

Efficient Vehicular Content Distribution for B5G C-V2X Networks: A Matching Theory Approach

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Abstract—With the rapid development of cellular vehicle-to-everything (C-V2X) networks, a great number of vehicular users (VUEs) will be connected for content distribution, which is with the challenges of high mobility of VUEs and frequent network handovers of 5G networks. Recently, a network architecture called 6G fully-decoupled radio access network (FD-RAN) was proposed, which has the potential to solve these challenges. This paper investigates the efficient vehicular edge content distribution in the fully-decoupled downlink beyond 5G (B5G) C-V2X networks, in which multiple base stations (BSs) can be collaborated to increase the data download volume of VUEs and realize the efficiency of vehicular content distribution. Considering the high mobility of vehicles, user fairness, and system capacity, we propose an effective vehicular content distribution method by leveraging the many-to-many matching theory. We transform the content distribution problem into the matching game between BSs and VUEs. Furthermore, we propose a vehicular content distribution algorithm (VCDA) to achieve a stable solution for efficient vehicular content distribution. Extensive simulation results demonstrate the efficiency and superiority of the VCDA, which is compared with the random multiple connection algorithm in which each VUE can select BSs within the limited range.

Index Terms—B5G C-V2X, vehicular content distribution, many-to-many matching theory, multiple connections.

I. INTRODUCTION

WITH the commercial deployment of 5G in the world, cellular vehicle-to-everything (C-V2X) networks are considered to be an important part of the beyond 5G (B5G) [1]. Lots of applications are developed to improve road safety, realize intelligent transportation, and provide entertainment services for vehicle users (VUEs) [2]–[4], which are inseparable from the efficient vehicular content distribution. How to realize content distribution in the vehicular environment with massive data requests, high mobility, and high density is a huge challenge.

Nowadays, vehicular content distribution has attracted a lot of attention. Shahzad and Antoniou [5] pointed out that the swelling data requested by VUEs is not viable for 5G networks in a dense urban scenario because of the high mobility of VUEs. What's more, the small coverage of 5G networks leads to network densification and frequent network handovers [6], which makes it difficult to realize the continuous management of vehicular content distribution. In [7], because the high mobility leads to the quite limited data download volume of each vehicle, Trullols et al. considered complex (nonlinear)

urban roads, let vehicles download content cooperatively, and transmitted content to requesting vehicles. Wang et al. [8] made full use of the two-way traffic flow and proposed a cooperative store-carry-forward mechanism to select the appropriate relay vehicles from the same and reverse traffic flow. In order to encourage vehicles to participate in cooperative content distribution, Hui et al. [9] proposed a multi-relay vehicles incentive and selection scheme for delay tolerant data. They leveraged the first price sealed auction method to select the vehicle with the lowest bidding price and the required transmission capacity as the relay vehicle. In [10], Saad et al. studied a new cooperation strategy between roadside units, and proposed a distributed alliance formation algorithm. For the current 5G networks, the high mobility of VUEs and frequent network handovers make it difficult to meet the rapidly increasing content request of VUEs, so it is urgent to explore the flexible network architecture and efficient vehicular content distribution methods.

For the dilemma of the previous research, the 6G fully-decoupled radio access network (FD-RAN) proposed by Yu et al. [11] has the potential to solve these challenges. FD-RAN physically decouples the base stations (BSs) into the control BSs, uplink BSs (UL BSs), and downlink BSs (DL BSs). DL BSs are only responsible for downlinking data transmission and are controlled by the control BS for uniform resource scheduling. Such full physically decoupling is beneficial to information fusion and resource collaboration. Thus, the cooperation between DL BSs can be better realized in FD-RAN, where multi-connection becomes the default association mode. Compared with the single connection in 5G, multi-connection can provide users with a better transmission rate without frequent handovers. Through the flexible cooperation between DL BSs and better resource scheduling, FD-RAN can potentially solve these challenges and improve the efficiency of vehicular content distribution.

