly considering three parameters (i.e., hop counts, node mobility, and residual energy), Abbas *et al.* [29] also utilized the fuzzy-logic-based method to evaluate the trust levels of nodes for the purpose of constructing an optimal path between the source and destination. Wu *et al.* [30] combined long-term evolution (LTE) and IEEE 802.11p to distribute content and propose a fuzzy-logic-based two-level clustering method to select stable cluster head nodes.

Compared with the existing works, we focus on content distribution in the VEC network. We take a full consideration of the diversity of vehicles and contents, and the selections of CRVs. Based on that, we formulated an optimization problem to maximize the system utility for content distribution. In order to efficiently solve the formulated optimization problem, we gradually transform it into a zero-one programming problem and propose an immune clone-based algorithm to obtain the optimal solution with fast convergence.

III. System Model

A. System Description

Fig. 1 shows the architecture of a VEC network where the task data are offloaded from request vehicles to the computational node of RSU for computing. After computing the task, the result content is distributed to request vehicles in two ways. For the first one, the RSU distributes the content to request vehicles directly through V2I communication, as shown in V1 of Fig. 1. For the other, content is first prefetched in some collaborative vehicle (i.e., CRV) and then distributed to request vehicles through V2V communication, as shown in V2 and V3 of Fig. 1. The request vehicles can be private cars, public buses, or emergency cars. We denote the set of vehicles as $\mathbb{V} = \{1, 2, 3, \ldots, N\}$, the set of RSUs as $\mathbb{M} = \{1, 2, 3, \ldots, M\}$, the communication radius of all RSUs as R_1, and the communication radius of all vehicles as R_2. We divide time into time slots, the indexes of which are normalized to the integer value $t \in \mathbb{T} = \{1, 2, \ldots, T\}$. We use $\hat{\mathbb{V}} = \{1, 2, 3, \ldots, \hat{N}\}$ to denote the set CRVs. Due to technology and commercial constraints, the costs and data rates of V2I and V2V communications are different. In order to obtain a maximum system utility for content distribution under the resource-constrained VEC network, proper communication mode should be scheduled. Within each RSU, a control center gathers content requests from vehicles while scheduling the communication resources of V2I and V2V through a dedicated control channel [2]. For convenience, the main notations are summarized in Table I.

B. Instantaneous Achievable Content Transmission Rate

In this article, we model the path loss as $d^{-\alpha}$, where d and α denote the distance from the transmitter to the receiver and the path loss exponent, respectively. Moreover, the channel fading coefficient is denoted by h, which is a circularly symmetric complex Gaussian random variable [31]. Considering the spectral density of the white Gaussian noise power is N_0, the achievable content transmission rate between a transmitter and its receiver at a time slot t is given by

$$C(t) = B(t)\log_2\left(1 + \frac{P_{\mathsf{tr}}|h|^2}{B(t)N_0 d^{\alpha}}\right) \tag{1}$$

where $B(t)$ denotes the bandwidth at a time slot t, and P_{tr} denotes the transmission power of transmitters.

V2I link connects the RSU and vehicle through the LTE radio resource [32]. The LTE radio resources are divided into resource blocks (RBs). We denote the number of available LTE RBs as K_{LTE}. The vehicles share K_{LTE} RBs to receive the corresponding content from the RSU. Each vehicle is assigned with $\lfloor (K_{\mathsf{LTE}})/(N_{\mathsf{V2I}}(t)) \rfloor$ RBs, where $\lfloor \cdot \rfloor$ denotes the floor function and $N_{\mathsf{V2I}}(t)$ denotes the number of content request vehicles from the RSU at a time slot t. Accordingly, the content transmission rate that the ith $(1 \leq i \leq N_{\mathsf{V2I}}(t))$ vehicle can achieve from RSU is formulated as

$$\begin{aligned} C_{i,\mathsf{RSU}}(t) &= \left\lfloor \frac{K_{\mathsf{LTE}}}{N_{\mathsf{V2I}}(t)} \right\rfloor \log_2\left(1 + \frac{\Omega}{\left\lfloor \frac{K_{\mathsf{LTE}}}{N_{\mathsf{V2I}}(t)} \right\rfloor N_0}\right) \\ &= \left\lfloor \frac{K_{\mathsf{LTE}}}{N_{\mathsf{V2I}}(t)} \right\rfloor \log_2\left(1 + \frac{P_{\mathsf{RSU}}|h|^2}{\left\lfloor \frac{K_{\mathsf{LTE}}}{N_{\mathsf{V2I}}(t)} \right\rfloor N_0 d^{\alpha}_{i,\mathsf{RSU}}(t)}\right) \end{aligned} \tag{2}$$

TABLE I
MAJOR NOTATIONS

Notation	Definition
$\mathbb{V}$, $\mathbb{M}$, $\hat{\mathbb{V}}$	The set of vehicles, RSUs and CRVs
R_1, R_2	Communication radius of RSU and CRV
$B(t)$	Bandwidth at time-slot t
N_0	Spectral density of white Gaussian noise power
h	Channel fading coefficient
d	Distance between transmitter and receiver
α	Path loss exponent
K_{LTE}	Number of available LTE RBs
K_{DSRC}	Number of available DSRC RBs
N_{V2I}	Number of content request vehicles from RSU
N_{V2V}	Number of content request vehicles from CRV
P_{RSU}	Transmission power of RSU
P_{CRV}	Transmission power of CRV
$C_{i,\mathsf{RSU}}$	Transmission rate between vehicle i and RSU
$C_{i,\mathsf{CRV}}$	Transmission rate between vehicle i and CRV
T^{enc}	Encounter duration between two vehicles
$traj(\mu)$	Trajectory of vehicle μ
$trip(\mu)$	Time-stamped trajectory of vehicle μ
$CA(t)$	Content amount during the t-th time-slot
p_n^1, p_c^2	Value of PoV and PoC
$p_{n,c}$	Value of *dual-importance*
u_n	Utility vehicle n obtains
$Q_{n,m,c}^{\mathsf{RSU}}$	Gain vehicle n obtains when receiving content c from RSU m
$Q_{n,\hat{n},c}^{\mathsf{CRV}}$	Gain vehicle n obtains when receiving content c from CRV $\hat{n}$
$a_{n,m}$	Binary variable indicating content distribution between vehicle n and RSU m
$b_{n,\hat{n}}$	Binary variable indicating content distribution between vehicle n and CRV $\hat{n}$
p^{RSU}	Communication cost per unit time for V2I
p^{CRV}	Communication cost per unit time for V2V

where P_{RSU} denotes the transmission power of RSU, and $d_{i,\mathsf{RSU}}(t)$ represents the distance between the vehicle i and the RSU at a time slot t.

The V2V link connects the request vehicles and the CRVs through dedicated short-range communications (DSRC) [33]. We denote the number of DSRC RBs and content request vehicles from the CRV at a time slot t as K_{DSRC} and $N_{\mathsf{V2V}}(t)$, respectively. A CRV can distribute content to multiple request vehicles simultaneously. All $N_{\mathsf{V2V}}(t)$ vehicles share K_{DSRC} RBs to communicate with the CRV. Each request vehicle is assigned with $\lfloor (K_{\mathsf{DSRC}})/(N_{\mathsf{V2V}}(t)) \rfloor$ RBs. Similarly, the content transmission rate between the jth $(1 \leq j \leq N_{\mathsf{V2V}}(t))$ vehicle and the CRV is expressed by

$$C_{j,\mathsf{CRV}}(t) = \left\lfloor \frac{K_{\mathsf{DSRC}}}{N_{\mathsf{V2V}}(t)} \right\rfloor \log_2\left(1 + \frac{\Omega}{\left\lfloor \frac{K_{\mathsf{DSRC}}}{N_{\mathsf{V2V}}(t)} \right\rfloor N_0}\right)$$

$$= \left\lfloor \frac{K_{\mathsf{DSRC}}}{N_{\mathsf{V2V}}(t)} \right\rfloor \log_2\left(1 + \frac{P_{\mathsf{CRV}}|h|^2}{\left\lfloor \frac{K_{\mathsf{DSRC}}}{N_{\mathsf{V2V}}(t)} \right\rfloor N_0 d_{j,\mathsf{CRV}}^{\alpha}(t)}\right) \tag{3}$$

where P_{CRV} denotes the transmission power of CRV, and $d_{j,\mathsf{CRV}}(t)$ is the distance between the vehicle j and the CRV at a time slot t.

The instantaneous achievable content transmission rate is used for the evaluation of content amount in the later section.

C. Encounter Duration Prediction

For arbitrary request vehicle $n \in \mathbb{V}$, its average speed is denoted as v_n. For CRVs, we denote the speed of arbitrary CRV $\hat{n} \in \hat{\mathbb{V}}$ as $v_{\hat{n}}$. Accordingly, the expected encounter duration T^{enc} between the CRV $\hat{n}$ and the request vehicle n can be calculated as

$$E\left(T^{\mathsf{enc}}\right) = \frac{2R_2}{|v_n - v_{\hat{n}}|}. \tag{4}$$

The encounter duration between the CRV and the request vehicle is used for the calculation of the path similarity factor (PSF) in Section IV.

D. Vehicle Trajectory Description

In the considered scenario, we characterize the trajectory of vehicles by using a set of stops, where vehicles travel from one stop to another according to the predetermined path. For arbitrary vehicle $\mu \in \mathbb{V} \cup \hat{\mathbb{V}}$, we define two terms traj(μ) and trip(μ) to describe its trajectory. traj(μ) is defined as traj(μ)=$(s_1, s_2, \ldots, s_\iota)$, where ι denotes the number of stops that vehicle n traverses. trip(μ) denotes a time-stamped trajectory and is defined as trip(μ)=$((s_1, \tau_1), (s_2, \tau_2), \ldots, (s_\iota, \tau_\iota))$. For arbitrary element (s_j, τ_j) $(1 \leq j \leq \iota)$ in trip(μ), it indicates that vehicle μ arrives at stop s_j at time τ_j. The vehicle trajectories are used for the calculation of PSF in Section IV.

