國 立 交 通 大 學

資訊科學與工程研究所

博 士 論 文

雙階層車載隨意網路暨同儕網路之資訊擷取系統研究

A Study of a Two-Tier VANET/P2P System for Information Retrieval Services

研 究 生：鄭建明

指導教授：曹孝櫟　教授

中 華 民 國 一0三 年 六 月

雙階層車載隨意網路暨同儕網路之資訊擷取系統研究

A Study of a Two-Tier VANET/P2P System for Information Retrieval Services

研 究 生：鄭建明　　Student：Chien-Ming Cheng

指導教授：曹孝櫟 教授　　Advisor：Prof. Shiao-Li Tsao

國 立 交 通 大 學

資 訊 科 學 與 工 程 研 究 所

博 士 論 文

A Dissertation

Submitted to Institute of Computer Science and Engineering

College of Computer Science

National Chiao Tung University

in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in

Computer Science

June 2014

Hsinchu, Taiwan, Republic of China

中華民國一 O 三年六月

雙階層車載隨意網路暨同儕網路之資訊擷取系統研究

學生：鄭建明 指導教授：曹孝櫟 教授

國立交通大學資訊科學與工程研究所博士班

中文摘要

資訊與通訊科技的進步讓車輛可合作分享與擷取有用的資訊，以提供智慧型運輸系統之服務。為了提供這類服務，需要設計一套資訊擷取系統，有效率地在移動的車輛和路邊設施之間擷取資訊。在這篇論文中，我們首先分析與歸納於車載環境提供資訊擷取服務之系統架構。當車輛密度高時，採用短距離的車間隨意通訊（intervehicle ad hoc communication）之單階層系統可於短時間內取得所需資訊。另一方面，採用長距離的基礎建設無線通訊（infrastructure-based communication）與同儕網路（peer-to-peer networking）之單階層系統則可提供高成功率的資訊擷取，而不受限於車輛的數量。然而，對於提供資訊擷取服務，單階層系統可能遭遇較低的擷取成功率或需要較長的通訊時間。為了善用兩種無線通訊系統，我們提出雙階層車載隨意網路（VANET）暨同儕網路（P2P）之系統架構，此雙階層系統整合一個低階的車載隨意網路與另個高階的同儕網路，於車載環境提供資訊擷取服務。我們分析比較單階層系統與所提出之雙階層系統，並透過模擬實驗的方式評估效能。實驗結果顯示，相較於單階層車載隨意網路之系統，雙階層系統可明顯提高資訊擷取的成功率；相較於單階層基礎建設通訊式同儕網路之系統，雙階層系統可降低資訊擷取所需的時間與訊息負擔。最後，我們提出適應性搜尋協定以提升雙階層系統於資訊擷取的效能。此搜尋協定採用 Bloom filter 以收集路段的可到達狀況，評估路段的可到達機率而調整資訊擷取時的訊息傳送方式。對於雙階層資訊擷取系統，模擬實驗結果顯示，相較於原有的搜尋機

制，此適應性搜尋協定可減少資訊擷取所需的時間與訊息負擔，亦可達到資訊擷取的高成功率。

A Study of a Two-Tier VANET/P2P System for Information Retrieval Services

Student: Chien-Ming Cheng

Advisor: Prof. Shiao-Li Tsao

Institute of Computer Science and Engineering
College of Computer Science
National Chiao Tung University

ABSTRACT

With advance in information and communication technologies, vehicles on roads can cooperatively share and retrieve information in a distributed manner to support Intelligent Transportation Systems (ITS) services such as traffic management and infotainment services. To support such services, a system is needed to retrieve information and data from moving vehicles and roadside facilities in an efficient manner. In this dissertation, we first classify system architectures for information retrieval services in a vehicular environment. Single-tier systems based on short-range intervehicle ad hoc communication can achieve the shortest latency if vehicle density is sufficient. On the other hand, single-tier systems based on long-range infrastructure-based wireless communication and peer-to-peer (P2P) networking technology can provide a high success rate without the need for a sufficient density. However, the single-tier systems relying on either vehicular ad hoc networks (VANETs) or an application-layer P2P overlay over infrastructure-based networks may suffer from low success rate or long latency in information retrieval. To take advantage of both ad hoc and infrastructure-based communications, we propose a two-tier

VANET/P2P architecture that integrates low-tier VANETs and a high-tier infrastructure-based P2P overlay network for providing information retrieval services in the vehicular environment. We provide a qualitative analysis of the single-tier and the proposed two-tier architectures. The performance of different system architectures is evaluated and analyzed through simulation. Our results demonstrate that an information retrieval system based on the proposed two-tier VANET/P2P architecture can significantly improve success rate compared to the single-tier VANET-based systems while reducing lookup latency and message overhead compared to the single-tier infrastructure-based P2P systems. In the last part of this dissertation, we propose an adaptive lookup protocol to improve the efficiency of information retrieval in the two-tier VANET/P2P system. The proposed protocol uses the concept of the Bloom filter to collect reachability information of road segments. Therefore, adaptive routing of lookup queries between low-tier and high-tier networks according to reachability probability can be employed. Simulation results show that compared to the conventional two-tier lookup mechanism, the adaptive lookup protocol can reduce the lookup latency and lookup overhead, and also achieve a high success rate in information lookups.

誌謝

完成這篇論文首先須感謝指導老師—曹孝櫟教授，在博士班期間給予的教導和幫助。感謝交大張明峰教授和王協源教授擔任我的論文指導及審查委員，於博士論文計畫書審查與校內論文口試時，給予許多寶貴的建議。感謝清大許健平教授、中正黃仁竑教授、台大黃寶儀教授和成大鄭憲宗教授擔任我的博士學位考試委員，撥冗指導我的博士論文。

感謝交大 BRASS 實驗室的夥伴們，包括一正、凱翔、金璋、宥霖、邦翔、誌謙、中暉、名杰、雅筑、建臻、政龍、薪中、科文、珮筠、佳育、易聖、勇旗、承威、培書、宇安、星斐、佳駿、冠志等，謝謝大家多年來在研究、課程、計畫的合作和幫助。同時，感謝系辦助理蘇誼嫻小姐和曹雅珽小姐兩位的多年幫忙。

最後，也是最重要的，要感謝我的家人。感謝父親和母親的關心和體諒，更感謝姊姊在高雄全心全力細心照顧家人。特別要感謝老婆—慧怡，支持和鼓勵我完成博士論文，尤其辛苦地孕育了我們的第一個寶寶—可愛的女兒。

TABLE OF CONTENTS

中文摘要 i

Abstract iii

誌謝 v

Table of Contents vi

List of Tables ix

List of Figures x

Chapter 1 Introduction 1

Chapter 2 Single-Tier Information Retrieval Systems 5

2.1 Single-Tier VANET System 6

2.2 Single-Tier P2P over VANET System 8

2.3 Single-Tier Infrastructure-Based P2P System 11

Chapter 3 A Two-Tier VANET/P2P Information Retrieval System 14

3.1 Assumptions 15

3.2 Superpeer Election in Low-Tier VANETs 16

3.3 High-Tier Peer-to-Peer Overlay Organization 18

3.3.1 Unstructured Peer-to-Peer Overlay 18

3.3.2 Structured Peer-to-Peer Overlay 20

3.4 Information Sharing and Retrieval 22

3.4.1 Information Lookup in VANETs 22

3.4.2 Information Lookup in Unstructured Peer-to-Peer Overlay 23

3.4.3 Information Lookup in Structured Peer-to-Peer Overlay 24

3.4.4 An Example of Information Retrieval 25
3.5 A General VANET/P2P System Model 26
3.6 Design Issues and Comparisons 28
3.6.1 Network Connectivity 28
3.6.2 Information Sharing 29
3.6.3 Information Lookup 30
3.6.4 Peer-to-Peer Overlay Construction 31
3.7 Performance Evaluation 35
3.7.1 Setup 35
3.7.2 Results 37
3.8 Summary 46
Chapter 4 Adaptive Two-Tier Lookup Protocol 47
4.1 Reachability Model 49
4.2 Lookup Initiation 53
4.3 Lookup Forwarding 57
4.4 Performance Evaluation 60
4.4.1 Setup 61
4.4.2 Results in a Stationary Scenario 64
4.4.3 Results in a Mobility Scenario 68
4.5 Summary 79
Chapter 5 Conclusion and Future Directions 80

Bibliography 83

LIST OF TABLES

Table I: Comparison of architectures for information retrieval services. 33

Table II: Simulation parameters. 61

LIST OF FIGURES

Figure 2.1: Example of single-tier VANET architecture. 6

Figure 2.2: Example of single-tier P2P over VANET architecture based on Chord. 9

Figure 2.3: Example of single-tier infrastructure-based P2P architecture based on Chord. 12

Figure 3.1: Example of two-tier VANET/P2P system. 14

Figure 3.2: Example of two-tier VANET/P2P system based on Gnutella. 19

Figure 3.3: Example of two-tier VANET/P2P system based on Chord. 21

Figure 3.4: Example of information retrieval in two-tier VANET/P2P system based on a Gnutella-based P2P overlay. 26

Figure 3.5: A general VANET/P2P model and the two-tier system based on the model. 27

Figure 3.6: Single-tier systems based on the general VANET/P2P model. 28

Figure 3.7: Lookup success rate for different approaches. 38

Figure 3.8: Lookup latency for different approaches. 40

Figure 3.9: VANET bandwidth usage for different approaches. 41

Figure 3.10: P2P overlay bandwidth usage for different approaches. 42

Figure 3.11: Lookup success rate under different clustering periods. 43

Figure 3.12: Lookup latency under different clustering periods. 44

Figure 3.13: Lookup success rate under different clustering hops. 45

Figure 3.14: Lookup latency under different clustering hops. 45

Figure 4.1: Example of conventional information retrieval in the two-tier VANET/P2P system. 48

