

Effective Gateway Association Schemes for Performance Improvement of V2I Communications in Heterogeneous Vehicular Networks

(Invited Paper)

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Abstract—Vehicular communication is one of the key enabling technologies for the emerging intelligent transportation systems, which generally consists of direct links between vehicles in proximity (vehicle-to-vehicle, V2V) and roadside infrastructure (vehicle-to-infrastructure, V2I). However, due to the high velocity of vehicles, the throughput of V2I links can be highly dynamic for vehicles passing through different areas. To improve the performance of V2I communications, vehicles with strong V2I links are selected as mobile gateways to relay the data of vehicles in dark areas via V2V communications. In this paper, we study the gateway association problem, for which we formulate a multiple knapsack problem with assignment restrictions to model our optimization task and propose two distributed association schemes to maximize the number of vehicles served by mobile gateways. Simulation results show that our proposed schemes outperform the distance-based and the random association schemes in various scenarios with different traffic densities.

Index Terms—Heterogeneous vehicular networks (HetVNETs), mobile gateway association, multiple knapsack problem with assignment restrictions.

I. INTRODUCTION

Vehicular networks can provide a variety of applications for transportation systems, ranging from traffic safety and efficiency to entertainment services, by using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [1]. Dedicated short-range communications (DSRC) based on IEEE 802.11p protocol in PHY/MAC layer can efficiently support low-latency V2V communications for local areas [2]. Recently, long term evolution (LTE) is introduced to vehicular networks to provide large-coverage and high data rate V2I communications [3] since the forthcoming cloud radio access network or heterogeneous network can support the transmission requirements of vehicular communication at low cost [4, 5]. Therefore, heterogeneous vehicular network (HetVNET) that integrates DSRC with LTE is expected to well meet the communication requirements of future intelligent transportation systems [6], where vehicles can exchange real-time information with DSRC and access to Internet via LTE.

Due to the high velocity of vehicles, the throughput of V2I links can be highly dynamic for vehicles passing through different areas. To provide stable data rate for all vehicles,

a few number of vehicles with high V2I data rates can be selected as mobile gateways (MGs) to relay source vehicles (SVs) in dark areas. Moreover, these MGs served as relays can reduce the handoff load caused by the high mobility of vehicles from the viewpoint of LTE networks. In [7], an integrated VANET-3G heterogeneous wireless networks using MGs is introduced, where vehicles are dynamically grouped into clusters according to the directions of movement, received signal strength, and inter-vehicular distance. The MGs are selected based on an adaptive management mechanism. In [8], a cooperative traffic transmission algorithm is proposed to select gateway for SVs in a joint LTE Advanced-VANET hybrid network, where QoS traffic class, cluster head features, and load of cellular network, are taken into consideration. In [9], a multihop-cluster-based IEEE 802.11p-LTE hybrid architecture is proposed, where vehicles are clustered via a multihop algorithm and a relative mobility metric is introduced to select MG.

However, as far as the authors have known, existing works do not consider the data rate requirements of vehicles or the V2I throughput limitations of MGs. In this paper, we investigate how to associate SVs with given MGs in the HetVNET. We formulate a multiple knapsack problem with assignment restrictions (MKAR) and propose two distributed association schemes based on greedy and dynamic programming strategies. Numerical results show that our proposed schemes outperform the distance-based method and the random association one in scenarios with different traffic densities.

The rest of this paper is organized as follows. In Section II, we introduce system model and formulate an MKAR problem to illustrate the associations among vehicles. Two distributed association schemes are proposed in Section III, which try to maximize the number of vehicles served by given MGs. In Section IV, simulation results are given with discussions. We conclude our work in Section V.

II. PROBLEM FORMULATION

Consider a road segment with multiple vehicles passing through the service area of a road side unit (RSU) with eNodeB functions, as shown in Fig. 1. A few number of vehicles are selected as MGs (red cars) which serve as relay to help other SVs (grey cars) communicate with the RSU. Denote by

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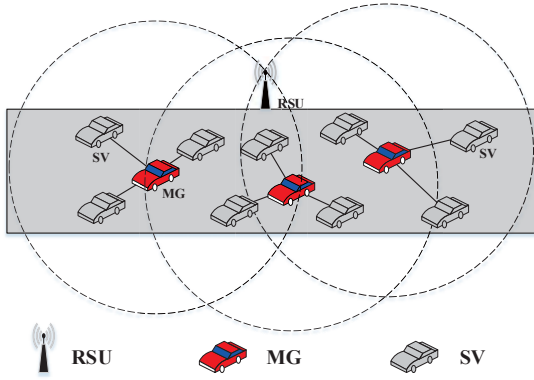


Fig. 1. Illustration of system model.