E. Evaluation of Content Amount

Content amount, similar to the concept of mobile service amount (MSA) that can be traced back to [34], describes the content transmission capacity between the RSU or CRV and the request vehicle. The content amount during the tth time slot is formulated as

$$CA(t) = \int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} C\left(\hat{t}\right) d\hat{t} \tag{5}$$

where t_{start} denotes the start time of the time slot t, $|t|$ denotes the length of the time slot t, and $C(\hat{t})$ is the achievable instantaneous content transmission rate at the moment $\hat{t}$ $(t_{\mathsf{start}} \leq \hat{t} \leq t_{\mathsf{start}}+|t|)$ as defined in (1). Substitute (1) into (5), $CA(t)$ is then formulated as

$$CA(t) = \int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} B\left(\hat{t}\right) \log_2\left(1 + \frac{P_{\mathsf{tr}}|h|^2}{B\left(\hat{t}\right) N_0 d^{\alpha}\left(\hat{t}\right)}\right) d\hat{t} \tag{6}$$

where $d(\hat{t})$ is an unknown variable while other parameters are knowable. Fortunately, since the vehicle speed can be regarded as a constant during t, $d(\hat{t})$ can be predicated. We denote the coordinate of the mth RSU as $(x_m^{\mathsf{RSU}}, y_m^{\mathsf{RSU}})$, the coordinate of the nth request vehicle as $(x_{n,t_{\mathsf{start}}}, y_{n,t_{\mathsf{start}}})$, the speed of the vehicle n as v_n, and the angle between the direction of v_n and the x-axis of the reference coordinate system as ϕ_n. Accordingly, the position of the vehicle n at $\hat{t} \in (t_{\mathsf{start}}, t_{\mathsf{start}} + |t|)$ is formulated as

$$\begin{cases} x_{n,\hat{t}} = x_{n,t_{\mathsf{start}}} + v_n t' \cos \phi_n \\ y_{n,\hat{t}} = y_{n,t_{\mathsf{start}}} + v_n t' \sin \phi_n \end{cases} \tag{7}$$

where $t' = \hat{t} - t_{\mathsf{start}}$. Thus, the distance between the nth request vehicle and the mth RSU at the moment $\hat{t}$ is

$$d_{n,\mathsf{RSU}_m}(\hat{t}) = \sqrt{\left(x_{n,\hat{t}} - x_m^{\mathsf{RSU}}\right)^2 + \left(y_{n,\hat{t}} - y_m^{\mathsf{RSU}}\right)^2}. \tag{8}$$

Let $d_{n,\mathsf{CRV}_{\hat{n}}}(\hat{t})$ denote the distance between the nth request vehicle and the $\hat{n}$th CRV. Similar to (8), $d_{n,\mathsf{CRV}_{\hat{n}}}(\hat{t})$ is formulated as

$$d_{n,\mathsf{CRV}_{\hat{n}}}(\hat{t}) = \sqrt{\left(x_{n,\hat{t}} - x_{\hat{n},\hat{t}}^{\mathsf{CRV}}\right)^2 + \left(y_{n,\hat{t}} - y_{\hat{n},\hat{t}}^{\mathsf{CRV}}\right)^2} \tag{9}$$

where $(x_{\hat{n},\hat{t}}^{\mathsf{CRV}}, y_{\hat{n},\hat{t}}^{\mathsf{CRV}})$ denotes the position of the $\hat{n}$th CRV at the moment $\hat{t}$, which are calculated by

$$\begin{cases} x_{\hat{n},\hat{t}}^{\mathsf{CRV}} = x_{\hat{n},t_{\mathsf{start}}}^{\mathsf{CRV}} + v_{\hat{n}} t' \cos \phi_{\hat{n}} \\ y_{\hat{n},\hat{t}}^{\mathsf{CRV}} = y_{\hat{n},t_{\mathsf{start}}}^{\mathsf{CRV}} + v_{\hat{n}} t' \sin \phi_{\hat{n}} \end{cases} \tag{10}$$

where $v_{\hat{n}}$ denotes the speed of the nth CRV, and $\phi_{\hat{n}}$ denotes the angle between the direction of $v_{\hat{n}}$ and the x-axis of the reference coordinate system.

Accordingly, the received content amount of the request vehicle n through V2I communication during the time slot t can be expressed as

$$CA_{n,m}^{\mathsf{RSU}}(t) = \int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} \left\lfloor \frac{K_{\mathsf{LTE}}}{N_{\mathsf{V2I}}(\hat{t})} \right\rfloor \log_2\left(1 + \frac{P_{\mathsf{RSU}}|h|^2}{\left\lfloor \frac{K_{\mathsf{LTE}}}{N_{\mathsf{V2I}}(\hat{t})} \right\rfloor N_0 d_{n,\mathsf{RSU}_m}^{\alpha}(\hat{t})}\right) d\hat{t}. \tag{11}$$

The received content amount of the request vehicle n from the $\hat{n}$th CRV through V2V communication during the time slot t can be expressed as

$$CA_{n,\hat{n}}^{\mathsf{CRV}}(t) = \int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} \left\lfloor \frac{K_{\mathsf{DSRC}}}{N_{\mathsf{V2V}}(\hat{t})} \right\rfloor \log_2\left(1 + \frac{P_{\mathsf{CRV}}|h|^2}{\left\lfloor \frac{K_{\mathsf{DSRC}}}{N_{\mathsf{V2V}}(\hat{t})} \right\rfloor N_0 d_{n,\mathsf{CRV}_{\hat{n}}}^{\alpha}(\hat{t})}\right) d\hat{t}. \tag{12}$$

The content amount is used in the utility function in the problem formulation part in the later section.

IV. DI Evaluation and Problem Formulation

A. 2-D DI Evaluation

We divide both vehicles and contents into three categories according to their attributes. For the vehicle type, we use $\mathbb{V}^1$, $\mathbb{V}^2$, and $\mathbb{V}^3$ ($\mathbb{V}^1 \cup \mathbb{V}^2 \cup \mathbb{V}^3 = \mathbb{V}$) to denote the set of emergency-like vehicles, public-like vehicles, and private-like vehicles, respectively. For the content type, we use $\mathbb{W}^1$, $\mathbb{W}^2$, and $\mathbb{W}^3$ to denote the set of real-time content related to traffic safety, real-time content related to nonsafety, and nonreal-time content, respectively. For the arbitrary vehicle n ($n \in \mathbb{V}$) and the request content c ($c \in \mathbb{W}^1 \cup \mathbb{W}^2 \cup \mathbb{W}^3$), the PoV and PoC are defined as

TABLE II
2-D DI Evaluation-I

SI (*PoV* \ *PoC*)	1	2	3
1	1	2	4
2	3	5	7
3	6	8	9

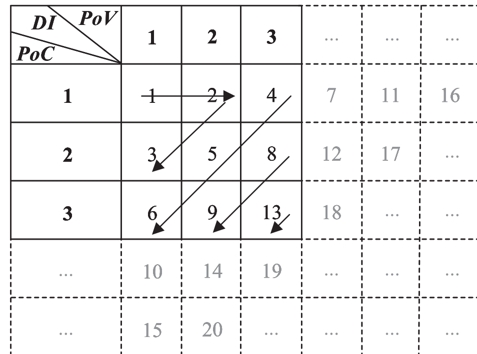

Fig. 2. Extension table of DI evaluation.

$$p_n^1 = \begin{cases} 1, & n \in \mathbb{V}^1 \\ 2, & n \in \mathbb{V}^2 \\ 3, & n \in \mathbb{V}^3 \end{cases} \tag{13}$$

$$p_c^2 = \begin{cases} 1, & c \in \mathbb{W}^1 \\ 2, & c \in \mathbb{W}^2 \\ 3, & c \in \mathbb{W}^3 \end{cases} \tag{14}$$

where p_n^1 and p_c^2 denote the PoV value and PoC value, respectively. Since different types of vehicles may request different types of content, it is difficult to decide whether to distribute content based on PoV or PoC. To this end, we introduce the concept of 2-D DI to reflect the priority relationship between PoV and PoC. We create a 2-D table, as shown in Table II, to determine the DI value based on three rules: 1) the higher the PoV, the greater the DI and 2) with the same PoV, the higher PoC, the greater the DI. Actually, based on a real-time scheduling method used in the operation system [35], the 2-D DI evaluation table can be extended to more than three types of vehicles and content. Generally, DI value can be expressed as

$$p_{n,c} = \frac{\left(p_n^1 + p_c^2 - 1\right)\left(p_n^1 + p_c^2 - 2\right)}{2} + p_n^1 \tag{15}$$

where $p_{n,c}$ is the value of DI, and p_n^1 and p_c^2 represent the values of PoC and PoV, respectively. According to (15), the extension table of DI evaluation is shown in Fig. 2. Actually, since we just use the DI values within the solid frame part of Fig. 2, they are not necessarily continuous with the direction of the arrow. But these values are monotonous, we can sort them continuously, as what we present in Table II. The 2-D

DI is used for the utility function in the problem formulation part in the following.

B. Problem Formulation

For the resource-constrained VEC network for content distribution, the purpose is to distribute the content to the request vehicles to meet their requirements under limited link resources. We use system utility to represent the gain and cost during content distribution. System utility is the sum of utilities of all the request vehicles. In this article, we aim at obtaining as many gains as possible under limited link resources. In other words, we aim at maximizing the system utility. For each vehicle $n \in \mathbb{V}$, we use $u_n(t)$ to represent its utility. The utility consists of two parts, one is gain and another is cost. We use the DI-and-capacity-based function to represent the gain when n obtains content from RSU or CRV, shown as

$$Q^{\mathsf{RSU}}_{n,m,c}(t) = \frac{1}{p^t_{n,c}} \ln\Big(CA^{\mathsf{RSU}}_{n,m}(t)\Big) \tag{16}$$

$$Q^{\mathsf{CRV}}_{n,\hat{n},c}(t) = \frac{1}{p^t_{n,c}} \ln\Big(CA^{\mathsf{CRV}}_{n,\hat{n}}(t)\Big) \tag{17}$$

where $p^t_{n,c}$ denotes the 2-D DI during the time slot t. Another part of utility is the communication cost. We use p^{RSU} and p^{CRV} to denote the communication cost per unit time for V2I and V2V links, respectively. Accordingly, $u_n(t)$ can be formulated as

$$\begin{aligned} u_n(t) = {} & a^t_{n,m} Q^{\mathsf{RSU}}_{n,m,c}(t) + b^t_{n,\hat{n}} Q^{\mathsf{CRV}}_{n,\hat{n},c}(t) \\ & - a^t_{n,m} p^{\mathsf{RSU}} |t| - b^t_{n,\hat{n}} p^{\mathsf{CRV}} |t| \end{aligned} \tag{18}$$

where $a_{n,m}(t)$ is a binary variable that indicates the content distribution between the vehicle n and the RSU m during the time slot t, which is 1 when the vehicle n receives content from the RSU m or 0 when it does not receive content from the RSU m. Similarly, $b_{n,\hat{n}}(t)$ is also a binary variable that indicates the content distribution between the vehicle n and the CRV $\hat{n}$ during the time slot t, which is 1 when the vehicle n receives content from the CRV $\hat{n}$ or 0 when it does not receive content from the CRV $\hat{n}$, $|t|$ represents the length of a time slot. To simplify the expressions, we denote $\boldsymbol{a}(t) = \{a_{1,1}(t), \ldots, a_{1,M}(t), \ldots, a_{N,1}(t), \ldots, a_{N,M}(t)\}$ and $\boldsymbol{b}(t) = \{b_{1,1}(t), \ldots, b_{1,\hat{N}}(t), \ldots, b_{N,1}(t), \ldots, b_{N,\hat{N}}(t)\}$.