Figure 4.2: Algorithms for maintaining reachability information using *m*-bit Bloom filters. 51

Figure 4.3: Lookup initiation for the normal peer and initiating superpeer....................56

Figure 4.4: Lookup forwarding in the P2P overlay and VANETs. 59

Figure 4.5: Example of the adaptive lookup protocol in the two-tier VANET/P2P system. 59

Figure 4.6: Lookup success rate in a stationary scenario. 65

Figure 4.7: Lookup latency in a stationary scenario. 66

Figure 4.8: VANET lookup overhead in a stationary scenario. 67

Figure 4.9: P2P lookup overhead in a stationary scenario. 68

Figure 4.10: Lookup success rate in a mobility scenario. 70

Figure 4.11: Lookup latency in a mobility scenario. 72

Figure 4.12: VANET lookup overhead in a mobility scenario. 73

Figure 4.13: P2P lookup overhead in a mobility scenario. 73

Figure 4.14: Lookup success rate in a mobility scenario. 75

Figure 4.15: Lookup latency in a mobility scenario. 76

Figure 4.16: VANET lookup overhead in a mobility scenario. 78

Figure 4.17: P2P lookup overhead in a mobility scenario. 78

CHAPTER 1 INTRODUCTION

Advances in information and communication technologies enable vehicles on roads to cooperatively share information and data to support intelligent transportation systems (ITS) services, such as vehicle safety [1], traffic management [2], [3], and infotainment services [4], without requiring a centralized server. For example, current traffic conditions in a specific road segment can be obtained by sending queries to the vehicles either driving on the road segment or near the area. In addition, a gas station may advertise its price information in a local area so that nearby vehicles can receive these messages. The growing necessity for sharing and retrieving required information among vehicles has motivated the creation of an information retrieval infrastructure in a vehicular environment.

Information sharing and retrieval require the support of wireless communication to transmit and receive data to and from moving vehicles. Recently, two major types of wireless communication technologies have been considered in the vehicular environment [5]. They are short-range ad hoc communication, such as IEEE 802.11p, also known as intervehicle communication (IVC), and long-range infrastructure-based communication, such as Mobile WiMAX and LTE. IVC provides direct and low-latency communication between vehicles without requiring an infrastructure support [6]. Vehicles communicate with each other in a hop-by-hop manner to establish vehicular ad hoc networks (VANETs). A number of systems have been proposed to share traffic information [2], [7] and content delivery [4] over VANETs. However, these systems require a sufficient number of vehicles participating in VANETs. VANETs may become disconnected under low vehicle densities, and thus, information and data may not be exchanged among vehicles where low vehicle densities occur.

On the other hand, infrastructure-based wireless communication, which can offer a wide range of communication to vehicles, does not suffer from a network disconnectivity problem. Recent research [3] has used infrastructure-based cellular communication to implement a cooperative traffic information service among vehicles. In particular, an application-layer service overlay is built over an infrastructure-based network using peer-to-peer (P2P) networking technology [8]. Vehicles cooperatively share and retrieve traffic information over the infrastructure-based P2P overlay network. However, significant service delays may be introduced in this type of system because of limited network bandwidths and high communication latencies through base stations and mobile communication core networks.

The systems described above utilize VANETs, infrastructure-based networks, or an application-layer P2P overlay network to provide information retrieval services in the vehicular environment. We classify these systems as single-tier information retrieval systems. As vehicles are envisioned to support multiple wireless access technologies [5], [9], they can communicate with each other via not only direct ad hoc communication but also infrastructure-based communication. Direct intervehicle communication provides low communication latencies (e.g., a few milliseconds) in connected areas while infrastructure-based communication offers a wide range of communication with longer latencies (e.g., on the order of hundreds of milliseconds). To exploit the two communication systems, we propose a two-tier VANET/P2P architecture that integrates low-tier VANETs and a high-tier infrastructure-based P2P overlay network. In low-tier VANETs, vehicles can directly exchange and collect information using IVC efficiently. In addition, certain vehicles are elected to establish a P2P overlay through infrastructure-based communication to alleviate the disconnectivity problem in VANETs. Vehicles cooperatively share information with each other and send queries through low-tier

VANETs and the high-tier P2P overlay to retrieve information of interest. An information retrieval system based on the two-tier VANET/P2P architecture can achieve a high lookup success rate, low lookup latency, and low maintenance overhead compared with the single-tier systems.

The conventional design of the information lookup in the two-tier VANET/P2P system simultaneously performs queries over the low-tier VANETs and high-tier P2P overlay network. Although this increases the lookup success rate and improves the lookup response time, this approach may introduce redundant lookup messages and delays. For example, it is unnecessary to forward and broadcast lookups to the P2P overlay if the lookup message can be delivered to the intended destination through well-connected VANETs. Moreover, a query should be directed from the P2P overlay to VANETs to minimize the lookup latency if the query can be routed to the destination through the VANETs. Making full use of VANETs can improve the lookup speed and reduce redundant lookups in the infrastructure communication network whose radio resources are relatively expensive. Therefore, we propose an adaptive lookup protocol for the two-tier VANET/P2P system. The proposed protocol uses the concept of the Bloom filter [10] to exchange reachability information of road segments among vehicles in VANETs. The reachability of a road segment indicates whether the road segment can be reached through low-tier VANETs. The Bloom filter is a space-efficient probabilistic data structure that can considerably reduce storage and wireless communication overheads for information exchanges between vehicles. Although the reachability information maintained by Bloom filters can only provide an estimation regarding whether a query can be routed to a specific road segment through the VANETs, simulation results show that the design fits and can accommodate the dynamic nature of a vehicular environment. The proposed protocol forwards lookups adaptively between the low-tier VANETs and high-tier P2P overlay network according to the reachability of the destination. Therefore, compared with the conventional two-tier lookup mechanism, the latency of information retrieval and the lookup message overheads can be significantly reduced in the two-tier VANET/P2P system by applying the adaptive lookup protocol.

The rest of this dissertation is organized as follows. Chapter 2 presents single-tier architectures and existing systems for information retrieval in a vehicular environment. Chapter 3 proposes a two-tier VANET/P2P information retrieval system, compares different system architectures, and provides a performance evaluation through simulation. Chapter 4 proposes an adaptive lookup protocol to improve the performance of the two-tier VANET/P2P system. Finally, Chapter 5 concludes this dissertation and suggests some future directions.

CHAPTER 2 SINGLE-TIER INFORMATION RETRIEVAL SYSTEMS

ITS have attracted considerable interest from both academia and industries in recent years. Several ITS services, which improve driver convenience, rely on the sharing and retrieval of relevant information among vehicles. For instance, a cooperative traffic information system is a typical example of information retrieval services in a vehicular environment. Vehicles collaboratively collect traffic-related information and exchange the information among themselves. A navigation system in vehicles can provide drivers with optimal routes according to collected traffic information.

To support information retrieval services, a vehicle is assumed to be able to obtain its geographic position and moving speed via Global Positioning System (GPS) or other means. It has a map database consisting of road topology information. A computing system is installed in the vehicle to process and analyze data. Vehicles can be equipped with wireless interfaces for ad hoc communication and/or infrastructure-based communication to share information with other vehicles and roadside units. In addition, vehicles may organize themselves into an application-layer service overlay (i.e., a P2P overlay) for efficient information sharing and retrieval.

According to the use of wireless technologies and system architectures, we classify vehicular systems for information retrieval services into four different architectures: single-tier VANET, single-tier P2P over VANET, single-tier infrastructure-based P2P, and two-tier VANET/P2P. To our knowledge, this is the first work to provide the classification of architectures and analysis of alternative vehicular information retrieval systems. This chapter presents the first three single-tier architectures and existing systems, and the next chapter presents the proposed two-tier VANET/P2P architecture.

2.1 Single-Tier VANET System

Vehicles communicate with each other through IVC to establish VANETs. They periodically broadcast messages via IVC to exchange information (e.g., speeds and positions) with neighboring vehicles. A part of the information that a vehicle receives from others may also be propagated to its neighbors through broadcast messages. Thus, information could be disseminated to vehicles located far away in a hop-by-hop manner. This system architecture is classified as single-tier VANET system. Figure 2.1 shows the single-tier VANET architecture.

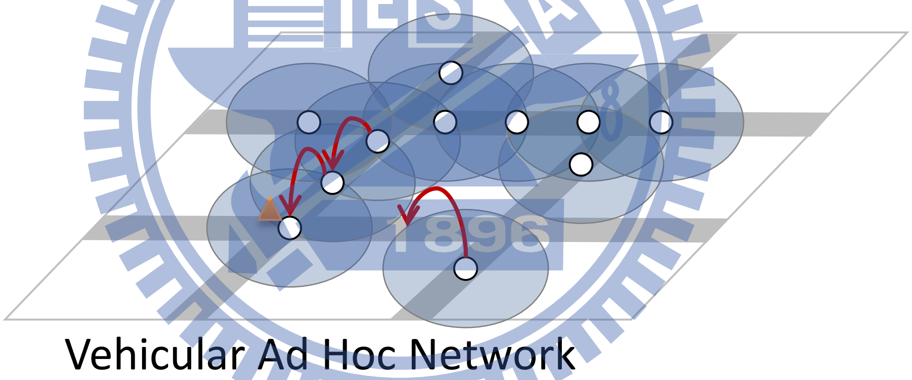


Figure 2.1: Example of single-tier VANET architecture.