TABLE I
NOTATIONS

Symbol	Semantics
d_{ij}	Distance between vehicle i and j
d_{th}	Maximum transmission range of vehicle
g_{ij}	Binary variable indicating whether SV j is within the transmission range of MG i or not
\mathcal{M}	Set of MGs
\mathcal{N}	Set of SVs
R_i	Capacity constraint of MG i
r_j	Rate requirement of SV j
x_{ij}	Binary variable indicating whether MG i is the relay vehicle of SV j or not

$\mathcal{M} = \{1, 2, \dots, M\}$ as the set of MGs and $\mathcal{N} = \{1, 2, \dots, N\}$ the set of SVs. The distance between MG i and SV j is d_{ij} , and the maximum range of V2V communication is d_{th} . R_i is the relay capacity of MG i and r_j the data rate requirement of SV j . Some frequently used symbols are listed in Table I.

Binary variable x_{ij} denotes whether SV j is served by MG i or not,

$$x_{ij} = \begin{cases} 1 & \text{if SV } j \text{ is served by MG } i, \\ 0 & \text{otherwise,} \end{cases}$$

and our optimization gateway association problem can be formulated as follows:

$$\max_{\{x_{ij}\}} \sum_{i \in \mathcal{M}} \sum_{j \in \mathcal{N}} x_{ij}, \quad (1a)$$

$$s.t. \sum_{j \in \mathcal{N}} r_j x_{ij} \leq R_i, \forall i \in \mathcal{M}, \quad (1b)$$

$$\sum_{i \in \mathcal{M}} x_{ij} \leq 1, \forall j \in \mathcal{N}, \quad (1c)$$

$$d_{ij} x_{ij} \leq d_{th}, \forall i \in \mathcal{M}, j \in \mathcal{N}, \quad (1d)$$

$$x_{ij} \in \{0, 1\}, \forall i \in \mathcal{M}, j \in \mathcal{N}. \quad (1e)$$

(1a) is the objective function that tries to maximize the number of SVs. (1b) is the capacity constraint of the MGs. (1c) indicates each SV can be served by at most one MG. (1d) ensures the distance between MG i and SV j does not exceed maximum transmission range of V2V communications.

We introduce a matrix G whose element g_{ij} indicates whether SV j is within the transmission range of MG i or

not, i.e., $g_{ij} = 1$, if $d_{ij} \leq d_{th}$, and $g_{ij} = 0$, otherwise. Then, Eq. (1) can be transformed into the following form:

$$\max_{\{x_{ij}\}} \sum_{i \in \mathcal{M}} \sum_{j \in \mathcal{N}} x_{ij} g_{ij}, \quad (2a)$$

$$s.t. \sum_{j \in \mathcal{N}} r_j x_{ij} g_{ij} \leq R_i, \forall i \in \mathcal{M}, \quad (2b)$$

$$\sum_{i \in \mathcal{M}} x_{ij} \leq 1, \forall j \in \mathcal{N}, \quad (2c)$$

$$x_{ij} \in \{0, 1\}, \forall i \in \mathcal{M}, j \in \mathcal{N}, \quad (2d)$$

III. PROPOSED ALGORITHMS

Eq. (1) define a multiple knapsack problem with assignment restrictions (MKAR) [10, 11]. The MGs are knapsacks and the SVs are items packed into knapsacks. The throughput of MG is the capacity of knapsack and the data rate of SV is the weight of item. The MKAR is an NP-hard problem that is difficult to solve even for moderate scale. We introduce two distributed algorithms generalized from the methods developed in [10] to address our optimization task. Denote A_j as the set of MGs that can relay SV j and B_i the set of SVs served by MG i . First, we introduce a distributed association scheme based on greedy strategy.

- Each SV announces its information to the neighboring vehicles. The information contains vehicle identity, position and data rate requirement. Each MG and SV will gather the information of neighboring SVs and store the information in their own table for gateway association. The table of MG m is denoted by U_m^{MG} and the table of SV n is given by U_n^{SV} .
- Each SV examines if its data rate requirement is the minimal among the neighboring vehicles. The SV with the minimal data rate requirement will broadcast an MG request (MG_REQ) message. At the same time, the SV sets a timer T .
- An MG receives the MG_REQ message broadcasted by the SV and examines whether its remaining capacity is sufficient to serve the SV. If it is the case, the MG will unicast an ACK message to the SV. Otherwise, the MG_REQ message will be discarded by the MG.
- If the SV receives an ACK message, it will be served by the MG that sends the ACK message and discard other ACK messages received after this one. At the same time, this SV will announce its association information to neighboring MGs and SVs so that they can remove the information regarding this SV from their tables.
- When timer T expires, which means that this SV can not be served by any MG, this SV will also announce to the neighboring MGs and SVs so that they can remove the information regarding this SV from their tables.