For the purpose of maximizing the system utility, we first sum over the utilities of all request vehicles over all time slots. To get more insights about the system utility in each time slot, the summation is then divided by the number of time slots (denoted by T) and the length of a time slot (denoted by $|t|$). Since both T and $|t|$ are constants, the division operation would not affect maximizing the system utility. Therefore, the maximization of system utility is formulated by an optimization problem P1 in (19), where $B^{\mathsf{LTE}}_{n,m}(t)$ denotes the LTE RBs request vehicle n can be assigned from the RSU m, and $B^{\mathsf{DSRC}}_{n,\hat{n}}(t)$ denotes the DSRC RBs request vehicle n can be assigned from the CRV $\hat{n}$

$$\begin{aligned} \text{(P1)} \quad & \max_{\boldsymbol{a}(t),\boldsymbol{b}(t)} \quad U^1 = \frac{1}{|t|}\frac{1}{T}\sum_{t=0}^{T}\sum_{n=1}^{N}\sum_{\hat{n}=1}^{\hat{N}}\sum_{m=1}^{M} u_n(t) \\ \text{s.t.} \quad & \text{1-C1}: \sum_{n=1}^{N} a_{n,m}(t) B^{\mathsf{LTE}}_{n,m}(t) \le K_{\mathsf{LTE}} \\ & \qquad \forall t \in \mathbb{T}, m \in \mathbb{M} \\ & \text{1-C2}: \sum_{n=1}^{N} b_{n,\hat{n}}(t) B^{\mathsf{DSRC}}_{n,\hat{n}}(t) \le K_{\mathsf{DSRC}} \\ & \qquad \forall t \in \mathbb{T}, \hat{n} \in \hat{\mathbb{V}} \\ & \text{1-C3}: a_{n,m}(t) \in \{0,1\} \\ & \qquad \forall n \in \mathbb{V}, m \in \mathbb{M}, t \in \mathbb{T} \\ & b_{n,\hat{n}}(t) \in \{0,1\} \quad \forall n \in \mathbb{V}, \hat{n} \in \hat{\mathbb{V}}, t \in \mathbb{T} \\ & \text{1-C4}: \sum_{m=1}^{M} a_{n,m}(t) + \sum_{\hat{n}=1}^{\hat{N}} b_{n,\hat{n}}(t) \le 1 \\ & \qquad \forall t \in \mathbb{T}, n \in \mathbb{V}. \end{aligned} \tag{19}$$

In problem P1, 1-C1 and 1-C2 describe the RB restraints for V2I and V2V links, respectively, and 1-C3 describes the indicators of V2I and V2V link for each vehicle. 1-C4 represents the constraint that a vehicle should not be allocated to more than two links, i.e., a vehicle cannot receive the content from RSUs and CRVs simultaneously.

Problem P1 is an MIP problem characterized by stochastic programming and cannot be solved efficiently [36], [37]. For simplicity, it is assumed that the link selections of request vehicles in any two time slots are independent, hence we only consider P1 in one time slot. Accordingly, we reformulate P1 as

$$\begin{aligned} \text{(P2)} \quad & \max_{\boldsymbol{a},\boldsymbol{b}} \quad U^2 = \frac{1}{|t|}\sum_{n=1}^{N}\sum_{\hat{n}=1}^{\hat{N}}\sum_{m=1}^{M} u_n \\ \text{s.t.} \quad & \text{2-C1}: \sum_{n=1}^{N} a_{n,m} B^{\mathsf{LTE}}_{n,m} \le K_{\mathsf{LTE}} \quad \forall m \in \mathbb{M} \\ & \text{2-C2}: \sum_{n=1}^{N} b_{n,\hat{n}} B^{\mathsf{DSRC}}_{n,\hat{n}} \le K_{\mathsf{DSRC}} \quad \forall \hat{n} \in \hat{\mathbb{V}} \\ & \text{2-C3}: a_{n,m} \in \{0,1\} \quad \forall n \in \mathbb{V}, m \in \mathbb{M} \\ & b_{n,\hat{n}} \in \{0,1\} \quad \forall n \in \mathbb{V}, \hat{n} \in \hat{\mathbb{V}} \\ & \text{2-C4}: \sum_{m=1}^{M} a_{n,m} + \sum_{\hat{n}=1}^{\hat{N}} b_{n,\hat{n}} \le 1 \quad \forall n \in \mathbb{V} \end{aligned} \tag{20}$$

where 2-C1, 2-C2, 2-C3, and 2-C4 are converted from 1-C1, 1-C2, 1-C3, and 1-C4 in (19) excluding t, respectively.

V. Fuzzy-Logic-Based CRV Selection

A. Problem Analysis and Transformation

Through observation of P2, three aspects that are related to the optimal result should be taken into consideration. The first one is the CRV aspects, i.e., how to select the most proper CRV for content distribution and how many CRVs are selected out within the coverage of one RSU. The second one is the RSU aspect, i.e., how to decide the number of RSUs in the formulated problem P2. The third and most vital one is the association of a request vehicle with RSU or CRV, i.e., it has to be decided that whether a request vehicle should be connected to an RSU or a CRV for the purpose of maximizing the system utility.

For the first two aspects, we divide the the road into segments and only one RSU exists in the middle of each segment. We denote the set of segments as $\mathbb{S}^{\mathsf{seg}}$ and the number of segments is M. Within the coverage of an RSU, since a request vehicle cannot receive content from multiple CRVs simultaneously, we only select the most proper CRV if more than one collaborative vehicles exists with the coverage of the RSU. In this case, the variable $\hat{n}$ can be removed from (20). In order to simplify some variables in problem P2, we replace some parameters in (20) by ξ_n, $\omega_{\mathsf{V2I}}(\hat{t})$, and $\omega_{\mathsf{V2V}}(\hat{t})$, which are formulated as

$$\xi_n = \frac{2}{\left(p_n^1 + p_c^2 - 1\right)\left(p_n^1 + p_c^2 - 2\right) + 2p_n^1} \tag{21}$$

$$\omega_{\mathsf{V2I}}\left(\hat{t}\right) = \frac{P_{\mathsf{RSU}}|h|^2}{N_0 d_{n,\mathsf{RSU}}^{\alpha}} \tag{22}$$

$$\omega_{\mathsf{V2V}}\left(\hat{t}\right) = \frac{P_{\mathsf{CRV}}|h|^2}{N_0 d_{n\mathsf{CRV}}^{\alpha}}. \tag{23}$$

We use U_l' to represent the system utility of the arbitrary segment $l \in \mathbb{S}^{\mathsf{seg}}$. Based on (20) and the replacement of variables, U_l' is expressed (24), as shown at the bottom of the page, where $a_{n,l}'$ is a binary variable that indicates the content distribution between the vehicle n and the RSU in the segment l, $b_{n,l}'$ is a binary variable that indicates the content distribution between the vehicle n and the most proper CRV in the segment l, and N_l' is the number of request vehicles in segment l, and $N_{\mathsf{V2I}}(\hat{t})$ and $N_{\mathsf{V2V}}(\hat{t})$ are replaced by $\sum_{n=1}^{N_l'} a_{n,l}'$ and $\sum_{n=1}^{N_l'} b_{n,l}'$, respectively. To simplify the expressions, we denoted $\boldsymbol{a'} = \{a_{1,1}', \ldots, a_{N_1',1}', \ldots, a_{1,M}', \ldots, a_{N_M',M}'\}$ and $\boldsymbol{b'} = \{b_{1,1}', \ldots, b_{N_1',1}', \ldots, b_{1,M}', \ldots, b_{N_M',M}'\}$ Hence, combined with (24), problem P2 can be reformulated as problem P3 shown in (25), as shown at the bottom of the page, where $\mathbb{V}_l'$ is the set of request vehicles in the segment l.

Problem P3 is a nonlinear integer programming problem or rather a nonlinear zero-one programming problem, which can be solved through some heuristic algorithms. Therefore, the essential process is how to transform P2 to P3, i.e., how to deal with the first two aspects. In our proposed EdgeVCD, a fuzzy-logic-based method is proposed to deal with the CRV selection for the first aspect. For the second aspect, we consider two cases: 1) CRV exists in the segment l and 2) no CRV exists in the segment l. In the following, we first elaborate on the first aspect.

B. Selecting the Most Proper CRV

In order to select the most proper CRV, we take three factors into consideration. The first factor is the moving speed of CRV. This factor is used to ensure that the mobility of the selected CRV is stable. The second factor is the path similarity of CRV with request vehicles. This factor is to avoid frequent switching between request vehicles and different CRVs. The third factor is the channel condition. This factor indicates a preference to CRVs that are able to provide better wireless links to request vehicles. Since the evaluation of fitness involves three factors, it is hard to select the most proper CRV that subject to the three constraints in polynomial time. Fortunately, as a computational

$$\begin{aligned} U_l' = \frac{1}{|t|}\sum_{n=1}^{N_l'} a_{n,l}' &\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} \left\lfloor \frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{N_l'} a_{n,l}'} \right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2I}}\left(\hat{t}\right)}{\left\lfloor \frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{N_l'} a_{n,l}'} \right\rfloor}\right) d\hat{t}\right) - p^{\mathsf{RSU}}|t|\right) \\ &+ b_{n,l}'\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} \left\lfloor \frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{N_l'} b_{n,l}'} \right\rfloor \log_2\left(1 + \frac{\omega_{V2V}\left(\hat{t}\right)}{\left\lfloor \frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{N_l'} b_{n,l}'} \right\rfloor}\right) d\hat{t}\right) - p^{\mathsf{CRV}}|t|\right) \end{aligned} \tag{24}$$

$$\begin{aligned} \text{(P3)} \max_{\boldsymbol{a'},\boldsymbol{b'}} \; U^3 = \frac{1}{|t|}\sum_{l=1}^{M} U_l' = \sum_{l=1}^{M}\sum_{n=1}^{N_l'} a_{n,l}' &\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} \left\lfloor \frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{N_l'} a_{n,l}'} \right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2I}}\left(\hat{t}\right)}{\left\lfloor \frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{N_l'} a_{n,l}'} \right\rfloor}\right) d\hat{t}\right) - p^{\mathsf{RSU}}|t|\right) \\ + b_{n,l}'&\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|} \left\lfloor \frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{N_l'} b_{n,l}'} \right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2V}}\left(\hat{t}\right)}{\left\lfloor \frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{N_l'} b_{n,l}'} \right\rfloor}\right) d\hat{t}\right) - p^{\mathsf{CRV}}|t|\right) \\ \text{s.t.} \quad & \text{3-C1}: a_{n,l}' \in \{0, 1\}, b_{n,l}' \in \{0, 1\} \quad \forall n \in \mathbb{V}_l', l \in \mathbb{S}^{\mathsf{seg}} \\ & \text{3-C2}: a_{n,l}' + b_{n,l}' \le 1 \quad \forall n \in \mathbb{V}_l', l \in \mathbb{S}^{\mathsf{seg}} \end{aligned} \tag{25}$$

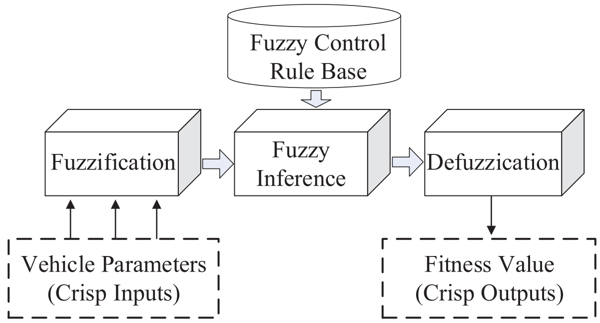

Fig. 3. Fuzzy-logic system.

intelligence technique and first proposed by Zadah, fuzzy logic is widely used and very suited in decision making and can benefit the CRV selection [30].