The single-tier VANET architecture is easy to be utilized to support vehicle safety applications. In [1], vehicles in a geographical area are grouped together and exchange safety-related information via IVC. When vehicles are far from each other, they report safety information to roadside entities, which then forward this information to other vehicles. A vehicle safety system based on the single-tier VANET architecture requires the installation and maintenance of roadside entities to distribute safety-related information to all vehicles. A number of decentralized traffic information systems also have been developed based on this architecture. Vehicles cooperatively observe traffic conditions of local areas and exchange traffic information among themselves using IVC. A vehicle can generate traffic reports for road segments based on its observations and traffic messages obtained from other vehicles. A common approach is to aggregate and average the speeds of vehicles on a road segment to derive the traffic report for the road segment. In the Self-Organizing Traffic Information System (SOTIS) [2], [11], vehicles periodically broadcast their driving status (e.g., current speeds and positions) with parts of the information of other road segments that are collected from neighboring vehicles. A vehicle processes and analyzes the collected traffic information and stores analysis results in a database. As a result, each vehicle gathers traffic information of the local road segments (for example, a radius of 50 km) with an average information delay of up to 20 minutes. StreetSmart focuses on discovering and disseminating congestion information [12]. Vehicles use data clustering algorithms to aggregate the collected data and exchange only the most significant information such as areas of unexpected speed. However, the traffic information may be outdated or incomplete, especially for road segments far away from the vehicle.

In addition to cooperative traffic information sharing, content delivery has emerged as another promising paradigm for information retrieval in the vehicular environment. CarTorrent [13] adopts a BitTorrent-like swarming protocol [14] to provide content sharing among vehicles in VANETs. Vehicles use a gossip mechanism to periodically disseminate their content availability information, and to gather statistics from other vehicles. In addition to downloading content blocks from the Internet through roadside access points (APs), vehicles can obtain content blocks from other vehicles thorough direct IVC when moving out of an AP coverage. A service infrastructure over VANETs was proposed in [15] to provide users with time-sensitive information regarding traffic conditions and roadside services using IVC. An application-layer communication protocol [16] is utilized to perform location-aware queries between vehicles over VANETs. However, a query failure would occur if a route between the source and target location areas cannot be found due to insufficient VANET connectivity.

Systems based on the single-tier VANET architecture use only intervehicle ad hoc communication, and may assume the presence of a sufficient number of participating vehicles in VANETs for transmitting information and data. In VANETs, information can be quickly disseminated among vehicles through IVC. However, the dissemination requires a sufficient number of vehicles participating in the network. When the vehicle density is insufficient, vehicles may not be able to form a fully connected VANET. In that case, information cannot be distributed to all vehicles or retrieved over a large distance. To improve the connectivity, additional roadside units connected via a backbone network could be used to exchange information with vehicles via wireless communication [17]. However, the additional roadside units introduce extra installation and maintenance costs. Another issue for the single-tier VANET system is the broadcast storm problem in a high-vehicle-density environment if each vehicle rebroadcasts every received message. A number of solutions have been presented to alleviate the problem [18], [19]. For example, a vehicle rebroadcasts the query message only if it is closer to the road segment where the requested information is located than the previous node.

2.2 Single-Tier P2P over VANET System

P2P networking has been widely adopted as an efficient technique for information sharing and retrieval in a distributed manner [8]. The above architecture can be further extended to a single-tier P2P over VANET architecture. Vehicles form an application-layer P2P overlay network on top of VANETs. The P2P overlay can be unstructured such as Gnutella [20], or structured such as Chord [21]. The vehicles share their resources (e.g., data content and traffic information) and retrieve resources from others through the P2P overlay. The communication between vehicles in the application-layer P2P overlay relies on the routing protocol of the underlying VANETs [22]. A vehicle should establish a routing path in the VANETs first; then an application-layer message can be transmitted along the route to another vehicle through the VANETs. Figure 2.2 shows an example of the P2P over VANET architecture based on a structured P2P overlay (i.e., Chord).

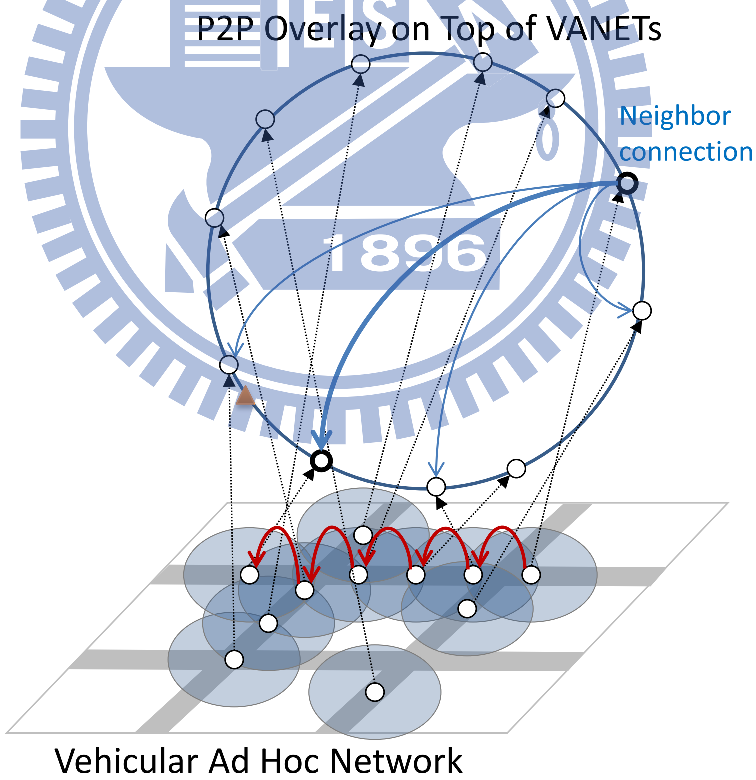


Figure 2.2: Example of single-tier P2P over VANET architecture based on Chord.

The key difference between the P2P over VANET architecture and the previous architecture is the information lookup. In the previous architecture, a vehicle floods a query message to all neighboring vehicles within the IVC range. In this architecture, a vehicle explicitly forwards the query to certain vehicles by exploiting the application-layer P2P lookup mechanism and the underlying VANET routing. For example, in an unstructured P2P overlay such as a Gnutella-based system, the lookup is based on time-to-live (TTL)-limited flooding in the application-layer P2P overlay. If a vehicle does not have the desired information, it forwards the query to its Gnutella neighbors, not direct VANET neighbors, through the VANET routing paths. On the other hand, in a structured P2P overlay such as a Chord-based system, a vehicle examines its finger table to select the Chord neighbor whose identifier is closest to the key of the requested information. The vehicle directly forwards the query message to the neighbor through the established VANET routing path. The lookup procedure continues until the query reaches the vehicle responsible for the key. Moreover, because vehicles are usually moving, the participating vehicles and P2P overlay topology continuously change. The P2P overlays thus require performing periodic stabilization procedures to maintain neighbor connections. For example, in an unstructured P2P overlay such as Gnutella, vehicles must periodically send query messages (i.e., PING) to their P2P neighbors. A response message (i.e., PONG) is sent in reply if a P2P neighbor remains in the overlay. When a vehicle detects the departure of a neighbor, it randomly connects to another vehicle as its new P2P neighbor.

Recent studies of P2P file-sharing systems in mobile and vehicular ad hoc networks have adopted the architecture. The P2P overlay enables users to locate the resources they need in such an environment. To improve performance of the application-layer P2P protocol, cross-layer approaches that extract useful information from the lower-layer protocol messages for supporting the construction and maintenance of the upper-layer P2P network were proposed [4]. Although the architecture can also be applied to a traffic information system, maintaining the services is difficult due to dynamics of traffic information and high vehicular mobility.

In the P2P over VANET architecture, the application-layer P2P overlay is utilized for vehicles to locate the requested information efficiently. Although the architecture may minimize redundant rebroadcasts of query messages, additional efforts are required for maintaining the application-layer P2P overlay in VANETs. The transmission of lookup and maintenance messages through the P2P overlay requires the use of underlying VANET routing protocols and must introduce routing overhead in the bandwidth-limited VANETs. Additionally, due to the P2P overlay being built on top of the VANETs, the architecture also suffers from the same disconnectivity problem under low vehicle densities as the previous single-tier VANET system.

2.3 Single-Tier Infrastructure-Based P2P System

To overcome the disconnectivity problem of VANETs, another single-tier architecture involves forming an application-layer P2P overlay in an infrastructure-based network, instead of on top of VANETs. This system architecture is classified as single-tier infrastructure-based P2P system. Vehicles are required to have a broadband wireless interface to access the infrastructure-based network. Vehicles communicate with each other through infrastructure-based communication instead of direct ad hoc communication. The P2P overlay could also be unstructured or structured. Figure 2.3 shows an example of the single-tier infrastructure-based architecture based on a structured P2P overlay (i.e., Chord).