The pseudo-code of the proposed greedy gateway association procedure is described in Algorithm 1. For each SV, M iterations are required for the worse case. Thus, the complexity of the greedy algorithm is bounded by $O(MN)$.

We also introduce a distributed association scheme based on dynamic programming.

Algorithm 1: Greedy Algorithm

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1 Initialize  $G_i = \emptyset$ ,  $S_i = R_i$ ,  $U_m^{MG} = \{j | d_{mj} \leq d_{th}\}$ ,
 $U_n^{SV} = \{j | d_{nj} \leq d_{th}\}$ ,  $i \in \mathcal{M}$ ,  $j \in \mathcal{N}$ ,  $m \in \mathcal{M}$ ,  $n \in \mathcal{N}$ ;
2 Repeat:
3 if SV  $j$  with  $r_j \leq r_k, \forall r_k \in U_j$  then
4   for  $i \in A_j$  do
5     if  $r_j \leq S_i$  then
6        $S_i = S_i - r_j$ ;
7        $G_i = G_i \cup \{j\}$ ;
8        $U_m^{MG} = U_m^{MG} \setminus \{j\}$ ;
9        $U_n^{SV} = U_n^{SV} \setminus \{j\}$ ;
10    break
11  if  $T$  is expired then
12     $U_m^{MG} = U_m^{MG} \setminus \{j\}$ ;
13     $U_n^{SV} = U_n^{SV} \setminus \{j\}$ ;

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- Each SV broadcasts an MG_REQ message containing its identity, position and data rate requirement. Each MG gathers MG_REQ messages from SVs within its transmission range and stores these messages into its table. The table of MG m is denoted by U_m^{MG} .
- Each MG uses dynamic programming algorithm to calculate the SVs it can serve and multicasts the ACK message to these SVs.
- When an unserved SV receives an ACK message, it will send a response (RES) message to the MG that multicasts the ACK message and discard other ACK messages received after this one.
- If an MG receives RES messages from all vehicles it tends to serve, it will multicast the service (SER) message to these SVs. If this MG does not receive any RES messages from all vehicles, it will employ dynamic programming algorithm again to calculate the SVs it can serve.
- When an SV receives the SER message from the same MG, the MG that sends the SER message serves this SV. Then the SV informs the neighboring MGs to update its service state and the neighboring MGs remove this SV from their tables.

The pseudo-code of the dynamic programming gateway association scheme is described in Algorithm 2. Generally, its complexity is much higher than the greedy algorithm.

IV. SIMULATION RESULTS

Consider a road segment with multiple vehicles passing through the area served by a road side unit (RSU) with eNodeB functions, where all SVs and MGs are uniformly distributed in this road segment. For MG i , its relay capacity R_i is distributed uniformly in an interval of (100,120). For SV j , its data rate requirement r_j is distributed uniformly in an interval of (10,40). The maximum transmission range d_{th} of V2V communications is set to 300 m. We compare the

Algorithm 2: Dynamic Programming Algorithm

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1 Initialize  $G_i = \emptyset$ ,  $U_m^{MG} = \{j | d_{mj} \leq d_{th}\}$ ,  $i \in \mathcal{M}$ ,  $m \in \mathcal{M}$ ,
 $j \in \mathcal{N}$ ;
2 while MG  $i$  does not receive all RES from SV  $j, j \in G_i$  do
3    $V_{(|U_i^{MG}|+1) \times (|R_i|+1)} = \mathbf{0}$ ,  $G_i = \emptyset$ ;
4   for  $j = 1$  to  $|U_i^{MG}|$  do
5     for  $k = 1$  to  $R_i$  do
6       if  $k < r_j$  then
7          $V_{j+1,k+1} = V_{j,k+1}$ ;
8       else
9          $V_{j+1,k+1} = \max\{V_{j,k+1}, V_{j,k+1-r_j} + 1\}$ ;
10     $k = R_i$ ;
11    for  $j = |N \cap B_i|$  to 1 do
12      if  $V_{j+1,k+1} > V_{j,k+1}$  then
13         $G_i = G_i \cup \{j\}$ ;
14         $k = k - r_j$ ;
15    MG  $i$  multicast ACK to SV  $j, j \in G_i$ ;
16  $U_m^{MG} = U_m^{MG} \setminus \{j\}, j \in G_i$ ;

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performance of our proposed gateway association schemes with the distance-based algorithm developed in [12] and the random association one proposed in [13]. All results are averaged based on 500 Monte Carlo simulations. The distance-based association algorithm and random association algorithm are summarized as follows.