A fuzzy-logic system includes *fuzzification, fuzzy control rule base, fuzzy inference,* and *defuzzification*, as shown in Fig. 3. Through an input fuzzy membership function (MF), *fuzzification* is to convert numerical input variables into linguistic inputs, while *defuzzification* converts the fuzzy output into numerical value. The *fuzzy inference* calculates the fuzzy output according to the predefined *fuzzy control rule base*. In the following, we will elaborate on the detailed process of the proposed fuzzy-logic-based CRV selection.

1) Fuzzification: Using a fuzzy MF, the process of converting a numerical value into a fuzzy value is called *fuzzification*. Among various MFs (such as triangular MF, trapezoidal MF, Gaussian MF, and Singleton MF), the triangular and trapezoidal MFs are most used and simple MFs. Accordingly, the triangular and trapezoidal MFs are utilized in this article to depict the input and output membership degrees. The MFs of the relative velocity factor (RVF), PSF, and channel quality factor (CQF) are shown in Fig. 4(a)–(c). For the RVF, we use {slow, medium, fast} to denote its fuzzy value. For the PSF, we use {low, medium, high} to denote its fuzzy value. For the CQF, we use {poor, medium, good} to denote its fuzzy value.

Since the three factors have different units, they should be first normalized before the fuzzification process. In the following, we present the detailed normalization process of the three factors.

RVF: A CRV π calculates RVF according to the velocity information as

$$\mathrm{RVF}(\pi) = \frac{\sum_{\xi=1}^{|\mathbb{V}_\pi^{\mathsf{ngb}}|} |\upsilon(\pi) - \upsilon(\xi)|}{|\mathbb{V}_\pi^{\mathsf{ngb}}|\upsilon_{\mathsf{max}}} \tag{26}$$

where $\mathbb{V}_s^{\mathsf{ngb}}$ denotes the set of request neighbor vehicles of π, v_{max} is the maximum speed of vehicles, and $\upsilon(s)$ and $\upsilon(\xi)$ denote the velocities of π and request neighbor vehicle ξ, respectively. A smaller RVF(π) indicates a lower average relative velocity between π and its request neighbor vehicles.

PSF: A CRV π calculates PSF according to the path information as

$$\mathrm{PSF}(\pi) = \frac{\sum_{i=1}^{|\mathbb{V}_\pi^{\mathsf{ngb}}|} S_{i,\pi}^{\mathsf{path}}}{|\mathbb{V}_\pi^{\mathsf{ngb}}| \max_{j\in\mathbb{V}_\pi^{\mathsf{ngb}}} S_{j,\pi}^{\mathsf{path}}} \tag{27}$$

where $S_{i,\pi}^{\mathsf{path}}$ and $S_{j,\pi}^{\mathsf{path}}$ denote the path similarity between the vehicle i and π, and between the vehicle j and π, respectively. The path similarity is defined as follows.

Definition 1: For arbitrary two vehicles $\pi 1$ and $\pi 2$, and their trips denoted by trip$(\pi 1)$ and trip$(\pi 2)$, we define the path similarity between $\pi 1$ and $\pi 2$ as the number of road segments both $\pi 1$ and $\pi 2$ pass at *nearly* the same time.

We use *Seg* to represent a road segment between any two adjacent stops. Then, $Seg_{s_i,s_{i+1}}^{\pi 1}$ denotes a road segment of trip$(\pi 1)$ between the stops s_i and s_{i+1}. For some s_i of trip$(\pi 1)$ and s_j of trip$(\pi 2)$, if $s_i = s_j$ and $s_{i+1} = s_{j+1}$, we call trip$(\pi 1)$ and trip$(\pi 2)$ have a same road segment, i.e., $Seg_{s_i,s_{i+1}}^{\pi 1} = Seg_{s_j,s_{j+1}}^{\pi 2}$. Accordingly, the path similarity between the vehicles $\pi 1$ and $\pi 2$ can be expressed as

$$S_{\pi 1,\pi 2}^{\mathsf{path}} = \sum_{i=1}^{|\mathrm{trip}(\pi 1)|-1} \sum_{j=1}^{|\mathrm{trip}(\pi 2)|-1} \delta_{i,j} \tag{28}$$

where $|\mathrm{trip}(\pi 1)|$ and $|\mathrm{trip}(\pi 2)|$ denote the number of stops of trip$(\pi 1)$ and trip$(\pi 2)$, respectively, $\delta_{i,j}$ is an indicator that indicates whether $Seg_{s_i,s_{i+1}}^{\pi 1}$ of trip$(\pi 1)$ is equal to $Seg_{s_j,s_{j+1}}^{\pi 2}$ of trip$(\pi 2)$, and is defined as

$$\delta_{i,j} = \begin{cases} 1, & Seg_{s_i,s_{i+1}}^{\pi 1} = Seg_{s_j,s_{j+1}}^{\pi 2}, |\tau_i - \tau_j| \le \theta \\ & |\tau_{i+1} - \tau_{j+1}| \le \theta \\ 0, & \text{otherwise} \end{cases} \tag{29}$$

where θ is a threshold value of time difference of arrival between CRV and request vehicle, which is equal to $E(T^{enc})$ as formulated in (4). $|\tau_i - \tau_j| \le \theta$ and $|\tau_{i+1} - \tau_{j+1}| \le \theta$ ensure that vehicles a and b pass the same segment at *nearly* the same time.

CQF: For simplicity, we use the hello packet reception ratio to calculate CQF, just like the *SQF* calculation in [30]. CQF is defined as the reception ratio of hello messages. A CRV π calculates the reception ratio of hello messages based on the following formula:

$$\mathrm{CQF}(\pi) = \frac{N^{\mathsf{rec}}}{N^{\mathsf{send}}} \tag{30}$$

where N^{rec} denotes the number of hello messages received from all request neighbor vehicles and N^{send} denotes the number of hello messages sent by all request neighbor vehicles. We then utilize CQF to estimate the channel condition. The CRV with a higher CQF value is more likely to be selected for content distribution.

Based on MFs and normalized values, the fuzzy value of RVF, PSF, and CQF can be determined. For example, if RVF is 0.2, then its fuzzy value is expressed as {slow: 0.5, medium: 0.5, fast: 0}. In the same way, if PSF is 0.4 and CQF is 0.6, then their fuzzy values are expressed as {low: 0, medium: 0.5, high: 0.5} and {poor: 0, medium: 0.8, good: 0.2}, respectively.

2) Fuzzy Inference: Based on IF-THEN rules, each CRV calculates the rank [a fitness value (FV) for content distribution] through the *fuzzy inference*. The design of knowledge-based rules is based on the understanding of the characteristics of VANETs [38]. The IF-THEN rules are defined in Table III and the linguistic variables for the rank are defined as {very

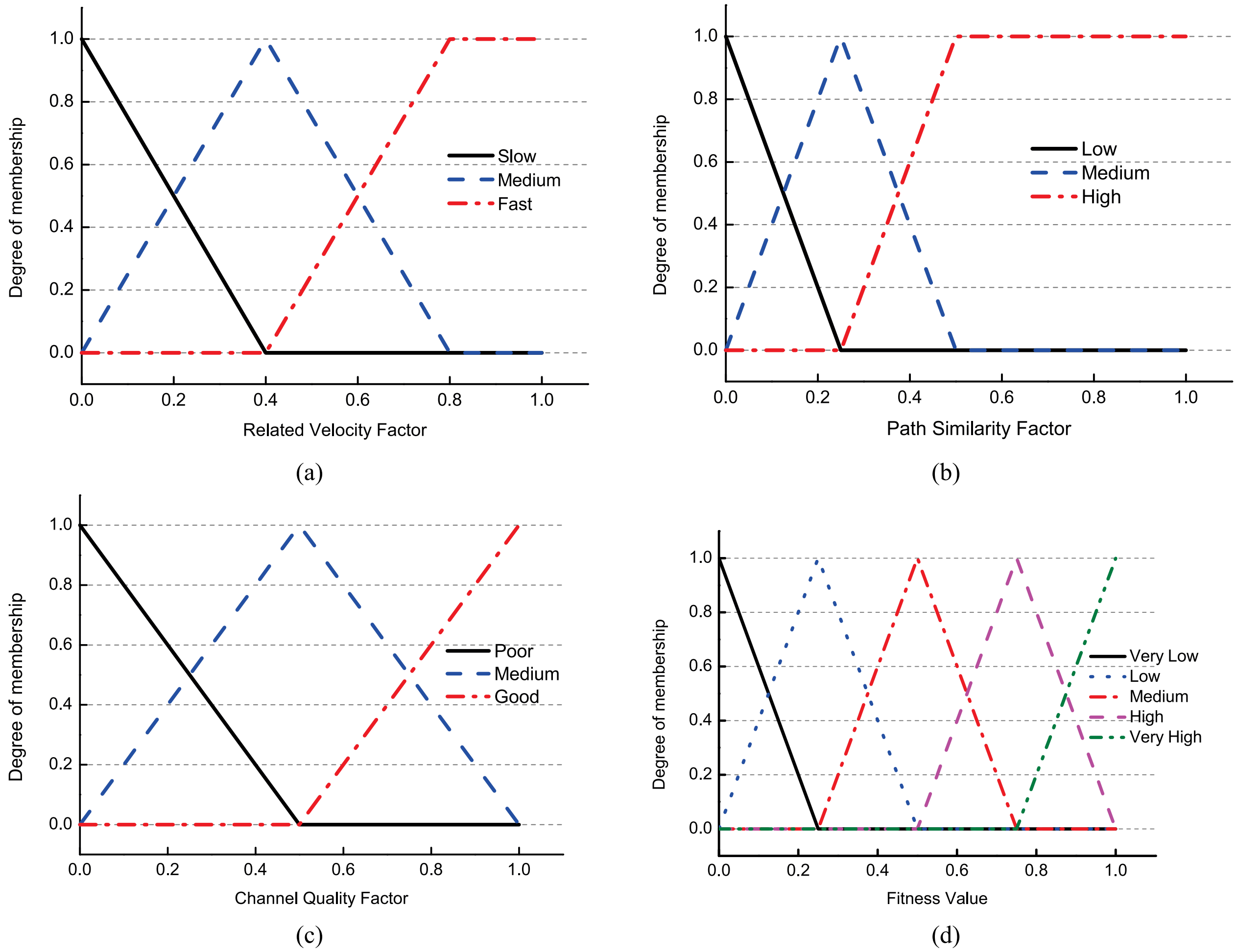

Fig. 4. Fuzzy MFs of inputs and outputs. (a) RVF MF. (b) PSF MF. (c) CQF MF. (d) FV MF.

low, low, medium, high, very high}. For instance, Rule No. 9 in Table III is described as IF RVF is slow, path similarity is high, and channel quality is good, THEN FV is very high.

3) Defuzzification: The process of converting linguistic outputs to numerical outputs is *deffuzication*. There are various defuzzification methods, such as center of gravity (COG), mean of maxima (MOM), and quality method (QM). COG is a very popular defuzzification method and is adopted in many works [30], [39]. In this article, we adopt COG as the defuzzification method, which is expressed as

$$\mathrm{FV} = \frac{\int \mu_3(x) \times x dx}{\int \mu_3(x) dx} \tag{31}$$

where x is the output variable, $\mu_3(x)$ is the triangular MF of output, as illustrated in Fig. 4(d), and FV is a fitness value. After the process of defuzzification, the CRV with the highest FV is selected as the most proper CRV.[1]

[1]The selection of the most proper CRV is performed in a distributed way based on the hello message exchanges. The readers can refer to the selection of first-level cluster head nodes in the work in [30] for the detailed process.