In this paper, we consider vehicular content distribution in the fully-decoupled downlink B5G C-V2X networks. We allocate multiple cellular base stations (BSs) to serve the VUE to meet the VUE's request for massive data content. Due to the high mobility of VUEs, to reduce the handovers of BSs as much as possible, we not only consider the current channel capacity between the VUE and the BSs, but also consider the channel capacity of the VUE in the future time

by simply predicting the position of the vehicle in the future time. In addition, the fairness of VUEs and system capacity also need to be considered. Facing these issues, we propose a vehicular content distribution algorithm (VCDA) to achieve a stable solution for the proposed efficient vehicular content distribution. Compared with the previous literature, the novelty and contributions of this paper are highlighted as follows:

- We leverage the fully-decoupled downlink B5G C-V2X networks to allocate multiple BSs for VUEs, which can increase the data download volume of each VUE and improve the efficiency of vehicular content distribution.
- We transform the content distribution into a matching problem and propose VCDA to achieve a stable solution based on the many-to-many matching theory.
- We conduct extensive simulations to prove the superiority of VCDA, which is compared with random single connection algorithm and random multiple connection algorithm.

The remainder of this paper is organized as follows. We first describe the system model in Section II. The content distribution algorithm is proposed in Section III. Results are presented in Section IV. Section V concludes the paper.

II. SYSTEM MODEL

A. Vehicular Content Distribution Scenario in B5G C-V2X Networks

As shown in Fig. 1, the considered system of this paper is the downlink scenario of the FD-RAN architecture, which is mainly composed of control BSs, edge cloud, DL BSs, and VUEs. The control BS is the core of content distribution, which collects and integrates real-time information from DL BSs. Because the control BS has a wide range of global information and large computing power, it is also the best place to execute the content distribution algorithm. In addition, it controls all DL BSs, transmits control information, and allocates BSs to each requesting VUE efficiently and reasonably to improve the overall benefit. Edge cloud has rich computing and caching resources. It can provide VUEs with various data contents and meet the personalized content requests to reduce the pressure of the centralized cloud, balance workload, reduce access latency, and improve interoperability [12].

B. Content Distribution Mechanism

Based on the content distribution scenario described in the previous subsection, this paper divides the content distribution into three stages, in which the control BS plays a core role. The three stages of the content distribution mechanism are as follows:

(1) The control BS collects and stores the base information of BSs and roads which maintains constant with time, such as the location and resources of all BSs, road topology, etc. DL BSs collect vehicle-related real-time information, including location, speed, data request, etc. Then this information is transmitted to the control BS for integration and processing.

(2) The control BS predicts the future location of the vehicle according to the obtained vehicle-related information, carries out the system modeling, and executes VCDA based

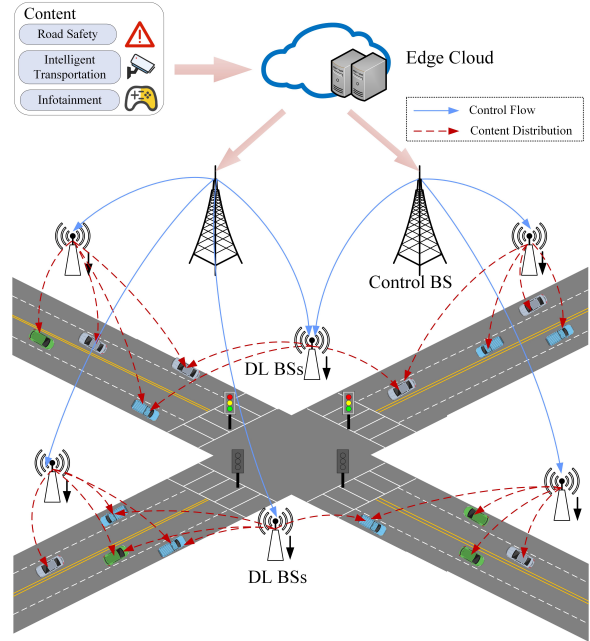


Fig. 1: Vehicular content distribution in the fully-decoupled downlink B5G C-V2X networks.

on the many-to-many matching theory to obtain the content distribution scheme, aiming to maximize the system capacity of the C-V2X network. After that, DL BSs submit to the arrangements of the control BS and serve the VUEs assigned to them.

(3) Each DL BS obtains the data content requested by the VUE from the edge cloud according to the control information sent by the control BS and distributes the content to the corresponding requesting VUE to accomplish the content distribution task.