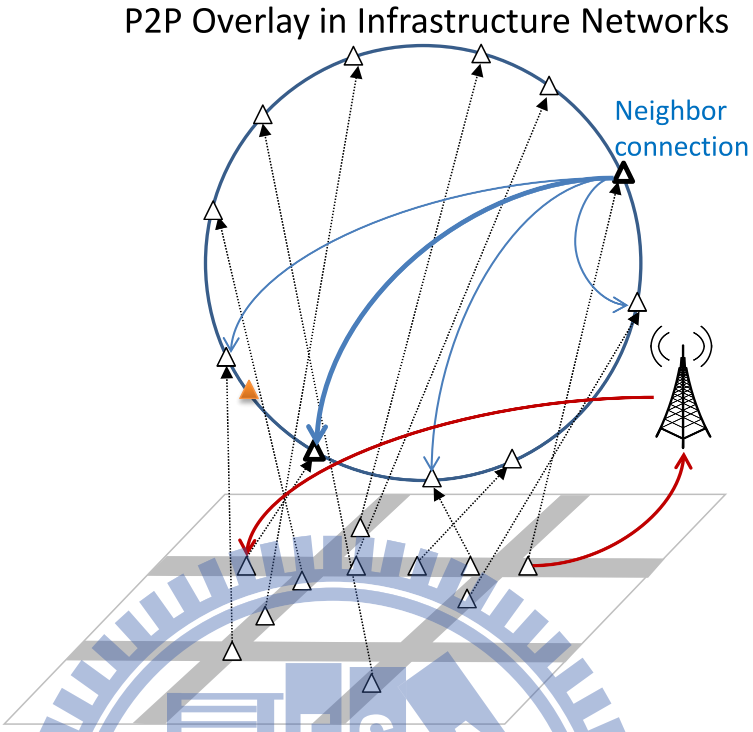


Figure 2.3: Example of single-tier infrastructure-based P2P architecture based on Chord.

A P2P-based traffic information system was proposed in [3] by exploiting cellular communication and P2P networking technology. In this system, vehicles form a structured P2P overlay and query traffic information through cellular communication, thereby avoiding the disconnectivity problem of VANETs. However, a previous study [23] has indicated that structured P2P systems suffer from frequent node join/leave (i.e., churn), and they are less efficient than unstructured P2P systems in a dynamic network environment such as mobile and vehicular networks. Although the approach utilizes an infrastructure-based communication system to avoid network disconnectivity, lookup delays in an infrastructure-based P2P overlay may increase because the communication latency of an infrastructure network is significantly greater than that of VANETs. Moreover, this architecture does not utilize the IVC, which is an efficient and low-latency solution for short-distance information exchanges.

CHAPTER 3 A TWO-TIER VANET/P2P INFORMATION RETRIEVAL SYSTEM

We propose an information retrieval system based on a two-tier VANET/P2P architecture, which consists of low-tier VANETs and a high-tier infrastructure-based P2P overlay network. Vehicles that participate in low-tier VANETs can communicate with each other through IVC, whereas only a portion of vehicles are elected to form a high-tier P2P overlay through infrastructure-based wireless communication. Each vehicle observes and collects information such as traffic condition in its local area. The information is shared among vehicles moving on roads, and may be requested by other vehicles. The required information can be retrieved through lookups performed in the low-tier and high-tier networks. Figure 3.1 shows an example of the proposed two-tier VANET/P2P system.

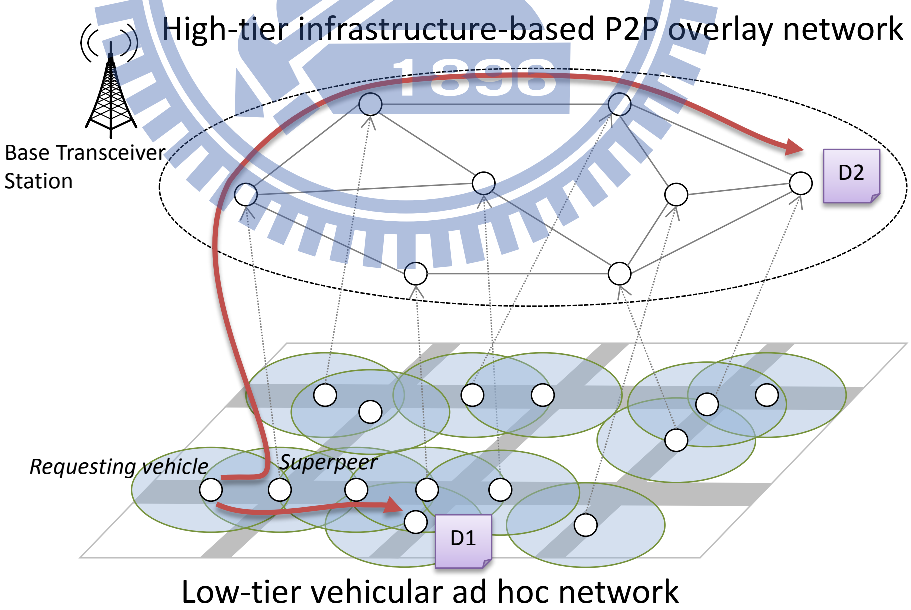


Figure 3.1: Example of two-tier VANET/P2P system.

In this chapter, we first present assumptions made by the proposed system in Section 3.1 and then present a detailed design of the two-tier VANET/P2P system in Sections 3.2, 3.3, and 3.4. Section 3.5 generalizes the proposed VANET/P2P architecture as a general system model. Section 3.6 discusses several design issues for information retrieval services in a vehicular environment and compares the proposed two-tier system with single-tier systems. Finally, we evaluate the performance of different systems through simulation in Section 3.7.

3.1 Assumptions

With continuous advances in technology, it is feasible to assume that each vehicle can obtain its driving conditions, such as current geographic location and current speed using in-vehicle sensors (e.g., GPS receivers). A vehicle is equipped with a digital map database consisting of information regarding road topology and roadside facilities (e.g., gas stations and parking lots). Road topology is divided into road segments, each of which is associated with a unique segment identifier (ID) and geographic location. Because vehicles are envisioned to communicate across multiple wireless interfaces, each vehicle is assumed to be equipped with two wireless communication interfaces: one for direct ad hoc communication and the other for infrastructure-based communication. However, the two-tier VANET/P2P system does not strictly require all the vehicles to be equipped with two wireless interfaces. A vehicle equipped with only one interface is able to communicate with others in the two-tier system through the vehicles equipped with the two wireless interfaces, as will be discussed later.

In a vehicular environment, information available to or requested by users is typically related to geographic locations. Therefore, the information requested through the system is assumed to be related to a road segment that can be identified by its segment ID. A request for information made by users explicitly specifies the road segment (i.e., segment ID) where the information is located. It is further assumed that the required information related to a road segment can be obtained from the vehicles currently driving on that road segment. Although there is a reasonable possibility that vehicles are aware of nearby information, data processing functions such as data aggregation and compression may need to be performed on the collected data to fulfill the requirements of particular applications. For example, to estimate the traffic condition of a road segment, a common approach is to collect speed information from vehicles driving on the road segment and then apply a data aggregation scheme to derive the average speed for the road segment [11]. A data compression scheme may also be adopted to disseminate multiple data in a single message to nearby vehicles. This data processing, which may be correlated with or independent of the retrieval process, is closely related to information types and application requirements. This study focuses on the service infrastructure (i.e., system architecture and retrieval mechanism), and leaves the integration of data processing and information retrieval services to achieve high-level applications and services to future work.

3.2 Superpeer Election in Low-Tier VANETs

VANETs are established among vehicles through IVC. In low-tier VANETs, vehicles are organized into groups (i.e., clusters). Several distributed clustering mechanisms have been proposed to form group structures in mobile and vehicular ad hoc networks based on metrics, such as node ID, connectivity degree, and vehicle mobility (e.g., direction and speed) [24], [25]. The two-tier VANET/P2P system adopts a heuristic Max-Min *d*-cluster formation [26] to form multi-hop clusters based on node IDs. Each vehicle is assigned a unique node ID, which can be generated, for example, by hashing the vehicle registration identifier. Vehicles periodically broadcast messages through IVC to exchange node information, such as node IDs and current location, with neighboring vehicles. After the exchanges, a vehicle is elected as a clusterhead if it has the largest ID among the vehicles within *d* hops or it is the largest node in the *d*-hop neighborhood of one of its *d*-hop neighbors. In addition to node IDs that the Max-Min *d*-cluster algorithm refers to, previous studies on clustering algorithms (e.g., [25]) further adopt vehicle mobility to obtain a stable cluster structure in a high-mobility vehicular environment. Improving the stability of the cluster structure by incorporating other clustering algorithms in the proposed two-tier system is a direction for future work.

Each vehicle can recognize it as a clusterhead or knows its clusterhead if it is not. In the two-tier system, a clusterhead is called a *superpeer*, and other vehicles in the cluster are called *normal peers*. Vehicles, including superpeers and normal peers, are able to communicate with one another through IVC in VANETs. No difference between superpeers and normal peers appears from a VANET perspective. The message overhead of maintaining the cluster structure decreases when the frequency of superpeer election decreases. However, if the superpeer election is performed much less frequently, the lookup success rate decreases. This is because normal peers may move out of range of their superpeers and cannot communicate with their superpeers if the superpeer election is conducted infrequently. On the other hand, normal peers may not be able to communicate with their superpeers through neighboring nodes when a larger cluster size in used. Therefore, we examine the effects of superpeer election frequency and cluster size on system performance in Section 3.7.

All normal peers rely on superpeers to access the high-tier P2P overlay; therefore, additional computation and communication costs are imposed on the superpeers. An issue of fairness arises as a vehicle serving as the superpeer all the time may be undesirable. To deal with this issue, one simple approach is to use a different node ID when a vehicle re-joins the system. For example, a vehicle can generate a different node ID by hashing its original ID with a random number upon joining. The vehicle with the largest node ID will not be elected as the superpeer again because it may have a different node ID. To achieve improved fairness, the ID generation can account for the time periods of being a superpeer. The longer the period, the smaller the node ID is generated next time. Moreover, an incentive mechanism can be incorporated into the information retrieval service so that users would be willing to take the role of superpeers.