- Distance-based association: Each SV always selects the nearest MG in its communication range. The nearest MG serves as a relay for an SV if its remaining capacity is sufficient to serve this SV; otherwise, this SV will continue to request service to the nearest MG after a certain period of time.
- Random association: Each SV randomly selects an MG in its communication range. The selected MG serves as a relay for an SV if its remaining capacity is sufficient to serve this SV; otherwise, this SV will continue to request service to the selected MG after a certain period of time.

Fig. 2 shows the number of satisfied SVs served by MGs as a function of the SVs. We can see that the dynamic programming association scheme can serve more SVs than other algorithms while the performance of the greedy scheme is close to the dynamic programming one. As the increasing of the number of SVs, both of our proposed schemes show significant performance improvement as compared with the distance-based association and random selection algorithms. The reason is that our proposed algorithms take the throughput limitation of an MG into consideration when associate an SV with the MG, which can exploit the throughput potential of the HetVNET fully so as to serve more SVs.

Fig. 3 shows the number of satisfied SVs served by MGs as a function of the number of MGs. Again, the performance of the dynamic programming scheme is the best while the greedy

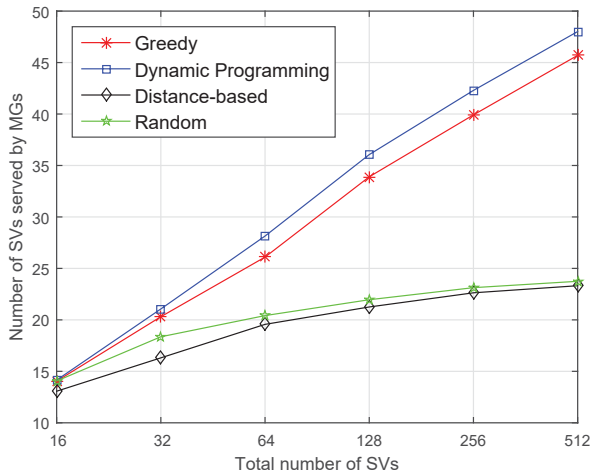


Fig. 2. Number of satisfied SVs as a function of the total number of SVs. The number of MGs is $M = 5$.

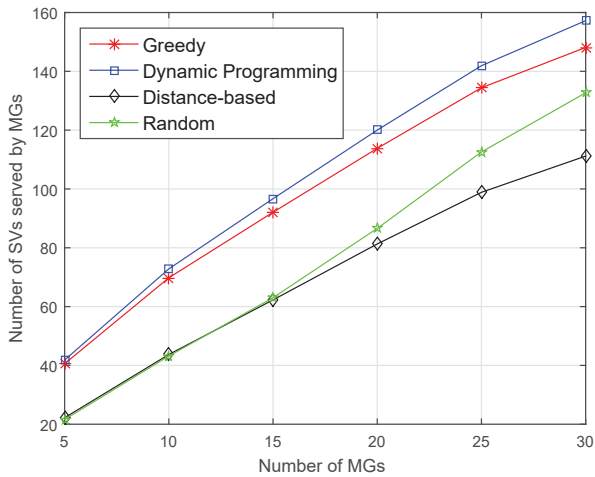


Fig. 3. Number of satisfied SVs as a function of the number of MGs. The number of SVs is $N = 200$.

scheme is just slightly worse than the dynamic programming one. The number of satisfied SVs increases as the increasing of the MGs for all schemes since more MGs mean that the HetVNET can serve more SVs in the statistical sense. Our proposed greedy scheme always serves the SV with the lowest rate requirement so that more SVs could be satisfied with the same number of MGs. On the other hand, the dynamic programming algorithm can obtain the (near)optimal solution to the single knapsack problem, resulting that each MG can serve the (near) maximum number of SVs.

In summary, the performance of dynamic programming scheme is better than the distance-based algorithm and the random association one as can be seen from Fig. 2 and Fig. 3, especially when the density of SV is high or the

number of MGs is small. Besides, we can see from Fig. 2 and Fig. 3 that the gap between the greedy scheme and the dynamic programming one is slight. However, the complexity of the greedy scheme is much lower than that of the dynamic programming algorithm. So we can choose an appropriate one to meet the diverse requirements in practical systems.

V. CONCLUSION

In this paper, we investigated the gateway association problem for the V2I communications in HetVNETs, where we formulate a multiple knapsack problem with assignment restrictions to illustrate practical scenarios and propose two distributed gateway association schemes with different complexity and performance. Simulations results have shown that our proposed schemes outperform other ones in scenarios with different traffic densities. In future, we will jointly consider the gateway selection and association problems to further improve the V2I communication performance in HetVNETs.

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