VI. Immune Clone-Based Optimal Link Selection

Until now, we have dealt with the first aspect of transforming problem P2 to P3. In the following, we first elaborate on how we analyze the second aspect. Based on the analysis, we then elaborate on our proposed immune clone-based algorithm for solving the optimization problem based on the analysis.

A. Two Cases for the Existence of CRV in One Road Segment

Once we divide the road into separated segments, where RSUs exist in the middle of them, there may be two cases for the existence of CRV. The first one is that at least one CRV exists in the current segment. In this case, we utilize the proposed fuzzy-logic-based method to select the most proper CRV for content distribution. The second case is that no CRV exists in the current segment. In this case, the request vehicles only receive the corresponding content from RSU or the CRV in the adjacent segments. In the following, we analyze the two cases in detail for the arbitrary segment l.

1) CRV Exists in Segment l: In this case, the most proper CRV selected for content distribution through the proposed fuzzy-logic-based method described in the above section. It is noteworthy that the system utilities in some segments will be

TABLE III
IF-THEN RULES BASE

Rule No.	IF (AND)			THEN
	RVF	*PSF*	*CQF*	*FV*
1	slow	low	poor	low
2	slow	low	medium	medium
3	slow	low	good	medium
4	slow	medium	poor	medium
5	slow	medium	medium	high
6	slow	medium	good	high
7	slow	high	poor	medium
8	slow	high	medium	high
9	slow	high	good	very high
10	medium	low	poor	low
11	medium	low	medium	low
12	medium	low	good	medium
13	medium	medium	poor	low
14	medium	medium	medium	medium
15	medium	medium	good	high
16	medium	high	poor	medium
17	medium	high	medium	medium
18	medium	high	good	high
19	fast	low	poor	very low
20	fast	low	medium	very low
21	fast	low	good	low
22	fast	medium	poor	very low
23	fast	medium	medium	low
24	fast	medium	good	medium
25	fast	high	poor	low
26	fast	high	medium	medium
27	fast	high	good	medium

changed if some request vehicles in the adjacent road segment $l-1$ or $l+1$ receive corresponding content from the CRV in the current road segment l. Here, we introduce the concept of "potential request vehicle." A request vehicle can be regarded as a potential request vehicle only if the distance between it and the CRV in the adjacent road segment is less than the communication radius of CRV. Therefore, the number of request vehicles N_l' in problem P3 should be redefined by the combination of the number of request vehicles in the segment l and some potential request vehicles in the adjacent road segments $l-1$ and $l+1$. We use $\sigma_{l,l-1}$ and $\sigma_{l,l+1}$ to represent the number of potential request vehicles in segments $l-1$ and $l+1$, respectively. Thus, $\sigma_{l,l-1}$ and $\sigma_{l,l+1}$ are expressed as

$$\sigma_{l,l-1} = \sum_{i=1}^{N_{l-1}'} e_i^{l-1} \tag{32}$$

$$\sigma_{l,l+1} = \sum_{j=1}^{N_{l+1}'} e_j^{l+1} \tag{33}$$

where e_i^{l-1} denotes whether the ith of N_{l-1}' request vehicles in segment $l-1$ is within the communication range of the CRV in segment l and e_j^{l+1} denotes whether the jth of N_{l+1}' request vehicles in segment $l+1$ is within the communication range of the CRV in segment l. Accordingly, e_i^{l-1} and e_j^{l+1} are formulated as

$$e_i^{l-1} = \begin{cases} 1, & d\left(i, \mathsf{CRV}^l\right) \le R_2 \\ 0, & d\left(i, \mathsf{CRV}^l\right) > R_2 \end{cases} \tag{34}$$

$$e_j^{l+1} = \begin{cases} 1, & d\left(j, \mathsf{CRV}^l\right) \le R_2 \\ 0, & d\left(j, \mathsf{CRV}^l\right) > R_2 \end{cases} \tag{35}$$

where $d(i, \mathsf{CRV}^l)$ represents the distance between the CRV in segment l and the ith request vehicle in segment $l-1$, $d(j, \mathsf{CRV}^l)$ represents the distance between the CRV in segment l and the jth request vehicle in segment $l+1$.

2) No CRV Exists in the Segment l: If no CRV exists in segment l, the request vehicles can only receive corresponding content from the RSU in segment l, or from the CRV in the adjacent road segments $l-1$ or $l+1$. Similar to the first case, the number of request vehicles N_l' should be redefined by the subtraction of some potential request vehicles that can receive corresponding content from the CRV in the adjacent road segments $l-1$ or $l+1$ from the request vehicles in the current road segment l. We use $\zeta_{l,l-1}$ and $\zeta_{l,l+1}$ to denote the number of potential request vehicles in the current road segment l that can receive corresponding content from CRVs in segments $l-1$ and $l+1$, respectively. The expressions of $\zeta_{l,l-1}$ and $\zeta_{l,l+1}$, similar to (32), are expressed as

$$\zeta_{l,l-1} = \varpi_{l-1} \sum_{i=1}^{N_l'} f_i^{l-1} \tag{36}$$

$$\zeta_{l,l+1} = \varpi_{l+1} \sum_{j=1}^{N_l'} f_j^{l+1} \tag{37}$$

where ϖ_{l-1} and ϖ_{l+1} denote the existence of CRV in segments $l-1$ and $l+1$, respectively, which are 1 when CRV exists or 0 when no CRV exists, f_i^{l-1} denotes whether the ith of N_l' request vehicles in segment l is within the communication range of the CRV in segment $l-1$ under the condition that there exists a CRV in segment $l-1$, and f_j^{l+1} denotes whether the jth of N_l' request vehicles in segment l is within the communication range of the CRV in segment $l+1$ under the condition that there exists a CRV in segment $l+1$. Accordingly, f_i^{l-1} and f_j^{l+1} are formulated as

$$f_i^{l-1} = \begin{cases} 1, & d\left(i, \mathsf{CRV}^{l-1}\right) \le R_2 \\ 0, & d\left(i, \mathsf{CRV}^{l-1}\right) > R_2 \end{cases} \tag{38}$$

$$f_j^{l+1} = \begin{cases} 1, & d\left(j, \mathsf{CRV}^{l+1}\right) \le R_2 \\ 0, & d\left(j, \mathsf{CRV}^{l+1}\right) > R_2 \end{cases} \tag{39}$$

where $d(i, \mathsf{CRV}^{l-1})$ denotes the distance between the ith request vehicle in segment l and the CRV in segment $l-1$, and $d(j, \mathsf{CRV}^{l+1})$ denotes the distance between the jth request vehicle in segment l and the CRV in segment $l+1$.

After minor adjustment of the number of request vehicles in each segment, we use U_l'' to represent the system utility of the arbitrary segment $l \in \mathbb{S}^{\mathsf{seg}}$. U_l'' is expressed as (40), as shown at the bottom of the next page, where $\tilde{N}_l$ is the number of request vehicles in segment l after minor adjustment, $a''_{n,l}$ is a binary variable that indicates the content distribution between vehicle n ($1 \leq n \leq \tilde{N}_l$) and the RSU in segment l, and $b''_{n,l}$ is a binary variable that indicates the content distribution between vehicle n ($1 \leq n \leq \tilde{N}_l$) and the most proper CRV in segment l. $\tilde{N}_l$ is expressed as

$$\tilde{N}_l = \begin{cases} N'_1 + \varpi_1\sigma_{1,2} - \varpi_2\zeta_{1,2}, \quad l = 1 \\ N'_l + \varpi_l\left(\sigma_{l,l-1} + \sigma_{l,l+1}\right) \\ -\varpi_{l-1}\zeta_{l,l-1} - \varpi_{l+1}\zeta_{l,l+1}, \quad 1 < l < M \\ N'_M + \varpi_M\sigma_{M,M-1} \\ -\varpi_{M-1}\zeta_{M,M-1}, \quad l = M. \end{cases} \tag{41}$$

To simplify the expressions, we denote $\boldsymbol{a''} = \{a_{1,1},'' \ldots, a_{\tilde{N}_1,1},'' \ldots, a_{1,M},'' \ldots, a''_{\tilde{N}_M,M}\}$ and $\boldsymbol{b''} = \{b_{1,1},'' \ldots, b_{\tilde{N}_1,1},'' \ldots, b_{1,M},'' \ldots, b''_{\tilde{N}_M,M}\}$. Accordingly, jointly considering the two cases mentioned above, problem P3 can be reformulated as problem P4, as shown in (42), at the bottom of the page, where 4-C1 and 4-C2 are similar to 3-C1 and 3-C2 in problem P3 except for the $\tilde{N}_l$ indicating the number of potential request vehicles in each road segments after adjustment from N'_l. In the formulated optimization problem P4, 4-C2 describes that a vehicle should not be allocated to more than two links, i.e., a vehicle receives content either from an RSU in the current road segment or a CRV in the current or adjacent road segments.

B. Immune Clone-Based Algorithm for Solving Optimization Problem P4

From the structure of problem P4, we know it is a nonlinear integer programming problem or rather a nonlinear zero-one programming problem. Problem P4 has more complex expressions than a general zero-one programming problem, which makes it hard to find the optimal solution. Fortunately, the development of intelligent optimization methods make it easier to solve problem P4. Inspired by the artificial immune system (AIS), we proposed an immune clone-based algorithm for solving P4. The concept of the immune clone is motivated by the AIS that simulates the natural immune system. AIS is a new intelligent optimization method and can solve complex problems. AIS has become another research focus in the area of artificial intelligence after evolutionary computation, fuzzy system, and neural network [40]. For the sake of readability, we first briefly introduce some important terms in AIS in the following.

1) *Antigen:* In immunology, any substance that can induce an immune response is called an antigen. In problem P4, the objective function U is the antigen.
2) *Antibody:* Antibody is a kind of protein that is produced mainly by the plasma cells to recognize and bind to antigens. In problem P4, a solution is an antibody.
3) *Antibody Population:* Several antibodies make up an antibody population. The number of antibodies in an antibody population is called the population size.
4) *Fitness:* Fitness is a value indicating how an antibody is suitable for the antigen. The higher the FV[2] is, the more suitable is the antibody suitable for the antigen.