3.3 High-Tier Peer-to-Peer Overlay Organization

The vehicles elected as superpeers use their infrastructure-based communication interfaces to form an application-layer P2P overlay where the superpeers cooperate to share information with each other and provide information retrieval services to other vehicles. P2P networking technology has been widely used as an efficient approach in content sharing and information retrieval without requiring a centralized server [8]. An application-layer P2P overlay is constructed by participating nodes (i.e., vehicles for the information retrieval service under consideration). P2P overlay networks can be classified as unstructured (e.g., Gnutella [20]) and structured (e.g., Chord [21]) according to network topology and content placement. We use Gnutella and Chord as examples to construct an unstructured and structured high-tier P2P overlay, respectively, and present the two overlay designs in the following.

3.3.1 Unstructured Peer-to-Peer Overlay

When a new superpeer joins a Gnutella-based P2P overlay, it first connects to any superpeer that is already in the overlay. In P2P systems, information about existed nodes in the P2P overlay can be obtained by contacting some well-known bootstrap node. The joining superpeer acquires the information of other superpeers in the overlay, randomly establishes connections with some of them, and maintains neighbor information in a neighbor table. After joining the P2P overlay, the new superpeer can share its information with other superpeers and retrieves information from the P2P overlay. Figure 3.2 shows an example of the two-tier VANET/P2P system based on a Gnutella-based P2P overlay.

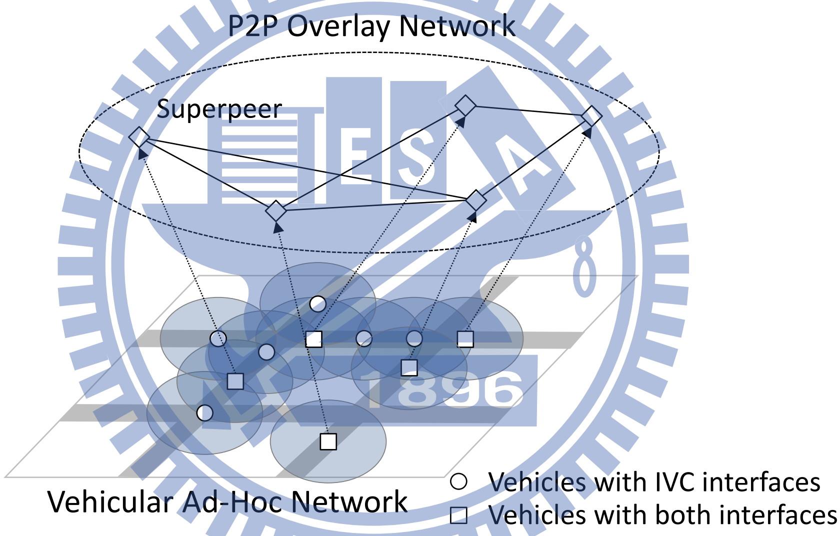


Figure 3.2: Example of two-tier VANET/P2P system based on Gnutella.

Since vehicles are usually moving, the members of the high-tier P2P overlay (i.e., superpeers) may continuously change. Thus, superpeers must perform a stabilization procedure to maintain their neighbor connections. To do so, superpeers periodically send PING messages to their neighbors, and receive PONG messages if a neighbor is still alive. When a superpeer detects the departure of a neighbor (i.e., no receipt of a PONG), it randomly connects to another superpeer as its new neighbor and maintains the new neighbor connection. The messages used to establish and maintain the P2P overlay are transmitted between superpeers using infrastructure-based wireless communication.

To further improve the stability of P2P overlay, a graceful departure mechanism can be applied to the two-tier system. After new superpeers join the P2P overlay, the previous superpeers stay a few seconds before stepping down in the P2P overlay. Therefore, there is an overlapping (or handover) period for old and new superpeers. This graceful departure mechanism ensures that the P2P overlay is stable and that there are always a sufficient number of superpeers to forward queries in a P2P overlay.

3.3.2 Structured Peer-to-Peer Overlay

In a Chord-based P2P overlay, superpeers establish a structured overlay in the form of a Chord ring. The ring topology is an *m*-bit identifier space ranging from 0 to 2^m-1. Each superpeer has a unique identifier (i.e., node ID) hashed from some identifier such as the vehicle identifier number (VIN). The node ID is mapped into the identifier space. The node ID used in the P2P overlay may be the same as or different from that used for superpeer election. Each superpeer maintains a finger table with at most *m* entries. The *i*th entry in the finger table of a superpeer with ID *n* is the first superpeer whose ID is at least 2^{i-1} away from *n* in the ring space. A superpeer *n* also maintains the predecessor, the superpeer whose ID immediately precedes *n*, and the successor, the superpeer whose ID most closely follows *n*. Figure 3.3 shows an example of the two-tier VANET/P2P system based on a Chord-based P2P overlay.

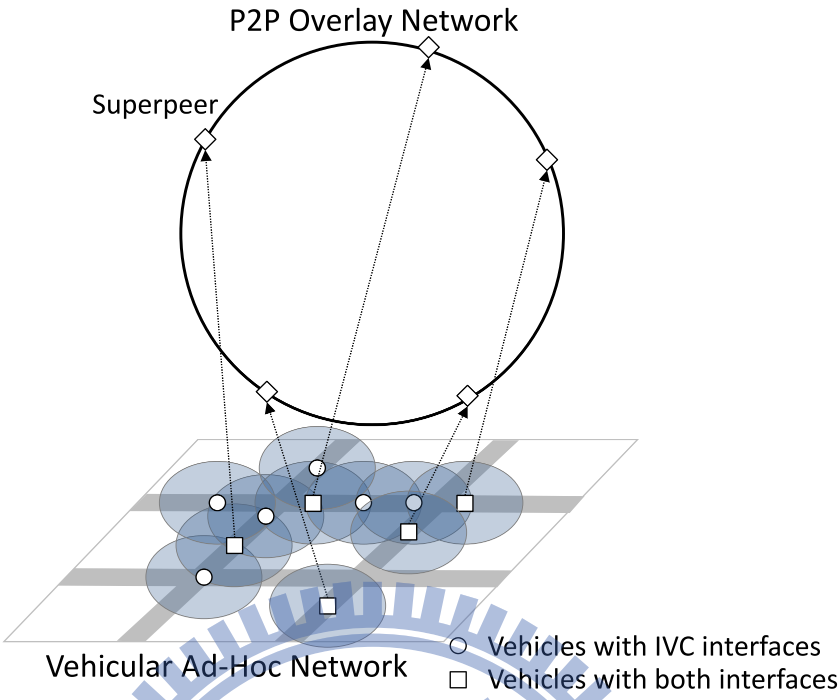


Figure 3.3: Example of two-tier VANET/P2P system based on Chord.

In the same identifier space, information related to a road segment is associated with a key that can be generated from the location and information-specific parameters. For example, a traffic report of a road segment has a key hashed from the segment ID and a pre-defined value indicating traffic condition as information type. In the Chord overlay, the information with key *k* is maintained by the successor, which is the first superpeer whose ID is equal to or follows *k* clockwise around the Chord overlay. Thus, each superpeer is responsible for a subset of keys and the associated information. To share information in such a structured P2P overlay, a superpeer must publish information to the responsible nodes after collecting information in the VANETs.

To maintain finger tables and the P2P overlay, each superpeer periodically performs a stabilization procedure to confirm the entries in its finger table. In addition, when an existing superpeer leaves or a new superpeer joins the P2P overlay, information may need to be updated on the new successors that are responsible for.

3.4 Information Sharing and Retrieval

In VANETs, vehicles cooperatively share their data with nearby vehicles and collect information available in their areas. Each vehicle stores the collected data and information in a local database. According to application-specific requirements, these data may be further processed and analyzed to generate the desired information. The results of analyzed data are retained for a certain period (e.g., a few seconds or minutes), after which they are expired. A user in a vehicle may send an inquiry for information, such as traffic conditions and available services for a specific location (i.e., a specific road segment). Information retrieval in the two-tier VANET/P2P system requires performing lookup queries in both the low-tier VANETs and high-tier P2P overlay network. A lookup message consists of a unique message ID, information regarding the requesting vehicle (e.g., its ID and location), the road segment ID of the destination, the requested information type (e.g., traffic conditions and gas prices), information regarding the forwarding vehicles (i.e., the vehicles that forward the message), and relevant parameters.

3.4.1 Information Lookup in VANETs

In VANETs, an information lookup is performed among vehicles in a hop-by-hop manner until a vehicle storing the requested information for the destination is located. To alleviate the broadcast storm problem, a time-to-live (TTL) mechanism and geographic forwarding scheme are used to forward the lookup message geographically closer to the destination at each hop.

In the two-tier system, a vehicle joining and leaving a cluster group does not affect lookup forwarding in VANETs. When a vehicle joins the two-tier system, it first determines if it is a superpeer or a normal peer. After the superpeer election process is complete, the vehicle can forward lookups in VANETs when receiving lookups from other vehicles through the VANETs, regardless of which type of peer it becomes. A vehicle ceases to assist in forwarding lookups in VANETs when it leaves the system.

3.4.2 Information Lookup in Unstructured Peer-to-Peer Overlay

In contrast to the lookups in VANETs, only superpeers are responsible for performing lookups in the high-tier P2P overlay. A superpeer may originate a lookup request for information itself or receive a request originated by a normal peer within the same cluster of VANETs. In both cases, the superpeer that initiates a lookup in the P2P overlay is called the *initiating superpeer*. The lookup procedure performed in the P2P overlay is based on the adopted P2P networking model.

