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Optimal Roadside Gateway Deployment for VANETs

***Abstract**. VANETs allowing the mobile vehicles exchange data with the roadside gateways are being used in various applications such as local electronic advertisement, intelligent transportation system and urban data collection. In this paper, we study the problem of deploying the gateways to provide the desired communication performance while minimizing the deployment cost. The key idea of our solution is to exploit the time-stable vehicular mobility pattern to find the optimal deployment places. We propose a graph model to characterize the observed mobility pattern. Then the gateway deployment problem is transformed into a vertex selection problem in a graph. By reducing it the minimum vertex coverage problem, we show the gateway deployment problem is NP-complete, so a heuristic algorithm MobGDeploy is proposed to search greedily the optimal deployment points. Extensive simulations are carried out to evaluate the performance, and the results show that the proposed algorithm outperforms others.*

***Streszczenie.** W artykule analizowano problem rozlokowania wjazdów w celu osiągnięcia pożądanej jakości komunikacji. Przyjęto założenie stabilnej czasowo mobilności pojazdów. Zaproponowano model grafu do opisu mobilności pojazdów. Wykorzystano metodę VANET – vehicular ad hoc network. (**Optymalne rozlokowanie wjazdów dla systemu VANET**)*

Keywords: Optimal Deployment, Vertex Coverage, Mobility Pattern.
Słowa kluczowe: VANET (vehicular ad hoc network), komunikacja drogowa.

Introduction

With the proliferation of the vehicular intelligent devices, vehicle to roadside communication has received considerable attention. With Roadside gateway, vehicles can download/upload data from/to the gateways installed in the fixed location on a road. It enjoys a large number of applications including local electronic advertisement, intelligent transportation system (ITS) and environment data collection.

In vehicle-roadside communication, the gateway can act as a router for vehicles to access the Internet. Saha [1] study the schedule scheme in application layer for the data requests and data transmission in the RoadSide unit in order to improve the system throughput. Cabernet [2] aims to deliver data to and from moving vehicles using WiFi access points. Aslam [3] address the issue of optimal placement of these RSUs along highways with the goal of minimizing the average time taken for a vehicle to report to a nearby RSU. Liu [4] studied how to place a set of well connected base stations in an ad hoc wireless network. Zhao [5] used the stationary relay nodes called ThrowBox to enhance the capacity in mobile delay tolerant networks. Leontiadis [6] propose to use the roadside infostation to distribute the message to the targeted vehicles. Banerjee [7] analyze the network performance by deploying three types of nodes: base stations, mesh and stationary relays.

In this paper, we study the problem of deploying gateways for mobile vehicles passing a geographical area. Its goal is to satisfy the connectivity requirement for all vehicles passing the coverage region while minimizing the deployment cost. We take advantage of a graph to model the time-stable statistical mobility pattern in a geographical area and show the deployment problem is NP-complete by reducing it into the minimum vertex coverage problem. A heuristic algorithm MobGDeploy is proposed to find the optimal installation places.

This paper is organized as follows. In section 2, the system model is given. In section 3, we formulate the gateway deployment problem and prove it is NP-complete, then develop a heuristic algorithm. In Section 4, we evaluate the solution performance in two scenarios. Finally, we make conclusions in the last section.

Mobility graph model

Considering a limited geographical region, vehicles enter and leave autonomously and continuously the region. All gateways can be installed at any place in the region. When a vehicle moves into the radio range of any gateway, it may use the opportunity to establish connectivity with the gateway and then send or receive data from it. This paper focuses on how to deploy these gateways to satisfy the meeting probability specified by users while minimizing the deployment cost, say, the number of the required gateways.

The optimal gateway deployment depends on the mobility patterns of the vehicles passing the geographical area. Recent studies[8] on some realistic traces of moving users show that users usually move around a set of landmarks such as home, office, park and so on. Specifically, users show preference for a small number of landmarks. Their second observation is the node trajectory is almost deterministic in some social environments. This means a node has its own mobility schedule and it generally moves between landmarks according to that schedule, subject to few random deviations.