[2]Here, the FV refers to the value of the optimization function of problem P4, i.e., U^4. It is noteworthy that the meaning of FV here is different from that in selecting the most proper CRV in Section V-B.

$$\begin{aligned} U''_l = \frac{1}{|t|}\sum_{n=1}^{\tilde{N}_l} a''_{n,l}&\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|}\left\lfloor\frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{\tilde{N}_l} a''_{n,l}}\right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2I}}\left(\hat{t}\right)}{\left\lfloor\frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{\tilde{N}_l} a''_{n,l}}\right\rfloor}\right)d\hat{t}\right) - p^{\mathsf{RSU}}|t|\right) \\ &+ b''_{n,l}\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|}\left\lfloor\frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{\tilde{N}_l} b''_{n,l}}\right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2V}}\left(\hat{t}\right)}{\left\lfloor\frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{\tilde{N}_l} b''_{n,l}}\right\rfloor}\right)d\hat{t}\right) - p^{\mathsf{CRV}}|t|\right) \end{aligned} \tag{40}$$

$$\begin{aligned} \text{(P4)} \max_{\boldsymbol{a''},\boldsymbol{b''}} \; U^4 = \sum_{l=1}^{M} U''_l = \frac{1}{|t|}\sum_{l=1}^{M}\sum_{n=1}^{\tilde{N}_l} a''_{n,l}&\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|}\left\lfloor\frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{\tilde{N}_l} a''_{n,l}}\right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2I}}\left(\hat{t}\right)}{\left\lfloor\frac{K_{\mathsf{LTE}}}{\sum_{n=1}^{\tilde{N}_l} a''_{n,l}}\right\rfloor}\right)d\hat{t}\right) - p^{\mathsf{RSU}}|t|\right) \\ &+ b''_{n,l}\left(\xi_n \ln\left(\int_{t_{\mathsf{start}}}^{t_{\mathsf{start}}+|t|}\left\lfloor\frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{\tilde{N}_l} b''_{n,l}}\right\rfloor \log_2\left(1 + \frac{\omega_{\mathsf{V2V}}\left(\hat{t}\right)}{\left\lfloor\frac{K_{\mathsf{DSRC}}}{\sum_{n=1}^{\tilde{N}_l} b''_{n,l}}\right\rfloor}\right)d\hat{t}\right) - p^{\mathsf{CRV}}|t|\right) \\ \text{s.t.} \quad & \text{4-C1}: a''_{n,l} \in \{0,1\}, b''_{n,l} \in \{0,1\} \quad \forall n \in \tilde{\mathbb{V}}_l, l \in \mathbb{S}^{\mathsf{seg}} \\ & \text{4-C2}: a''_{n,l} + b''_{n,l} \leq 1 \quad \forall n \in \tilde{\mathbb{V}}_l, l \in \mathbb{S}^{\mathsf{seg}} \end{aligned} \tag{42}$$

In problem P4, the fitness is the value of system utility, i.e., the value of U^4.

5) *Population Coding:* Population codes are neural representations at the level of groups of cells. For problem P4, the process of mapping the variables to the representation of antibodies is called population coding.
6) *Fitness Evaluation:* The process of calculating the FV for each antibodies is called fitness evaluation.
7) *Clone Operation:* It creates more of the same antibodies. In problem P4, it means creating more of the same solutions.
8) *Mutation Operation*: Changing the expressions of antibody is called mutation operation. In problem P4, it means adjusting the value of some variables in the solution.
9) *Population Updating:* Replacing low-fitness antibodies with high-fitness ones is called population updating.

The immune clone algorithm is a search algorithm for the iterative process. In the iterative process, a memory unit is created to reserve the best antibodies of the previous generation, which accelerates the iterative process to a global convergence. In the following, we present the detailed steps of the immune clone-based content distribution algorithm.

1) Initialization: The number of iterations η is initialized to 0, and the population $\Psi(\eta)$ is randomly generated as

$$\Psi(\eta) = \{\psi_1(\eta), \psi_2(\eta), \dots, \psi_p(\eta)\} \tag{43}$$

where p is the population size, each $\psi_i(\eta)$ $(1 \le i \le p)$ in $\Psi(\eta)$ is an antibody that represents the allocation of wireless links between request vehicles and CRVs or RSUs. Each antibody is expressed as a matrix A_i with $\tilde{N}_1 + \tilde{N}_2 + \cdots + \tilde{N}_M$ rows and $2 \times M$ columns. All the elements in the first M columns of A_i exactly represent all the $a''_{n,l}$ $(n \in \tilde{N}_l, l \in \mathbb{S}^{\mathsf{seg}})$ in problem P4. All the elements in the remaining N_s columns of A_i exactly represent all the $a''_{n,l}$ $(n \in \tilde{N}_l, l \in \mathbb{S}^{\mathsf{seg}})$. We also set up a memory unit, denoted by $MU(\eta)$ with the size of ς, and set it void initially.

2) Mapping of the Expression of Antibody to Content Distribution Scheme: We use row and col to denote the index of row and column of each A_i, respectively, where $1 \le \text{row} \le \tilde{N}_1 + \tilde{N}_2 + \cdots + \tilde{N}_M$ and $1 \le \text{col} \le 2 \times M$. The expression A_i of each antibody is mapped to its corresponding content distribution scheme according to the following criterion: 1) when $l = 1$ and $1 \le \text{row} \le N_1$, the elements in the first M columns is mapped to $a''_{n,1}$ in problem P4. Similarly, the elements in the remaining M columns are mapped to $b''_{n,1}$ in problem P4 and 2) when $1 < l \le M$ and $\tilde{N}_1 + \cdots + \tilde{N}_{l-1} + 1 \le \text{row} \le \tilde{N}_1 + \cdots + \tilde{N}_l$, the elements in the first M columns are mapped to $a''_{n,l}$ in problem P4. Similarly, the elements in the remaining M columns are mapped to $b''_{n,l}$ in problem P4.

3) Modification According to Constraints: The distance between each request vehicle and content distribution source must be taken into consideration. The situation that the element $\kappa_{\text{row,col}}$ in A equals 1 must be under the condition as described in (34), (35), (38), and (39), otherwise, set it to 0. For the arbitrary request vehicle, the constraints 4-C2 in P4 must be satisfied. To this end, the following operation is adopted: for arbitrary row in A_i, if there exist two or more elements that equal 1 simultaneously, let one element equals 1 randomly and other elements equal 0.

4) Fitness Evaluation: The FV of each antibody in $\Psi(\eta)$ is first calculated out according to (42), and then pick out ς $(\varsigma < p)$ antibodies that have the highest FVs. Thereafter, update $MU(\eta)$ according to the following two cases: 1) store the ς antibodies in $MU(\eta)$ if $MU(\eta)$ is empty and 2) if $MU(\eta)$ is not empty, combine the existing ς antibodies in $MU(\eta)$ with the ς antibodies that are newly picked out, and again, pick out ς antibodies that have the highest FVs among the combined $2 \times \varsigma$ antibodies to store in $MU(\eta)$.

5) Termination Condition Judgment: If the iterations reach preset maximum number of iterations, denoted by $\eta_{\max}$, pick out the antibody with the highest FV from $MU(g)$ and map it to its corresponding content distribution. Otherwise, go to step 6).

6) Clone Operation: Clone the antibodies in $MU(\eta)$ to produce more antibodies, the clone operation, denoted by Θ^c, is defined as

$$\Psi'(\eta) = \Theta^c(\Psi(\eta)) = \left[\Theta^c(\psi_1(\eta)), \dots, \Theta^c(\psi_\varsigma(\eta))\right]^T. \tag{44}$$

For each antibodies among the ς antibodies in $MU(\eta)$, the cloning number of the qth antibody $\psi_q(\eta)$ $(1 \le q \le \varsigma)$ is denoted by N_q^{clone}, which is defined as

$$N_q^{\mathsf{clone}} = \left\lceil \frac{\nu f(\psi_q(\eta))}{C^{\mathsf{conc}}(\psi_q(\eta)) \sum_{h=1}^{\varsigma} f(\psi_h(\eta))} \right\rceil \tag{45}$$

where ν is a control parameter and meets the condition that $\nu > \varsigma$, $f(\cdot)$ denotes antibody FV, and $\lceil \cdot \rceil$ denotes a ceil function. $C^{\mathsf{conc}}(\psi_q(\eta))$ denotes the concentration of antibody $\psi_q(\eta)$, which is defined as

$$C^{\mathsf{conc}}(\psi_q(\eta)) = \sum_{h=1}^{\varsigma} S_a(\psi_q(\eta), \psi_h(\eta)) \tag{46}$$

where $S^{\mathsf{anti}}(\cdot)$ is the similarity of antibodies and formulated as

$$S^{\mathsf{anti}}(\psi_q(\eta), \psi_h(\eta)) = \begin{cases} 1, & d_H(\psi_q(\eta)), \psi_h(\eta) < \theta \\ 0, & \text{otherwise} \end{cases} \tag{47}$$

where $d_H(\cdot)$ is the Hamming distance between two antibodies, and θ denotes a threshold. After the clone operation, the population is formulated as

$$\Psi'(\eta) = \left\{\psi'_1(\eta), \psi'_2(\eta), \dots, \psi'_{p'}(\eta)\right\} \tag{48}$$

where $p' = \sum_{q=1}^{\varsigma} N_q^{\mathsf{clone}}$ denotes the population size after the clone operation.

7) Mutation Operation: Change the binary code value of each antibody $\psi'_i(\eta)$ $(1 \le i \le p')$ in $\Psi'(\eta)$ with the probability of p^{mut}. That is to say, make the binary code value inverse with the probability of p^{mut} (i.e., from 0 to 1 or from 1 to 0). The mutation operation Θ^m is formulated as

$$\begin{aligned}\Psi''(\eta) &= \Theta^m(\Psi'(\eta)) \\ &= \left[\Theta^m(\psi'_1(\eta)), \dots, \Theta^m\left(\psi'_{p'}(\eta)\right)\right]^T.\end{aligned} \tag{49}$$

For each $\Theta^m(\psi_i'(\eta))$, the probability is calculated by

$$p\big(\psi_i'(\eta) \to \psi_i''(\eta)\big) = \Big(p^{\mathsf{mut}}\Big)^{d_H(\psi_i'(\eta),\psi_i''(\eta))}\Big(1-p^{\mathsf{mut}}\Big)^{\left(\ell-d_H\left(\psi_i'(\eta),\psi_\varsigma''(\eta)\right)\right)} \quad (50)$$

where ℓ is the length of the binary code for each antibody, which is equal to $(\tilde{N}_1 + \tilde{N}_2 + \cdots + \tilde{N}_M) \times 2 \times M$. After the mutation operation, the population is denoted as

$$\Psi''(\eta) = \left\{\psi_1''(\eta), \psi_2''(\eta), \ldots, \psi_{p'}''(\eta)\right\}. \quad (51)$$

8) Population Updating Operation: There are two cases in the process of updating the population for the purpose of maintaining the scale of population: 1) if $\sum_{q=1}^{\varsigma} N_q^{\mathsf{clone}} < p$, randomly generate $p - \sum_{q=1}^{\varsigma} N_q^{\mathsf{clone}}$ new antibodies and add them in the new antibody population, denoted by $\Psi(\eta+1)$ and 2) if $\sum_{q=1}^{\varsigma} N_q^{\mathsf{clone}} \geq p$, select out p antibodies with the highest FVs to form $\Psi(\eta+1)$. The population updating operation is represented by $\Psi(\eta+1) = \Theta^{\mathsf{u}}(\Psi''(\eta))$. Then, continue step 2).