C. Problem Formulation

Denote the VUEs set as $V = \{V_1, V_2, \dots, V_i, \dots, V_M\}$, where i is the index of the VUE and M is the number of VUEs. Denote the BSs set as $B = \{B_1, B_2, \dots, B_j, \dots, B_K\}$, where j is the index of the BS and K is the number of BSs. The set of subchannels corresponding to each BS is recorded as $S = \{S_1, S_2, \dots, S_j, \dots, S_K\}$, where S_j indicates that BS B_j has S_j subchannels.

Construct a matrix $\mathbf{A}(t)$ of size $M \times K$ to represent the connections between VUEs and BSs at time t . The elements in the matrix $\mathbf{A}(t)$ are recorded as $a_{i,j} \in \{0, 1\}$. $a_{i,j} = 1$ means the BS B_j serves the VUE V_i while $a_{i,j} = 0$ means the BS B_j does not serve the VUE V_i .

The BS B_j has S_j subchannels and serves S_j VUEs. The maximum service capacity of the BS B_j can be represented as follows:

$$\sum_{i \in V} a_{i,j} \leq S_j, \forall j \in B \quad (1)$$

In order to make full use of the channel resources of the BS, when the number of VUEs served by the BS B_j is less

than the number of subchannels, we assume that the BS B_j uniformly distributes the subchannels to the serving VUEs. The number of subchannels allocated by the BS B_j to the VUE V_i it serves is:

$$m_{i,j} = \lfloor \frac{S_j}{\sum_{i \in V} a_{i,j}} \rfloor \quad (2)$$

where $\lfloor \cdot \rfloor$ means rounding down.

Taking the fairness of VUEs into consideration, we set that each VUE can be served by b BSs at most. This restriction is expressed as follows:

$$\sum_{j \in B} a_{i,j} \leq b, \quad \forall i \in V \quad (3)$$

The channel capacity of VUE V_i on the BS B_j is

$$C_{i,j} = W_{i,j} \log_2(1 + SNR_{i,j}) \quad (4)$$

The bandwidth of each subchannel of BS B_j is denoted as W_j . The channel bandwidth allocated by BS B_j to VUE V_i is $W_{i,j} = m_{i,j} W_j$.

Referring to [13], we assume that nearby interfering BSs use different spectrum resource to avoid the interference among users. Thus, the signal-to-noise ratio (SNR) is:

$$SNR_{i,j} = \frac{P_{i,j} g_{i,j}}{n_{i,j}} \quad (5)$$

where $P_{i,j}$ is the power allocated by BS B_j to VUE V_i . We assume that all BSs distribute power to each subchannel uniformly, so $P_{i,j} = m_{i,j} \frac{P_j}{S_j}$, where P_j is the power of BS B_j . $g_{i,j}$ is the channel gain between BS B_j and VUE V_i . $n_{i,j}$ is additive gaussian white noise (AGWN), $n_{i,j} \sim N(0, \sigma_n^2)$.

At time t , the sum rate of VUE V_i is

$$C_{V_i}(t) = \sum_{j \in B} a_{i,j} C_{i,j} \quad (6)$$

At time t , the sum rate of BS B_j is

$$C_{B_j}(t) = \sum_{i \in V} a_{i,j} C_{i,j}(t) \quad (7)$$

Considering the high-speed mobility of vehicles, when designing the utility function of the VUE, we predict the location of the vehicle in the future (i.e., the future N time interval, the predicted time interval is recorded as τ), and calculate the future sum rate between the VUE and the BS. Assuming that the content distribution scheme remains unchanged in the future N time intervals, we take the future average transmission rate of VUE V_i at the current time t and N time intervals as the utility of VUE V_i at the current time t , which means:

$$U_{V_i}(t) = \bar{C}_{V_i}(t) = \frac{1}{N+1} \sum_{n=0}^N C_{V_i}(t+n\tau) \quad (8)$$

The utility of BS B_j is defined as follows:

$$U_{B_j}(t) = \bar{C}_{B_j}(t) = \frac{1}{N+1} \sum_{n=0}^N C_{B_j}(t+n\tau) \quad (9)$$