In a Gnutella-based P2P overlay, a lookup query is performed based on TTL-limited flooding. When a superpeer receives a query, it first checks if it has the requested information. If the superpeer has the information, it replies to the query. Otherwise, the superpeer decreases the TTL by one and forwards the query to all of its neighbors in the P2P overlay if the TTL is still greater than zero. The forwarding process is repeated until a superpeer storing the requested information is located or the TTL value of the lookup becomes zero. Different TTL values may be used for lookups in low-tier VANETs and in the high-tier P2P overlay.

The geographic positions of road segments are well-defined on a digital map and all vehicles are aware of their own locations. To improve lookup performance, the two-tier system applies a geographic routing mechanism to the lookups in the Gnutella-based P2P overlay. The geographic routing mechanism routes a query to the neighboring superpeers that are close to the road segment in the query. This approach considerably reduces lookup latency and the number of lookup messages compared with the conventional flooding approach.

Vehicle joining and leaving may affect the lookups performed in the high-tier P2P overlay. When a normal peer generates a lookup request, it broadcasts the request in VANETs and also requests its current superpeer to forward the lookup in the P2P overly. When a normal peer joins another cluster group, it turns to another superpeer of the new cluster and asks for assistance with P2P lookup forwarding. Conversely, when a vehicle is elected as a superpeer, it can perform lookups in the P2P overlay after the overlay joining process is complete. When a superpeer becomes a normal peer, the superpeer may still receive P2P lookup forwarding requests from its normal-peer neighbors if the normal peers have not yet updated their new superpeer. To avoid lookup failures, a graceful departure mechanism can be adopted in the P2P overlay. In that case, superpeers continue to handle P2P lookups for a short period after they step down from the role of superpeer.

3.4.3 Information Lookup in Structured Peer-to-Peer Overlay

In a Chord-based P2P overlay, when a superpeer receives a query for information with key *k*, it first checks whether or not it is responsible for the key. If it has the requested information, it replies to the query with the desired information. Otherwise, the superpeer forwards the query to its P2P neighbor whose ID immediately precedes *k* in the overlay. This forwarding procedure continues until the query reaches the successor of key *k*, i.e., the superpeer responsible for the key. Upon receiving the query, the responsible successor replies to the initiating superpeer, and then to the normal peer originating the query if needed.

3.4.4 An Example of Information Retrieval

Figure 3.4 provides an example of information retrieval in the proposed two-tier VANET/P2P system based on a Gnutella-based P2P overlay. In this example, a new vehicle *n*7 which only has an IVC interface wants to join the two-tier system. When joining, *n*7 first connects to VANETs via its IVC interface in step 1 and starts to disseminate information in step 2. In the VANETs, the distributed superpeer election algorithm is periodically performed in step 3. Once a vehicle which has both IVC and infrastructure-based communication interfaces, say *n*1, becomes a superpeer, it joins the unstructured P2P overlay in step 4. If *n*1 is a newly joined superpeer without existing superpeer information, it must connect to the bootstrap node to obtain existing superpeers. After that, *n*1 randomly connects to *n*2 and *n*3 as its P2P neighbors. The superpeers also have to maintain the information they receive from their neighboring vehicles within clusters. For example, *n*4 maintains information about road segment *s*1 (e.g., traffic condition) received from vehicles on *s*1, as in step 5. Moreover, superpeers periodically exchange PING/PONG messages to maintain the P2P overlay. These messages also contain the location of the vehicles, such as GPS coordinates, to enable geographic routing of the queries in the P2P overlay.

To retrieve the information of a particular road segment, a vehicle broadcasts a query in VANETs. For example, if *n*7 wants to know the traffic information of road segment *s*1, it first broadcasts the query via its IVC in step 6. If any node in *n*7's cluster has the unexpired traffic report for *s*1, it responds to *n*7. Otherwise, the query is continually propagated until it is eventually received by the superpeer of *n*7's cluster, i.e., *n*1. The superpeer then forwards this query to other superpeers via the P2P overlay in step 7. This query routing in the P2P overlay is based on the geographic routing mechanism. *n*1 first sends the query to all of its neighbors in the P2P overlay, i.e., *n*2 and *n*3. Then, *n*2 and *n*3 select one vehicle which is the node nearest to the road segment *s*1. *n*2 and *n*3 forward the query to *n*5 and *n*4, respectively. Finally, the superpeer *n*4 receives the request and responds to *n*7 through *n*1 in step 8.

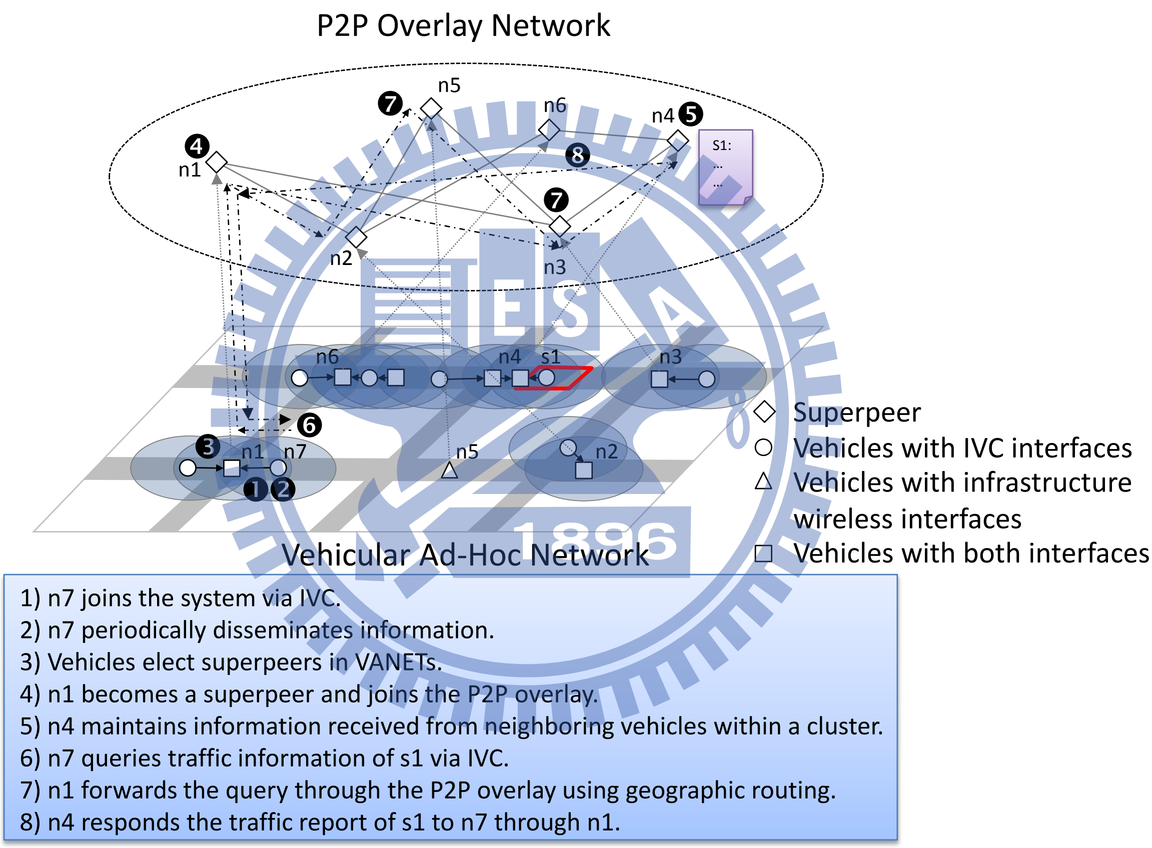
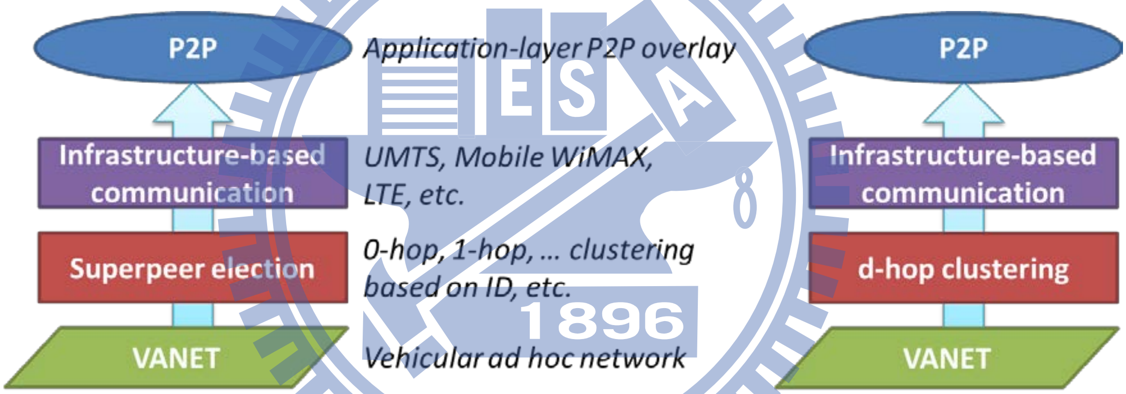


Figure 3.4: Example of information retrieval in two-tier VANET/P2P system based on a Gnutella-based P2P overlay.