We extract and analyze the traffic data over 18 hours in an area of around 3000m×3000m from the realistic vehicular mobility trace MMTS. The whole area is divided into a set of non-overlapped uniform zones with an area of 200m × 200m. By counting the number N_i of vehicles passing zone i and the number N_{ij} of vehicles entering zone j after leaving zone i for each time unit. Then we obtain the distribution of transition probability between two zones. The details of the analysis are omitted here due to the space limit. From this analysis, we observe the following two key characteristics. 1)The transition probabilities between two zones keep approximately stable which fluctuate around a mean value within two traffic peak time. 2)There are no obvious impact of the size of zone on the time stability of transition probability.

Based on the observation, we propose a *mobility graph* to capture this mobility pattern. Let us consider a connected and bounded geographical area A which is divided into non-overlapped uniform zones. A mobility graph is a directed graph G, whose vertex set $V(G)$ corresponds to the set of zones. Its edge set $L(G)$ corresponds to the set of mobility links between zones on which vehicles travel. There exists a mobility link between two neighboring zones i and j only if a vehicle leaves zone i and then enter zone j immediately. Each edge is associated with a transition probability which indicates the probability that any node move from i to j. Let T denote the time unit, the transition probability is computed as follows.

$$P^T(i,j) = \frac{|N_i(T) \cap N_j(T)|}{|N_i(T)|}$$

where $N_i(T)$ and $N_j(T)$ are respectively the set of vehicles locating in zone *i* and *j* within a time unit T. transition probability between two zones is basically time-stable for an long period of time and change for another duration in a day. Then the average of all time units in the total statistical time is computed as the final weight of the corresponding edge.

We also explore the mobility process of all vehicles passing the boundary of the area *A*. We introduce a virtual vertex *U* to represent the exterior zone beyond *A*. If there are the vehicles entering *A* from the bounding zone *i*, then a edge exists between vertex *U* and vertex *i*. The corresponding transition probability is computed in the similar way to the ordinary edges. An example is shown in Fig. 1. Its left part shows the geographical area is divided into 6 zones, say, zone from 1 to 6, and the corresponding Mobility Graph is depicted in right side. Here, we find all vehicles only move into the area from 1 and 4 zones with the probability of 0.8 and 0.2 respectively. Meanwhile, they only leave the area from zones 2 and 6 with the probability of 0.3 and 0.6 respectively. The thicker curves represent respectively the physical path 1-3-4-6 in the geographical area and that on the Mobility Graph.

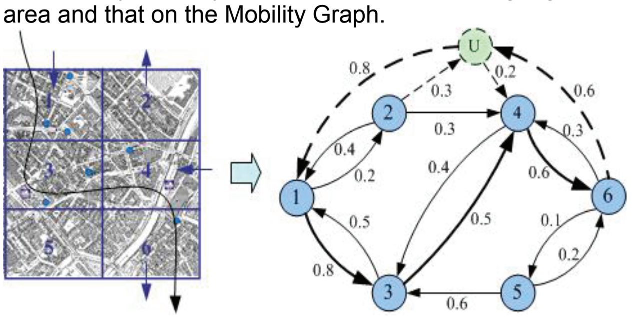


Fig.1. Mobility graph over a geographical area

Minimum gateway deployment problem

A. Problem Formulation

In order to formulate the the minimum gateway deployment problem (MGDP), we firstly present several definitions. The symbols and notations used in the paper are summarized in Table I.

Table I: Summary of major notations

A	Target geographical area
G	Mobility Graph
V(G)	Vertex set
L(G)	Edge set
M(G)	Transition matrix of graph
P(i,j)	Transition probability from vertex i to j
π_{ij}^{δ}	Transition probability from vertex i to j in at most δ hops
λ_{iR}	Visiting probability from vertex i to group R
$\hat{V}$	Optimal vertex set being searching
δ	Maximum path length
P_u	Meeting probability threshold specified by users

DEFINITION 1: *Transition Matrix*. Since there are the time-stable transition probabilities between all zones, the statistical mobility pattern can be represented by a time homogeneous Markov chain. It state space is exactly corresponding to the vertex set, say, all zones. Therefore, the transition probability distribution between the state space can be represented by the Transition Matrix *M(G).* A journey of a vehicle passing the area A can be denoted as a path in the Markov chain.