The utility function of the C-V2X network is defined as the total utility of all VUEs as follows:

$$U_{total} = \sum_{i \in V} U_{V_i}(t) \quad (10)$$

We can obtain the vehicular content distribution problem as

$$\begin{aligned} \max \quad & U_{total} \\ \text{s.t.} \quad & \sum_{i \in V} a_{i,j} \leq S_j, \forall j \in B \\ & \sum_{j \in B} a_{i,j} \leq b, \forall i \in V \\ & a_{i,j} \in \{0, 1\}, \forall i \in V, \forall j \in B \end{aligned} \quad (11)$$

III. VEHICULAR CONTENT DISTRIBUTION METHOD DESIGN

A. Many-to-many Matching Game

Due to two constraints and $a_{i,j} \in \{0, 1\}$, the problem (11) is a nonconvex problem [14]. The vehicular content distribution problem of multiple BSs services will be turned into a many-to-many bilateral matching game. We will use the matching theory to solve the vehicular content distribution problem (11). The time interval of vehicular content distribution is recorded as T_0 .

In the matching game, all players give priority to their own interests and will not make choices that harm their own interests. The control BS is the decision maker while all VUEs and BSs are selfish players. Each player knows the whole information of all players without additional communication costs because it is the control BS that has the whole information and executes the algorithm.

Definition 1 (Matching): If BS B_j serves VUE V_i , B_j and V_i become a match. Matching Ψ is to assign each BS in B to each VUE in V . It is the mapping of the set $V \cup B \cup \{0\}$ to all subsets of the set $V \cup B \cup \{0\}$. $\Psi(V_i)$ is the set of BSs that serve VUE V_i , and $\Psi(B_j)$ is the set of VUEs that BS B_j serves. $B_j \in \Psi(V_i)$ is equivalent to $V_i \in \Psi(B_j)$. $|\Psi(V_i)|$ is the number of BSs that serve VUE V_i and subject to $|\Psi(V_i)| \leq b$. $|\Psi(B_j)|$ is the number of VUEs that BS B_j serves and subject to $|\Psi(B_j)| \leq S_j$.

The final result of the matching game largely depends on the competition and choices among participants. In order to better describe the competition between players, we introduce the concept of preference.

Definition 2 (Preference of VUE): There are two different matchings Ψ and Ψ' , where $H_B = \Psi(V_i)$, $H'_B = \Psi'(V_i)$, and $H_B \neq H'_B$. For any VUE $V_i \in V$, its preference \succ_{V_i} for BSs can be described as follows:

$$(H_B, \Psi) \succ_{V_i} (H'_B, \Psi') \Leftrightarrow U_{V_i}(\Psi) > U_{V_i}(\Psi') \quad (12)$$

In this way, VUE V_i will prefer the BS subset H_B to the BS subset H'_B if VUE V_i gets more benefits from H_B than those from H'_B .

Definition 3 (Preference of BS): There are two different matchings Ψ and Ψ' , where $H_V = \Psi(B_j)$, $H'_V = \Psi'(B_j)$,

and $H_V \neq H'_V$. For any BS $B_j \in B$, its preference \succ_{B_j} for VUEs can be described as follows:

$$(H_V, \Psi) \succ_{B_j} (H'_V, \Psi') \Leftrightarrow U_{B_j}(\Psi) > U_{B_j}(\Psi') \quad (13)$$

In this way, BS B_j will prefer the VUE subset H_V to the BS subset H'_V if BS B_j gets more benefits from H_V than those from H'_V .

Stability in traditional one-to-one matching means that each player is satisfied with the current allocation and has no idea of changing the allocation after matching. Even in the many-to-one matching game, stable matching cannot be ensured, let alone the many-to-many matching game, mainly affected by peer effect. Inspired by reference [15], we give the concepts of swap and two-sided exchange stable (2ES) which are suitable for our model.

Swap means that the control BS arranges two VUEs to exchange their matching, while other VUEs keep their matching unchanged. The swap matching and swap pair are introduced to clearly describe the behavior of the swap.

Definition 4 (Swap Matching): For a given matching Ψ , $B_p \in \Psi(V_i)$, $B_q \in \Psi(V_j)$, $B_p \notin \Psi(V_j)$, $B_q \notin \Psi(V_i)$. If VUE V_i exchanges BS B_p for B_q with VUE V_j while other VUEs remain unchanged, the new matching after this exchange is called swap matching $\Psi_{jq}^{ip} = \Psi \setminus \{(V_i, B_p), (V_j, B_q)\} \cup \{(V_i, B_q), (V_j, B_p)\}$, where $B_q \in \Psi_{jq}^{ip}(V_i)$, $B_p \in \Psi_{jq}^{ip}(V_j)$, $B_q \notin \Psi_{jq}^{ip}(V_j)$, $B_p \notin \Psi_{jq}^{ip}(V_i)$.