3.5 A General VANET/P2P System Model

The proposed two-tier VANET/P2P system not only is a new system architecture but represents a general system model for information retrieval system in a vehicular environment. The general model consists of several layers for design considerations of the information retrieval system. From the lowest level of the model, vehicles can utilize IVC to form VANETs. They may adopt a clustering mechanism based on IDs or other metrics to perform superpeer election. Vehicles can further utilize infrastructure-based communication (e.g., UMTS, Mobile WiMAX, and LTE) if available. Finally, they may organize themselves into an application-layer P2P overlay using either intervehicle or infrastructure-based communication. Figure 3.5 shows the general VANET/P2P model and the two-tier information retrieval system based on this model.

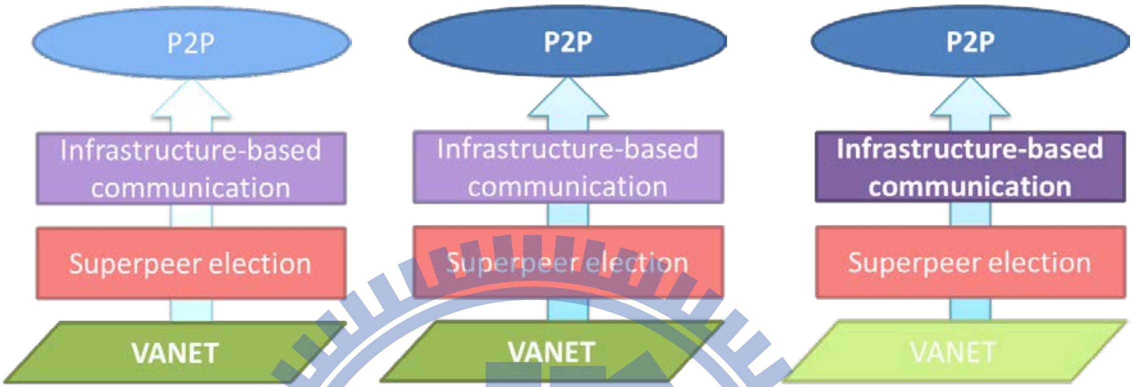


(a) General VANET/P2P model

(b) Two-tier system based on the model

Figure 3.5: A general VANET/P2P model and the two-tier system based on the model.

The three single-tier information retrieval systems described in Chapter 2 can also be constructed using the general VANET/P2P model. For the single-tier VANET system, vehicles utilize only IVC to form VANETs. Although they do not perform superpeer election, they can do it if they will. For the single-tier P2P over VANET system, vehicles form VANETs, perform no superpeer election, utilize no infrastructure-based communication, and form a P2P overlay on top of VANETs. For the single-tier infrastructure-based P2P system, vehicles utilize infrastructure-based communication to form a P2P overlay without any usage of IVC and superpeer election. Figure 3.6 shows the three single-tier systems based on the general VANET/P2P model.



(a) Single-tier VANET system (b) Single-tier P2P over VANET system (c) Single-tier infrastructure-based P2P system

Figure 3.6: Single-tier systems based on the general VANET/P2P model.

3.6 Design Issues and Comparisons

This section provides a qualitative analysis of single-tier and the proposed two-tier architectures for realizing information retrieval services in a vehicular environment. A quantitative analysis based on simulation is presented in the next section.

3.6.1 Network Connectivity

To share and retrieve information, vehicles participating in the single-tier systems are required to have either IVC interfaces for VANET and P2P over VANET systems, or broadband wireless network interfaces for infrastructure-based P2P systems. A vehicle cannot access the information retrieval service if it does not support the required communication system. By contrast, the proposed two-tier VANET/P2P system does not impose such a constraint on vehicles. A vehicle with only IVC capability shares and retrieves information in the low-tier VANETs as though it participates in VANET-based systems. Additionally, the vehicle can access the information available in the high-tier P2P overlay through communicating with superpeers via IVC. On the other hand, a vehicle with only infrastructure-based connectivity joins the high-tier P2P overlay where it can retrieve information from other superpeers, which may connect to other vehicles in VANETs using IVC. The proposed two-tier VANET/P2P architecture is more flexible so that it can accommodate vehicles with different wireless communication technologies.

3.6.2 Information Sharing

In both single-tier VANET-based and two-tier VANET/P2P systems, vehicles can broadcast information via IVC to disseminate information in VANETs. A vehicle may derive the desired information based on the information received from other vehicles. For example, in a traffic information system, vehicles periodically broadcast their observed traffic conditions via IVC. As a result, a vehicle can aggregate collected traffic information to generate a traffic report, which is more accurate than that based on a single observation. Information can be disseminated and propagated in a single-hop or multi-hop broadcast manner. Due to the limited bandwidth of VANETs, the single-hop broadcast of information is preferred to avoid overhead of multi-hop broadcasts and broadcast storms.

By contrast, no such information dissemination exists in the single-tier infrastructure-based P2P systems. Each vehicle knows only the information available in the areas it has visited and the information of responsible road segments that the vehicle handles when a structured P2P overlay is adopted. Vehicles cannot directly exchange information even when they are near to each other on a road. A vehicle must publish its information in the P2P overlay to share information with others and perform a lookup in the P2P overlay to obtain the required information.

3.6.3 Information Lookup

In the single-tier VANET system, the lookup for information can achieve a low latency, for example, a few milliseconds, through direct communication between vehicles; but may fail due to network partitioning under low vehicle densities. As the density increases, an increase occurs not only in the connectivity, but also in communication interferences and collisions. Therefore, both the success rate and lookup latency increase when more vehicles participate in the system. An efficient and effective lookup based on multi-hop communication remains a challenge for VANETs.

The single-tier P2P over VANET system integrates the P2P lookup mechanism and VANET routing protocols to perform information lookups in VANETs. With a P2P overlay built on top of the VANETs, the approach inherits the network disconnectivity problem and bandwidth limitations of VANETs. Moreover, the application-layer P2P overlay relies on VANET routing to transmit lookup and maintenance messages over VANETs. When the number of vehicles increases, messages for VANET routing, information lookup, and overlay maintenance are considerably increased in the VANETs. This architecture suffers a scalability problem.

When an application-layer P2P overlay is built through an infrastructure-based network, the lookup performance depends mainly on the adopted P2P approach, regardless of the vehicle density. However, the infrastructure-based wireless communication has a higher transmission delay than direct a hoc communication because of the communication through base stations and core networks. Therefore, lookups in the single-tier infrastructure-based P2P system achieve a high success rate but have long latencies.

In the proposed two-tier VANET/P2P system, lookups for short-distance information can be resolved quickly through the low-tier VANETs, and queries for long-distance information can take advantage of the high-tier P2P overlay to mitigate the network disconnectivity problem. The radio resource of the wireless infrastructure is also limited; therefore, adaptive schemes that perform lookups between the two networks (according to road networks, vehicular mobility, and network conditions) to minimize the lookup overhead over the high-tier P2P overlay need to be further studied. An adaptive lookup protocol for the two-tier VANET/P2P system is proposed and presented in the next chapter.

3.6.4 Peer-to-Peer Overlay Construction

P2P networking technology has been widely utilized to share resources in various systems such as file sharing systems. A P2P overlay can also be constructed among vehicles to provide sharing and retrieval of information in vehicular systems (e.g., traffic information systems). In particular, P2P traffic information systems differ from P2P file-sharing systems in many aspects, including highly dynamic participants, high data update and query rates, and highly correlated queries. These characteristics should be considered when designing P2P traffic information systems. In an unstructured P2P overlay such as a Gnutella-based system, the unstructured P2P overlay could accommodate the frequent changes of network topology. Vehicles collect traffic information, generate traffic reports, and locally maintain traffic reports without publishing reports to other vehicles. By contrast, more efforts are needed in a structured P2P overlay, such as a

Chord-based system, to maintain the overlay structure and publish traffic reports to the responsible vehicles.

The traffic conditions along a route to the destination are usually queried simultaneously. By adopting the geographic routing scheme that forwards lookups through an unstructured P2P overlay, the lookup forwarding path approximately follows the route toward the destination. Therefore, fewer lookups are required to obtain the required traffic information. By contrast, an individual lookup must be performed for each road segment in the structured P2P system. Another structured P2P approach, Content Addressable Network (CAN) [27], uses a two-dimensional coordinate space. The lookup routing path in the CAN space would come as close to the route in the road network as the geographic lookup routing in an unstructured P2P overlay. However, the CAN approach still requires considerable overlay maintenance overhead. The above characteristics cause the unstructured P2P approach to be more applicable than the structured P2P approach for the decentralized traffic information systems.

The two-tier system organizes superpeers in a P2P overlay as a hierarchical structure. As a result, the overall maintenance and lookup overheads are reduced because they grow as a function of the number of participants. The hierarchical design improves the scalability and performance of the P2P systems. However, load on superpeers may be high since they provide P2P lookup services to all vehicles. To reduce the load on superpeers and improve the performance of superpeer overlay, further improvements, such as a multi-level hierarchy and superpeer redundancy, are directions for future research.

Finally, Table I summarizes the comparisons of the four architectures for realizing information retrieval services in a vehicular environment.

Table I: Comparison of architectures for information retrieval services.