Proposition 1 (Convergence): The proposed immune clone-based content distribution algorithm converges with probability 1. We denote the global optimal solution as G^* and the number of optimal solutions of population Ψ as $\chi(\Psi)$. Then, the following formula always holds for the arbitrary initial state Ψ_0:

$$\lim_{\eta\to\infty} p\big\{\Psi(\eta) \cap G^* \neq \varnothing | \Psi(0) = \Psi_0\big\} = \lim_{\eta\to\infty} p\{\chi(\Psi(\eta)) \geq 1 | \Psi(0) = \Psi_0\} = 1. \quad (52)$$

Proof: Interested readers may refer to the Appendix. ■

VII. Performance Evaluation

In this section, we evaluate and discuss the performance of our proposed EdgeVCD in terms of convergence, population size, ratio of CRVs, number of vehicles, and iterations. We also compare EdgeVCD with some benchmarks: 1) the content distribution scheme without fuzzy-logic-based method (EdgeVCD-noFL); 2) the genetic algorithm-based content distribution scheme (EdgeVCD-GA); and 3) the game-theoretic approach to parked vehicle assisted content distribution (GTA-PVACD) [26]. The performance evaluation is operated in MATLAB 2017a simulator.

A. Simulation Scenario and Parameter Configurations

We consider a simple but practical urban simulation scenario. The length of per lane is 1600 m and the width of per lane is 4 m. Four RSUs are deployed along the road with an interval of 400 m, the communication range of RSUs and vehicles is 200 and 100 m, respectively. For the behavior of vehicles, we use part of the GAIA Open Dataset containing mobility traces of DiDi Express in Xi'an, China [41]. The data set contains the GPS coordinates of DiDi Expresses over 30 days and over thousands of districts and roads. We randomly choose the traces of 40−80 DiDi Expresses with one district and use them as mobility traces for the vehicles in our simulations. The ratio of the number of CRVs to all vehicles N is defined as r. For simplicity, communication costs for V2I and V2V communications per unit time are represented by the transmitting powers of V2I and V2V links, respectively. The values of PoC and PoV are generated randomly from $\{1, 2, 3\}$. The major simulation parameters are summarized in Table IV.

TABLE IV
SIMULATION PARAMETERS

Parameter	Value
Number of vehicles N	$40 \sim 80$
Ratio of CRVs r	$0.2 \sim 0.6$
Transmission power P_{RSU}	43 dBm
Transmission power P_{CRV}	21 dBm
Noise spectral density N_0	−174 dBm/Hz
Path loss index α	4
Termination generation $\eta_{\max}$	1500
Size of the population p	$20 \sim 80$
Size of the memory unit ς	10
Control parameter ν	20
Mutation probability p^{mut}	0.3
Bandwidth of RSU K_{LTE}	12 MHz
Bandwidth of CRV K_{DSRC}	6 MHz

B. System Utility and Average Utility

The system utility, as well as the average utility, are as shown in Fig. 5(a)–(d), respectively. The relationship between the system utility and iterations as well as p are shown in Fig. 5(a) when we fix $N = 40$. The figure indicates that system utility increases rapidly with the increase of iterations at the beginning and converges to an optimal value as the iterations increase. Furthermore, it is obvious that system utility for different p has almost identical curves, which guides us that choosing $p = 20$ is enough for the purpose of reducing computational complexity. Let $p = 20$ and $r = 0.2$, the relationships between the system utility and the number of vehicles are as shown in Fig. 5(b). It is obvious that all curves increase as the iterations increase and converge to optimal values, respectively. The system utility increases as N increases, which is because the system utility is the sum of utilities of all request vehicles. More important, our proposed EdgeVCD has a higher system utility than the benchmark scheme EdgeVCD-noFL. The reason is that the fuzzy-logic method that jointly considers three factors is adopted for the selection of most proper CRV if several CRVs coexists over a certain road segment, which contributes to the system utility. Furthermore, we set $p = 0.2$ and then reveal how the ratio of CRVs r impacts the system utility varying with N from 40 to 80 over two schemes, as shown in Fig. 5(c). It is obvious that system utility for all curves decline with the increase of r, which is due to the decrease of the number of request vehicles if r increases. Since the system utility is the sum of utilities of all request vehicles, the decrease of request vehicles thus results in the decrease of system utility. It is worth noting that our proposed EdgeVCD has a higher system utility than the benchmark scheme EdgeVCD-noFL, and the gap between the curves of the two schemes for a certain N is getting wider as

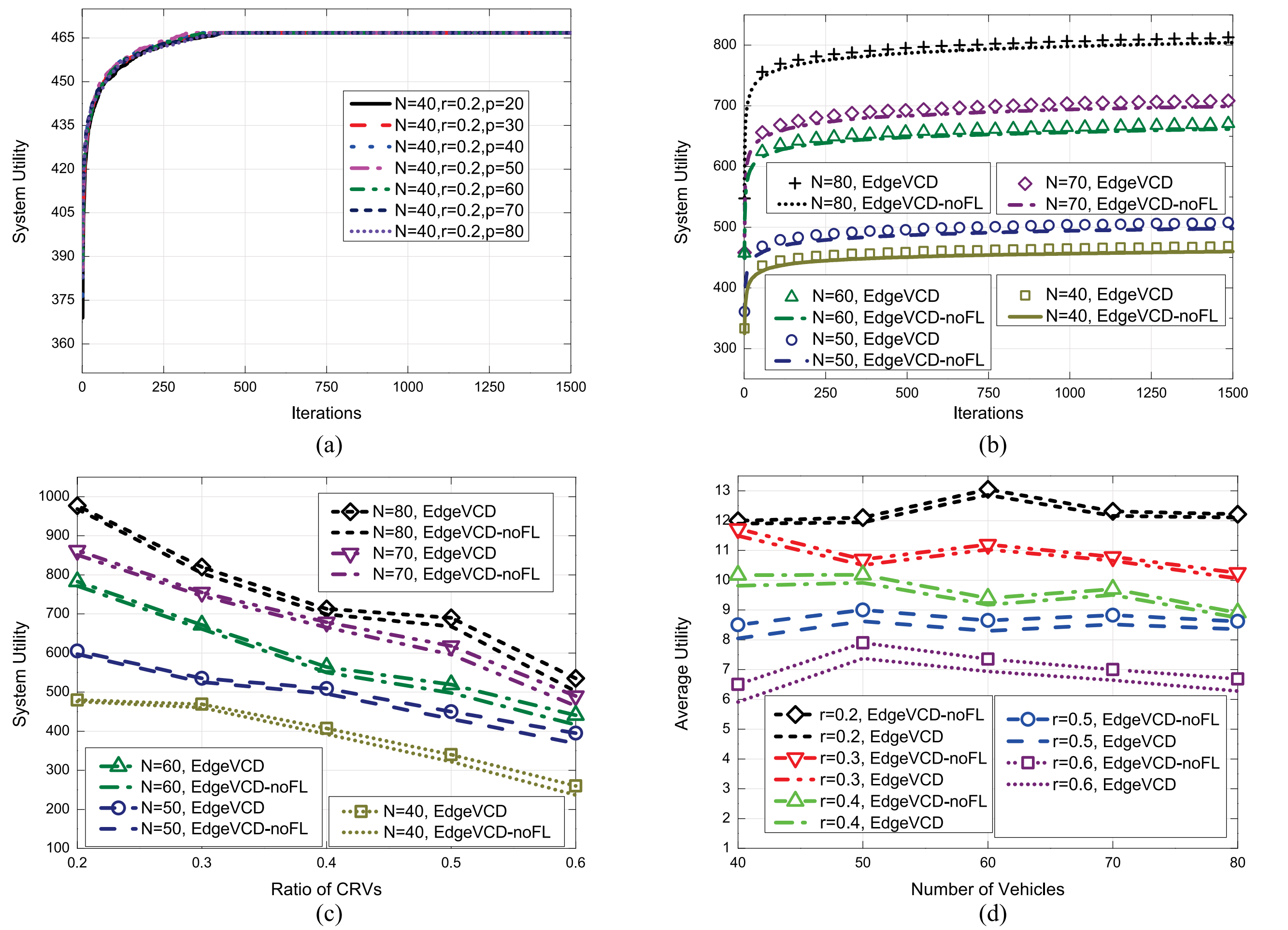

Fig. 5. System utility and average utility. (a) Convergence of the proposed EdgeVCD scheme. (b) Impact of iterations and the number of vehicles on system utility of EdgeVCD and EdgeVCD-noFL. (c) Impact of ratio of CRVs and the number of vehicles on system utility of EdgeVCD and EdgeVCD-noFL. (d) Impact of the number of vehicles and ratio of CRVs on the average utility of EdgeVCD and EdgeVCD-noFL.

r increases. This is because the probability of selecting CRV with higher FVs for content distribution will greatly increase as r increases. This contributes to the system utility.

We define the average utility as the ratio of system utility to the total number of vehicles. Fig. 5(d) illustrates the relationship between the average utility and N as well as r. Different from the system utility depicted in Fig. 5(c), where the curve with a higher value of N has a higher system utility for a certain r, it is not when $N = 80$ that the average utility depicted in Fig. 5(d) reaches the highest value among all five N values. Specifically, to achieve the highest average utility for different values of r, the value of N value varies. For example, average utility reaches the highest value when N is equal to 60, 40, 50, 50, and 50 for r equals 0.2, 0.3, 0.4, 0.5, and 0.6, respectively. Similar to the conclusion from Fig. 5(c), our proposed EdgeVCD has a higher average utility than the benchmark scheme EdgeVCD-noFL, and the gap between the curves of the two schemes for a certain N is getting wider as r increases.

In order to compare the system utility of proposed EdgeVCD with the benchmark schemes EdgeVCD-noFL and GTA-PVACD, we set $N = 40$, $r = 0.3$, and $p = 20$ and then reveal the system utility of the three schemes in Fig. 6. It is obvious that our proposed EdgeVCD has a higher system utility than EdgeVCD-noFL, the reason has been explained in the previous paragraph. It is worth noting that both our proposed EdgeVCD and the benchmark scheme EdgeVCD-noFL have a higher system utility than the benchmark scheme GTA-PVACD. This is because both the EdgeVCD and EdgeVCD-noFL schemes evaluate DI by jointly considering vehicle types and content types.

C. Convergence

Fig. 7 shows the convergence speed of our proposed EdgeVCD compared with EdgeVCD-GA when we fix $N = 40$, $r = 0.2$, and $p = 20$. It is obvious from Fig. 7 that the system utility of EdgeVCD converges when the iteration reaches 429 compared to 683 of EdgeVCD-GA. The reason is that our proposed EdgeVCD utilizes the memory unit to store ς most optimal antibodies in each iteration, which contribute to the rapid convergence of our proposed EdgeVCD-GA. What is more, an adaptive clone method is adopted during clone operation, where low-concentration and high-fitness antibodies have more clones. Accordingly, the diversity of the antibody population is guaranteed and a local optimum is avoided.

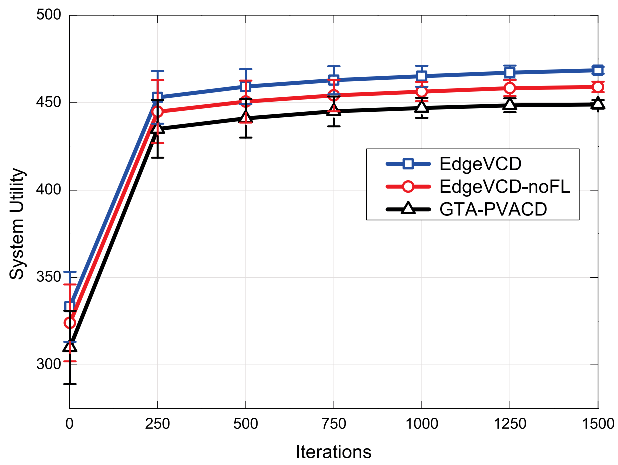

Fig. 6. Comparison for system utility of three schemes.