However, not all swaps are approved. For the sake of players' own benefits, one player in the swap may be reluctant to exchange. Then, we introduce the swap pair to explain the approval conditions of swap operations.

Definition 5 (Swap Pair): For a given matching Ψ , (V_i, V_j) is a pair in Ψ , if it has $B_p \in \Psi(V_i)$ and $B_q \in \Psi(V_j)$, and meets two following conditions:

- (1) $\forall \beta \in \{V_i, V_j, B_p, B_q\}$, $(\Psi_{jq}^{ip}(\beta), \Psi_{jq}^{ip}) \succ_{\beta} (\Psi(\beta), \Psi)$
- (2) $\exists \beta \in \{V_i, V_j, B_p, B_q\}$, $(\Psi_{jq}^{ip}(\beta), \Psi_{jq}^{ip}) \succ_{\beta} (\Psi(\beta), \Psi)$

the swap is approved. The pair (V_i, V_j) is called a swap pair. After exchanging, the utility of all players will not be reduced, and at least the utility of one player will be increased.

Definition 6 (Two-Sided Exchange Stable): If there is no swap pair, the match is two-sided exchange stable.

B. Vehicular Content Distribution Algorithm

Referring to [15], for the problem (11), we propose a vehicular content distribution algorithm (VCDA) based on the many-to-many matching theory, which is shown in Algorithm 1. The VCDA is divided into two stages as follows:

(1) *Initialization phase:* In the initial selection, the priority is decided by weight, which means the greater weight the VUE has, the higher priority it has to select the preferred subset of BSs who can serve a new VUE. From the perspective of the fairness of VUEs, we set the weight ω_i of VUE V_i at the time t to be inversely proportional to the average channel capacity of the past $(t-1)$ time, which means $\omega_i = \frac{t-1}{\sum_{n=1}^{t-1} C_{V_i}(n)}$. If the

average channel capacity of the VUE in the past time is small, it will have a higher priority to select at the current time. At the initial time, if VUEs have no past channel capacity, VUEs will select in random order.

(2) *Swap phase:* The control BS constantly searches for possible swap pairs and judges whether it meets the approval conditions. If approved, this pair exchanges with each other and the match is updated. This operation is iterated until the control BS can no longer find a new swap pair.

Algorithm 1: Vehicular Content Distribution Algorithm (VCDA)