DEFINITION 2: *Vertex Visiting Probability* (VVP) π_{ij}^{δ} is the probability of a node moves from vertex *i* to *j* within a given maximal length *δ*. It is computed as,

$$\pi_{ij}^{\delta} = \sum_{h=1}^{\delta} \pi_{ij}(h)$$

where $\pi_{ij}(h)$ is the probability of a node move from vertex *i* to *j* within the exact length *h*. Let *M* denote the transition matrix of mobility graph, then we have:

$$\pi_{ij}(h) = \mathrm{M}^h[i][j]$$

where M^h is the *h*-step transition probability, which can be computed as the *h*-th power of the transition matrix *M*.

DEFINITION 3: *Set Visiting Probability (SVP)* λ_{iR} is defined as the probability with which a node move from vertex *i* to at least one vertex *j*⊆*R*. It is derived as follows.

$$\lambda_{iR} = 1 - \prod_{j \in R} (1 - \pi_{ij}^{\delta})$$

Based on the above definitions, the minimum gateway deployment problem (MGDP) is transformed to the problem of selecting vertex subset, and is formulated as follow. Given a mobility graph *G* modeling the statistical mobility pattern over the area *A* and the meeting probability threshold P_u specified by users, the objective of MGDP is to find a smallest subset $\hat{V} \in$V(G) such that the SVP from any vertex to $\hat{V}$ is not smaller than the probability specified by user, say,

$$\textit{minimize } |\hat{V}| \text{ s. t.}$$

$$\hat{V} \subseteq V(G) \text{ and } \forall i \in V(G), \lambda_{i\hat{V}} \geq P_u$$

Then, we have the following theorem regarding the complexity of the MGDP.

Theorem 1. The MGDP problem is *NP-complete*.

Proof: The MGDP problem can be reduced to the classical minimum vertex cover problem which is a well-known NP-complete problem. First, for each vertex *i* ∈ V(G), we compute its *VVS* π_{ij}^{δ} to all vertex *j* according to the equation 2. Then we find a vertex subset

$$\mathrm{X}_i = \{ j \mid j \in V(G) \text{ and } \pi_{\mathrm{ij}}^{\delta} \geq P_u \}$$

It contains all reachable vertices from vertex *i* within the constraint of given path length and the visiting probability specified by user. By repeating the process, we can compute the above set for each starting vertex *i*. Then we construct a set $\Psi_i = \{ j \mid i \in \mathrm{X}_j \}$ for each vertex *i*, which includes those starting vertices from which a node can visit the vertex *i* within the constraint of the given path length and meeting probability threshold. Finally, the MGDP is equivalent to the problem of finding a subset $\hat{V}$,

$$\textit{minimize } |\hat{V}| \text{ s. t.}$$

$$\bigcup_{i \in \hat{V}} \Psi_i \supseteq V(G)$$

Obviously, the formulation is the classical minimum vertex cover problem, which has been shown NP-complete. Note that we just consider the visiting probability from all vertices to a single vertex in the $\hat{V}$ instead of the SVP, which usually is greater than the former. However, this point can not affect the correctness of the proving procedure because it just equivalent to that the meeting probability specified by user P_u is set to a smaller value. Consequently, MGDP is still a NP-complete problem.

B. The Proposed Deployment Algorithm

In order to solve the MGDP problem, we develop a heuristic algorithm *MobGDeploy* which use the greedy strategy to search optimal gateway deployment. The details of the algorithm are shown in Algorithm 1.

Algorithm 1. MobGDeploy algorithm.