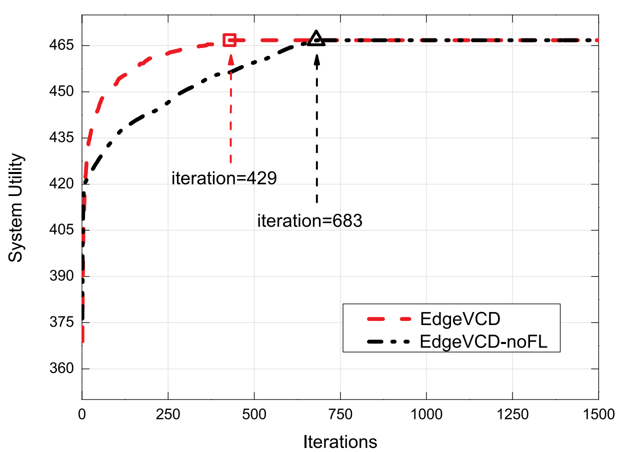

Fig. 7. Comparison for convergence of EdgeVCD and EdgeVCD-GA.

D. System Throughput

When the system utility reaches optimal values, the variations of system throughput of our proposed EdgeVCD against the number of vehicles and ratio of CRVs are shown in Figs. 8 and 9 when we fix $p = 20$. Fig. 8 indicates that system throughput for variable values of r increases with the increase of N except two points (i.e., for $r = 0.4$, $N = 80$ and for $r = 0.5$, $N = 60$). The reason is that system throughput is the sum of throughput of all request vehicles, the increase of N thus benefits system throughput. In addition, since the purpose of our proposed EdgeVCD is to maximize the system utility, not the system throughput, the variation tendency of system throughput may not be consistent with that of the system utility. Fig. 9 depicts the variations of system throughput for the variable N against r. As r increases, the system utility increases at the beginning and then decreases. This is because that when r gets a small value, the number of CRVs is also small, more request vehicles receive the corresponding content from RSUs, resulting in less bandwidth resources that can be allocated to each request vehicle and low system throughput. When r increases gradually, more CRVs can be used for content distribution and can distribute more corresponding content to request vehicles, thus the system throughput increases. When r keeps increasing, the number of request vehicles receiving corresponding content from CRVs and RSUs decreases, thus the system throughput decreases.

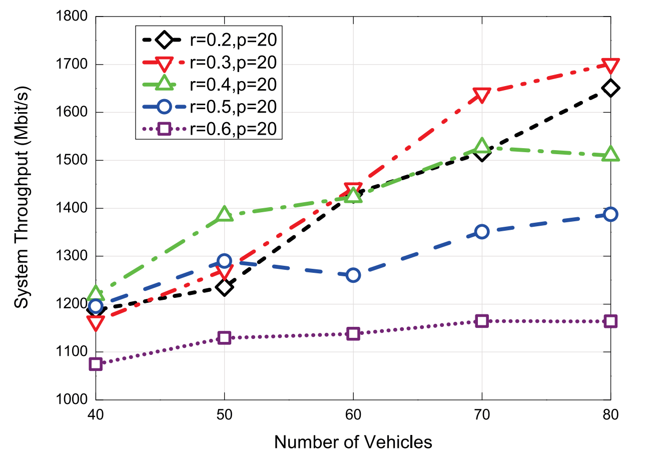

Fig. 8. Impact of the number of vehicles and ratio of CRVs on system throughput.

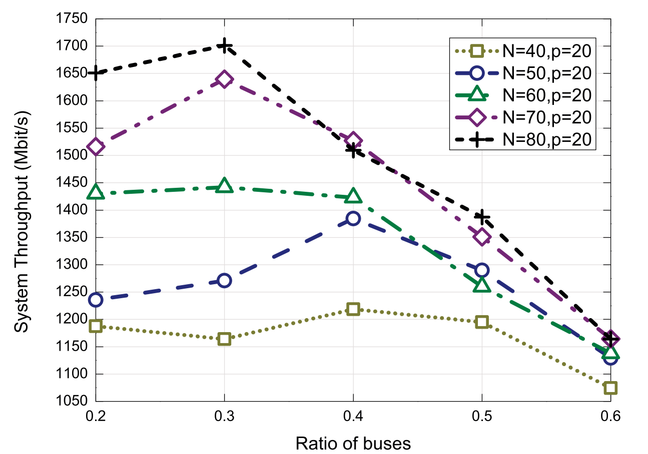

Fig. 9. Impact of ratio of CRVs and the number of vehicles on system throughput.

E. Spectrum Efficiency

Fig. 10 depicts the spectrum efficiency against the number of vehicles and ratio of CRVs. The spectrum efficiency is defined as the ratio of achieved system throughput to the bandwidth. With the number of vehicles increasing, spectrum efficiency decreases. Because the available bandwidth resource increases with the increase of N, and the increment of system throughput due to the increase of bandwidth resource is less than the increment of bandwidth resource due to the increase of N. Furthermore, for a certain N, the spectrum efficiency decreases as r increases. This is because the system throughput decreases as r increases, as shown in Fig. 9, thus the spectrum efficiency decreases.

VIII. Conclusion

In this article, we have investigated content distribution in the VEC network. We propose EdgeVCD, an intelligent algorithm-inspired content distribution scheme. Specifically, we propose a DI evaluation approach by jointly considering

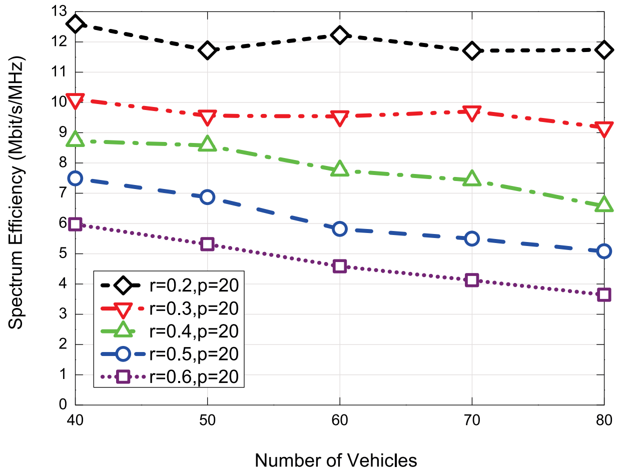

Fig. 10. Spectrum efficiency versus N and r.

PoV and PoC to decide the preference for PoV and PoC during content distribution. In order to make use of the limited V2I and V2V communication resources, we formulate an optimization to maximize the system utility for content distribution, which is an MIP problem. To obtain the optimal solution efficiently, we divide the road into small segments. Based on that, we propose a fuzzy-logic-based method to select the most proper CRV and redefine the number of content request vehicles in each segment. Thereafter, the original optimization problem is gradually transformed into a nonlinear integer programming problem. Inspired by the AIS, we propose an immune clone-based algorithm to solve it, which has a fast convergence to the optimal solution. Moreover, numerous simulations show the effectiveness of our proposed EdgeVCD compared with the existing works and also shown the significant impact of the population size, ration of CRVs, and number of vehicles on spectrum efficiency, system utility, system throughput, and convergence. In the future, we will consider the content size that distributed to each request vehicle and analyze the impact of various parameters on content size.

Appendix
Proof for the Convergence of EdgeVCD

A variable $p_0(\eta)$ is defined as

$$p_0(\eta) = p\{\chi(\Psi(\eta)) = 0\} = p\big\{\Psi(\eta) \cap G^* \neq \varnothing\big\} \tag{53}$$

and based on Bayes' formula, $p_0(\eta+1)$ can be formulated as

$$\begin{aligned} &p_0(\eta+1)\\ &\quad= p\{\psi(\Psi(\eta+1)) = 0\}\\ &\quad= p\{\chi(\Psi(\eta+1)) = 0|\chi(\Psi(\eta)) \neq 0\}p\{\chi(\Psi(\eta)) \neq 0\}\\ &\qquad+ p\{\chi(\Psi(\eta+1)) = 0|\chi(\Psi(\eta)) = 0\}p\{\chi(\Psi(\eta)) = 0\}. \end{aligned} \tag{54}$$

Base on the definition of $\psi(P)$, the following formula holds:

$$p\{\chi(\Psi(\eta+1)) = 0|\chi(\Psi(\eta)) \neq 0\} = 0. \tag{55}$$

Hence

$$p_0(\eta+1) = p\{\chi(\Psi(\eta+1)) = 0|\chi(\Psi(\eta)) = 0\}p_0(\eta). \tag{56}$$

It is assumed that ϵ is defined as

$$\epsilon = \min_{\eta} \chi(\Psi(\eta+1)) \geq 1|\chi(\Psi(\eta)) = 0, \eta = 0, 1, 2, \ldots \tag{57}$$

Hence

$$p\{\chi(\Psi(\eta+1)) \geq 1|\chi(\Psi(\eta)) = 0\} \geq \epsilon \ > 0 \tag{58}$$

then the following formula holds:

$$\begin{aligned} &p\{\chi(\Psi(\eta+1)) = 0|\chi(\Psi(\eta)) = 0\}\\ &\quad= 1 - p\{\chi(\Psi(\eta+1)) \neq 0|\chi(\Psi(\eta)) = 0\}\\ &\quad= 1 - p\{\chi(\Psi(\eta+1)) \geq 1|\chi(\Psi(\eta)) = 0\}\\ &\quad= 1 - \epsilon < 1. \end{aligned} \tag{59}$$

Therefore

$$\begin{aligned} 0 \leq p_0(\eta) &\leq (1-\epsilon)p_0(\eta)\\ &\leq (1-\epsilon)^2 p_0(\eta-1)\\ &\leq \cdots\\ &\leq (1-\epsilon)^{\eta+1}p_0(0). \end{aligned} \tag{60}$$

Since ϵ and $p_0(\eta)$ meet the following two conditions:

$$\lim_{\eta\to\infty} (1-\epsilon)^{\eta+1} = 0 \tag{61}$$

$$0 \leq p_0(\eta) \leq 1. \tag{62}$$

Hence

$$0 \leq \lim_{\eta\to\infty} p_0(\eta) \leq \lim_{\eta\to\infty} (1-\xi)^{\eta+1}p_0(0) = 0. \tag{63}$$

Hence

$$\lim_{\eta\to\infty} p_0(\eta) = 0. \tag{64}$$

Hence, the following formula holds:

$$\begin{aligned} \lim_{\eta\to\infty} p\big\{(\Psi(\eta)) \cap G^* \neq \varnothing|\Psi(0) = \Psi_0\big\} &= 1 - \lim_{\eta\to\infty} p_0(\eta)\\ &= 1. \end{aligned} \tag{65}$$

Namely

$$\lim_{\eta\to\infty} p\{\chi(\Psi(\eta)) \geq 1|\Psi(0) = \Psi_0\} = 1. \tag{66}$$

Proposition 1 is proved.

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