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1 Initialization Phase: for iteration  $n = 1, 2, \dots, M$  do
2   Set  $i^* = \arg \max_{i \in V} \{\omega_i\}$ .
3   VUE  $V_{i^*}$  selects the preferred subset of BSs who
   can serve a new VUE.
4   Remove  $V_{i^*}$  from  $V$ .
5 Swap Phase: for VUE  $i = 1, 2, \dots, M$  do
6   if a new possible swap exists then
7     The control BS finds another VUE  $V_j$  to make
     a possible swap pair  $(V_i, V_j)$  with
      $B_p \in \Psi(V_i)$  and  $B_q \in \Psi(V_j)$  which has
     never been found before.
8     if  $\Psi_{jq}^{ip}$  is approved then
9       Let VUE  $V_i$  and  $V_j$  exchange, set the
       current match  $\Psi = \Psi_{jq}^{ip}$ , and go to step 6.
10    else
11      Go to step 6.
12  else
13    Break.

```

TABLE I: SIMULATION PARAMETERS

Parameter	Definition	Value
M	number of VUEs	80/km
K	number of DL BSs	24
P_j	power of each DL BS	30dB
W_j	bandwidth of each DL BS	20MHz
S_j	number of subchannels of each DL BS	40
b	maximum number of accessible BSs	3
T_0	content distribution interval	1s
T	total number of distribution intervals	1000
τ	time interval for prediction	0.1s
N	number of time intervals for prediction	5

IV. SIMULATION RESULT

As shown in Fig. 2, we use two 1000-meter-long and mutually perpendicular roads to simulate urban roads. Each road is a two-way six-lane road with a lane width of 4 meters. The BSs are set every 100 meters and distributed 30 meters on both sides of the road. For road safety, the maximum driving distance between vehicles shall not exceed the safe driving distance. Considering the reaction time of the driver and braking time, we set the speed to 60 km/h and the corresponding safe

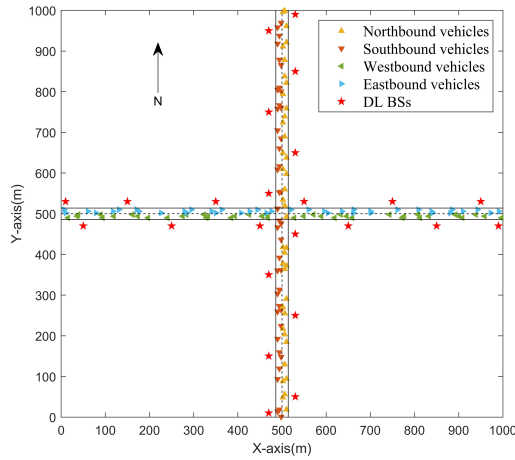


Fig. 2: Randomly generated two-dimensional urban simulated road.

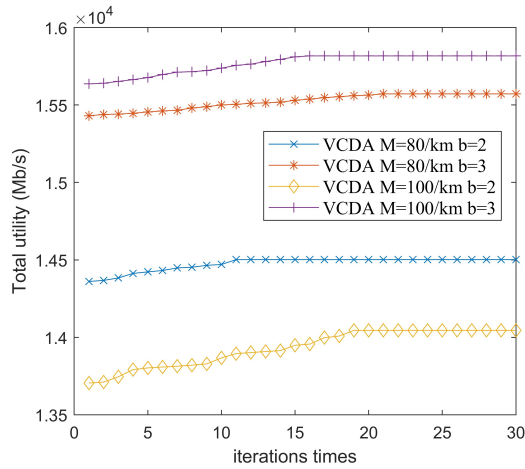


Fig. 3: Variation of total system utility with iterations.

driving distance to 40 meters. When calculating channel gain, we consider fast fading, shadowing, and path loss. We set path loss exponent $\alpha = 3$, fast fading parameters $\beta \sim E(1)$ and shadowing parameters $\ln(\gamma) \sim N(0, 8dB)$. Simulation parameters are listed in Table I.

Fig. 3 shows the details of the swap at the random time. It can be seen that with the iteration of VCDA, the swap is ongoing constantly, and the total utility of the C-V2X network continues to increase. Because we set the approval conditions of swap operations, after the swap, the utility of all VUEs will not be reduced, and at least the utility of one VUE will be increased. When the swap reaches a certain number of times, the utility of the C-V2X network will no longer change and begin to converge. At this time, there are no swap pairs in the system, reaching 2ES.