Input: G -Mobility Graph; δ -maximal path length; P_u -meeting probability specified by user

Output: $\widehat{V}$ -result set being searched

1 BEGIN
$M \leftarrow$ transition matrix of G
2 *compute the 1-step, 2-step,... δ-step transition matrix of M*
3 compute the VVP π_{ij}^{δ} between all nodes according to equation 2
4 $\widehat{V} \leftarrow \phi$
5 $S \leftarrow \phi$
6 While($|S| < |V(G)|$)
7 BEGIN
8 $j \leftarrow \arg\max_{x \in (V-\widehat{V})} \left(\left| \{ k \mid k \in (V-S), \lambda_{k(\widehat{V} \cup \{x\})} \geq P_u \} \right| \right)$
9 $\widehat{V} \leftarrow \widehat{V} \bigcup \{j\}$
10 $S \leftarrow S \bigcup \{k \mid \lambda_{k\widehat{V}} \geq P_u\}$
11 END
12 END

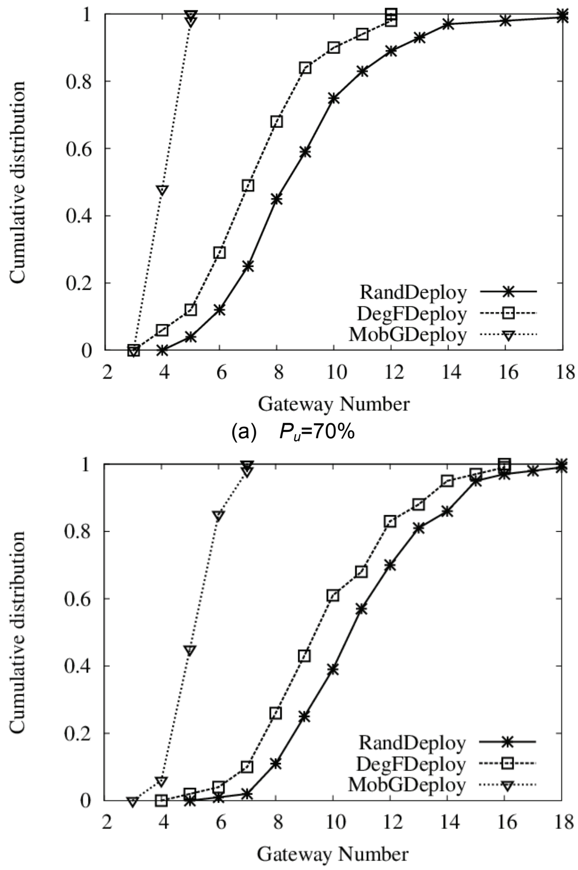
In this algorithm, the first 3 lines is to compute the *VVP* π_{ij}^{δ} from any vertex *i* to other vertex *j*. The vertex set being searched is initialized in line 4. In line 5, the algorithm initializes a set *S* from which the *SVP* to the set being searched $\widehat{V}$ is not smaller than the probability specified by user. Line 6 shows the following procedure terminates until all *SVP* from all vertices to the result set $\widehat{V}$ are not smaller than predefined probability. Line 7 is the key idea of MobGDeploy. It searches greedily the vertex which can maximize the number of vertices whose *SVP* to the result set is not smaller than the predefined threshold. The found vertice are added into the result vertex set in line 8. Finally the set *S* is updated after the new vertex is added. Clearly, the time complexity of this algorithm is O($|V|^3$).

4 Performance evaluation

In this section, we evaluate the performance of *MobGDeploy* algorithm in the simulation scenarios. In the scenario, a 1600*2000m^2 area is divided into 20 zones, each with 400*400m^2. Thus the corresponding mobility graph contains 21 vertices. The largest degree of each vertex is 4 because the vehicles only move from current zone to 4 neighboring zones. The average path length is δ=5 zones when a vehicle passes the whole area. The experiment is conducted for 200 runs. Each of those generates randomly the mobility graph with different random seeds.