In order to better evaluate VCDA, we compare VCDA with the random multiple connection algorithm in which each VUE can select up to b BSs within the limited range of 200meters

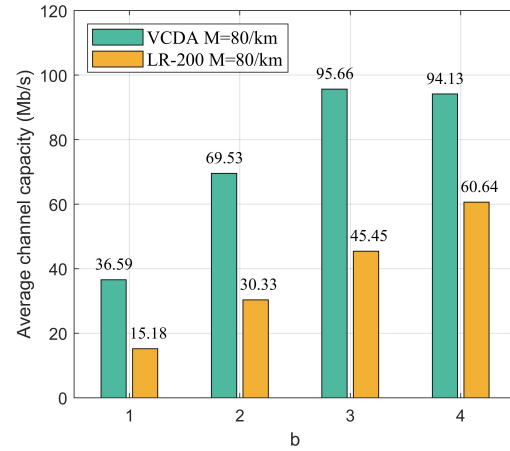


Fig. 4: Average channel capacity of VUEs versus b .

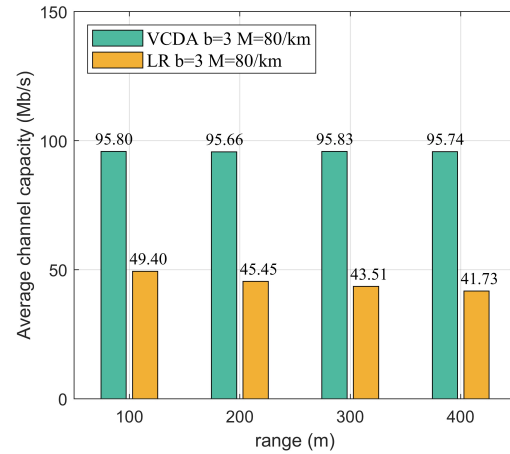


Fig. 5: Average channel capacity of VUEs versus range.

in random order (LR-200). As shown in Fig. 4, when the number of VUEs $M = 80/km$, the average channel capacity of VUEs increases with the growth of b . At the same time, VCDA has great advantages in the average channel capacity over the LR-200. When b is greater than or equal to 3, the average channel capacity does not change significantly. As shown in Fig. 5, when the number of VUEs $M = 80/km$ and $b = 3$, the average channel capacity of LR-200 reduces with the growth of range. Regardless of changes in the range, VCDA outperforms LR.

Fig. 6 presents the change of average channel capacity with the number of VUEs M . VCDA performs well before peak traffic hours. In addition, the average channel capacity of VUEs increases when VUEs can connect more BSs. When the number of VUEs reaches $80/km$, the average channel capacity of VUEs no longer changes accordingly because most VUEs connect less than b BSs due to the limited service capacity of BSs.

Fig. 7 shows the cumulative distribution function (CDF) of the average channel capacity with the number of VUEs

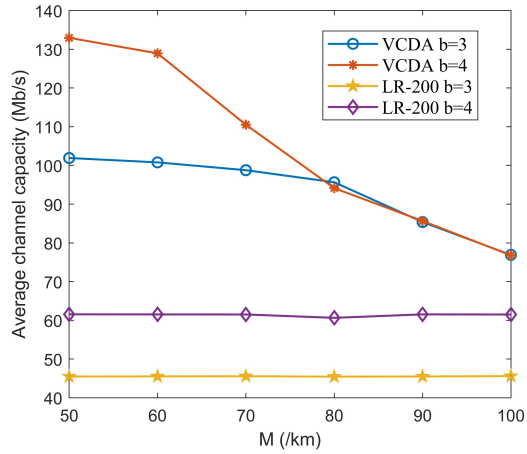


Fig. 6: Average channel capacity of VUEs versus M .

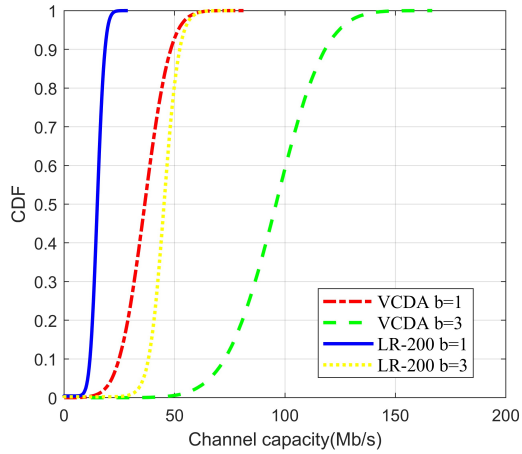


Fig. 7: CDF of the average channel capacity.

$M = 80/km$ and the maximum number of accessible BSs $b = 1, 3$. We observe that the speed of convergence becomes slower as the maximum number of accessible BSs b increases. Besides, Fig. 7 reflects that the channel capacity of most VUEs in VCDA is superior to that in LR-200.

V. CONCLUSION

In this paper, we have studied the efficient vehicular content distribution. Facing the challenges of the high mobility of VUEs and frequent network handovers of 5G networks, the fully-decoupled downlink B5G C-V2X networks, which has the potential to deal with these challenges, has been leveraged by us to allocate multiple BSs for VUEs. Specifically, considering the high mobility of vehicles, user fairness, and system capacity, we have proposed an effective vehicular content distribution method. We have transformed the content distribution problem into matching game and proposed the VCDA to achieve a stable solution based on the many-to-many matching theory. The simulation results have proven that the proposed VCDA can achieve efficient vehicular content

distribution in the fully-decoupled downlink B5G C-V2X networks. For future work, we will leverage more resource collaboration between the BSs to achieve higher vehicular content distribution efficiency.

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