We compare *MobGDeploy* with other two baseline algorithms. The first is the Random Deployment (*RandDeploy*), which select randomly a vertex to be added into the result set until the SVP of all vertices to the result set is not smaller than the predefined threshold. The second is the Degree First Deployment (*DegFDeploy*). Contrary to the RandDeploy, it chooses greedily the vertex with largest degree to be added to the result set. The higher the degree of a vertex is, the more popular the corresponding zone is. Thus DegFDeploy captures the stationary statistical pattern of the mobility in the target area in contrast to the *MobGDeploy*.

We compute the number of required gateways when the meeting probability specified by user is 70% and 90%. Fig. 2 shows the cumulative distribution of 200 experiment results. It can be seen that *MobGDeploy* require much less gateways than other algorithms. When the expected meeting probability of users is 70%, 3 gateways are needed for *MobGDeploy*, but *RandDeploy* and DegFDeploy need nearly 8 gateways in most cases. Similarly, *MobGDeploy* also outperform other two algorithms when the speicifed meeting probability is 90%. It can be explained as follows. *RandDeploy* blindly chooses the placement zones, so achieve the worst performance. DegFDeploy only uses the coarse statistical information of the mobility pattern in the area. Thus it has the poor performance in the random mobility graph. *MobGDeploy* utilizes the fine-grained statistical characteristic of mobility and can select the optimal places to install gateways.



(a) P_u=70%

(b) P_u=90%

Fig.3. CDF of the number of the required gateways

Conclusions

In this paper, we study the problem of deploying gateways for mobile vehicles in the vehicle to roadside communication system. The design goal is to satisfy the connectivity requirement for all vehicles passing the coverage region while minimizing the deployment cost. We use a mobility graph characterize the time stable mobility pattern, and show the gateway deployment problem is NP-complete by reducing it into the minimum vertex coverage problem. Finally, we propose a heuristic greedy algorithm MobGDeploy to find the optimal installation places. Extensive experiment in the synthetic scenarios is carried out to evaluate the performance of our solution. The results show that our solution achieves the desired coverage performance and minimizes the number of the required gateways.

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REFERENCES

[1] A. Saha, G. Park, K. Ahn, C. S. Kim, B. Lee, and Y. Rhee, "Data distribution of Road-Side information station in vehicular ad hoc net¬works (VANETs)," in Proceedings of the International Conference on Computational Science and Its Applications: Part II. Seoul, Korea: Springer-Verlag, 2009, pp. 503–512.

[2] M. J. Eriksson and S. Madden, "Cabernet: vehicular content delivery using WiFi," in Proceedings of the 14th ACM international conference on Mobile computing and networking, 2008, p. 199210.

[3] B. Aslam and C. C. Zou, "Optimal roadside units placement along highways", in 2011 IEEE Consumer Communications and Networking Conference (CCNC), 2011, pp. 814–815.

[4] B. Liu, Z. Liu, and D. Towsley, "On the capacity of hybrid wireless networks," in IEEE INFOCOM, vol. 2, 2003, p. 15431552.

[5] W. Zhao, Y. Chen, M. Ammar, M. Corner, B. Levine, and E. Zegura, "Capacity enhancement using throwboxes in DTNs," IN PROC. IEEE INTL CONF ON MOBILE AD HOC AND SENSOR SYSTEMS (MASS, pp. 31—40, 2006.

[6] I. Leontiadis, P. Costa, and C. Mascolo, "Persistent content-based information dissemination in hybrid vehicular networks", in Proceedings of the 2009 IEEE International Conference on Pervasive Computing and Communications, 2009, pp. 1–10.

[7] N. Banerjee, M. D. Corner, D. Towsley, and B. N. Levine, "Relays, base stations, and meshes: enhancing mobile networks with infrastructure", in Proc. of MobiCom 2008, pp. 81–91.

[8] J. Ghosh, S. Philip, and C. Qiao, "Sociological orbit aware location approximation and routing in MANET," in Broadband Networks, BroadNets 2005. 2nd International Conference on, 2005, pp. 641–650 Vol. 1.

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