Characteristics	System architecture			
	a. Single-tier VANET	**b. Single-tier P2P over VANET**	**c. Single-tier infrastructure-based P2P**	**d. Two-tier VANET/P2P**
Network connectivity	Intervehicle	Intervehicle	Infrastructure-based	Intervehicle or infrastructure-based, or both
Information sharing	Broadcast via IVC	Broadcast via IVC; sharing in VANET-based P2P overlay	Sharing in infrastructure-based P2P overlay	Broadcast via IVC; sharing in infrastructure-based P2P overlay
Information lookup	Multi-hop broadcast in VANETs; lowest latency if success; success rate and latency increase with vehicle density	P2P lookup in VANET-based P2P overlay; performance worse than single-tier VANET	P2P lookup in infrastructure-based P2P overlay; high success rate and latency; performance depends on P2P networking approach	Multi-hop broadcast in VANETs with superpeer lookup in infrastructure-based P2P overlay; good balance between success rate and latency
P2P overlay construction	None	Overlay built on top of VANETs	Overlay in infrastructure network	Superpeer-based overlay in infrastructure network

P2P system overhead	None	Overhead to maintain P2P overlay	Overhead to maintain P2P overlay	Less overhead to maintain superpeer-based P2P overlay
Challenges	Network disconnectivity; broadcast storm	Network disconnectivity; VANET routing overhead	Limited bandwidth; long delay	Superpeer election; superpeer load; redundant lookups

3.7 Performance Evaluation

The performance of single-tier systems and the proposed two-tier VANET/P2P system is evaluated using a traffic simulator and network simulator. This section presents simulation results and discusses them.

3.7.1 Setup

We use the micro-scope road traffic generator, Simulation of Urban MObility (SUMO) [28], to generate vehicular mobility traces that are then fed into the network simulator, QualNet [29]. The road topology is a 5000 m × 5000 m grid road network, in which each road segment is 500 meters with two lanes in each direction. The maximum vehicle speed is set to 13.9 m/s (i.e., 50 km/h). The number of vehicles varies from 200 to 1000. Each vehicle is equipped with both intervehicle and infrastructure-based wireless communication interfaces. The vehicular network uses IEEE 802.11a with the lognormal shadowing, two-ray path loss, and Rayleigh fading. The radio range is set to 250 meters. We assume that the high-tier infrastructure-based wireless network is Mobile WiMAX or UMTS which can provide a reliable communication between vehicles.

In VANETs, vehicles periodically broadcast messages to exchange information with neighboring vehicles for information sharing in both single-tier and two-tier systems, and superpeer election in only two-tier system. We use a traffic information system as an example of the information retrieval service. Each vehicle broadcasts its current speed and location, and then generates the traffic report of its current road segment based on its observation and traffic messages obtained from other vehicles. In two-tier VANET/P2P system, vehicles perform superpeer election every one second to form clusters. The cluster size is set to one hop. The TTL value for lookups in the VANETs is infinite so that all connected vehicles in the VANETs could receive the lookup queries. These settings help us to understand the net improvement by introducing a high-tier P2P overlay.

Gnutella and Chord are used as the representative unstructured and structured P2P overlay networks, respectively. In the Gnutella-based P2P overlay, each node maintains 15 neighbors, and the geographic routing mechanism is applied to perform P2P lookups for information with a TTL value of seven. In the Chord-based P2P overlay, the identifier space is set to 2^{15}. Each node maintains a finger table with 15 entries. In both P2P overlays, the stabilization procedures are performed every ten seconds to maintain the overlays. We simulate each scenario for 200 seconds and ten runs.

In all scenarios, the P2P over VANET architecture performs more poorly than the single-tier VAENT architecture with a success rate below 20% and lookup latency over 100 ms. Results of the P2P over VANET architecture are excluded from the comparisons in the figures below. Therefore, we consider five different design strategies among the other three system architectures: the single-tier VANET approach (1T-VANET); the single-tier infrastructure-based P2P approach using Chord (1T-struct); the single-tier infrastructure-based P2P approach using Gnutella (1T-unstruct); the two-tier approach using Chord (2T-struct); and the two-tier approach using Gnutella (2T-unstruct). We evaluate their performance in terms of lookup success rate, lookup latency, VANET bandwidth usage, and P2P overlay bandwidth usage, defined as follows.

- Lookup success rate is defined as the ratio of the number of successful lookups to the total number of lookup requests generated by vehicles. A lookup is successful if a requesting vehicle can receive responses containing the required information.
- Lookup latency is the average latency for a successful lookup. It measures the elapsed time between the time that a lookup request is generated and the time that the corresponding response is received by the requesting vehicle.

- VANET bandwidth usage measures VANET bandwidth used for lookups performed in VANETs.
- P2P overlay bandwidth usage measures infrastructure network bandwidth used for lookups and overlay maintenance performed in a P2P overly.

3.7.2 Results

Figure 3.7 shows the lookup success rate under different number of vehicles. This figure shows that the single-tier VANET system has the lowest lookup success rate, especially in low density scenarios. This is because some lookups cannot reach the vehicles with the requested information in the disconnected VANETs. This problem can be alleviated by increasing the number of vehicles or introducing an infrastructure-based P2P overlay.

Both single-tier structured P2P and unstructured P2P systems significantly improve the lookup success rate because an infrastructure network does not have the disconnectivity problem and vehicles can communicate with any other vehicles through infrastructure-based communication. For the single-tier P2P systems, lookup success rate is independent of vehicle densities, and incorrect neighbor or finger information on P2P nodes is mainly caused by churn (i.e., node join/leave), resulting in lookup failures. Simulation results show that the churn has an impact on the structured P2P approach. Although the churn problem can be alleviated by frequently performing stabilization procedures to maintain a stable structured P2P overlay, these frequent stabilization procedures introduce extra maintenance overhead. On the other hand, the unstructured P2P approach adapts to churn much more effectively than the structured P2P approach in a dynamic vehicular network, as the single-tier unstructured P2P system achieves nearly a 95% lookup success rate.

The two-tier structured P2P system outperforms the single-tier VANET system because it also conducts lookups over the P2P overlay and can mitigate the disconnectivity problem of the VANETs. The two-tier structured P2P system has a success rate slightly lower than the single-tier structured P2P system because the periodical superpeer election may cause node join/leave in the P2P overlay and the structured P2P approach is vulnerable to churn. By contrast, the two-tier unstructured P2P system is resilient to churn and achieves nearly a 95% lookup success rate, further accelerating the lookup and reducing maintenance costs compared to a single-tier unstructured P2P system, as will be shown later.

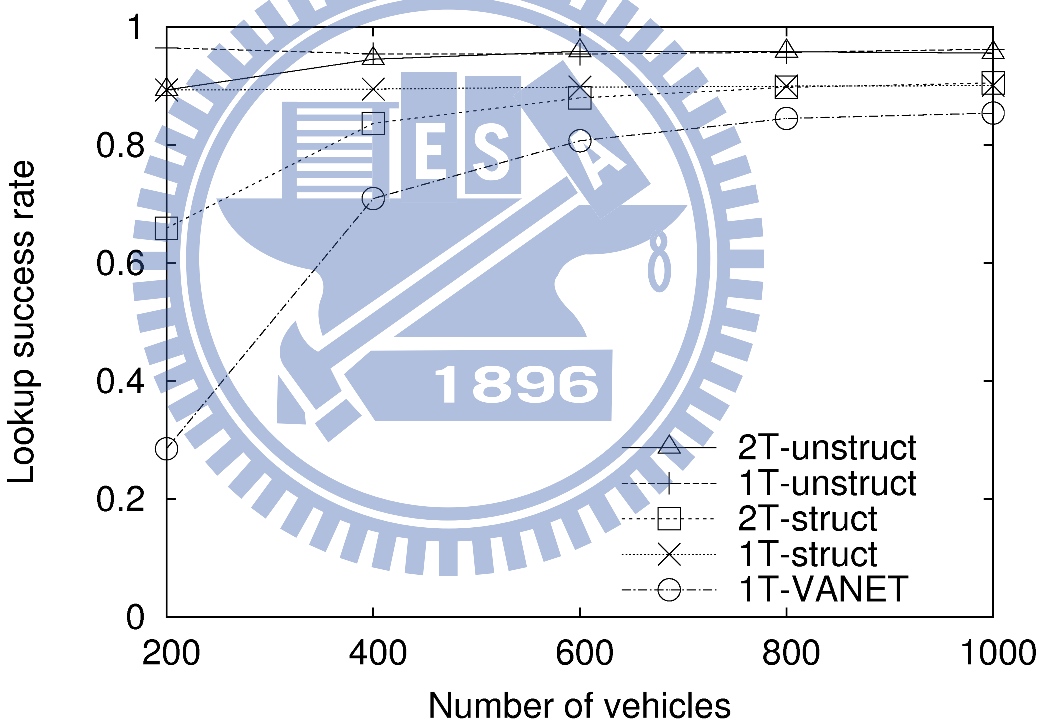


Figure 3.7: Lookup success rate for different approaches.

Figure 3.8 shows the average latencies of successful lookups. The single-tier VANET system achieves the shortest lookup latencies among all systems because of low-latency IVC. The lookup latency and success rate of the VANET system both increase with the number of vehicles because more vehicles are in a connected VANET and a query must be propagated for more hops to reach the vehicle with the desired information.

The single-tier structured P2P system has the longest latency because the lookup hop count in the Chord-based overlay is proportional to the logarithm of the Chord network size. A successful lookup requires approximately six to eight hops in the Chord-based overlay as one-hop latency in infrastructure networks could be 600 ms long. Compared to the single-tier structured P2P system, the single-tier unstructured P2P system improves lookup latency by 50%–60%, because the geographic lookup in the Gnutella-based overlay can reach every vehicle within three hops.

By combining VANETs and an infrastructure-based P2P overlay, lookups can be simultaneously distributed over the VANETs and P2P overlay to improve the latency further. The two-tier systems outperform the single-tier P2P systems because low latencies can be achieved through lookups performed in VANETs. In summary, the two-tier systems achieve higher lookup success rate than the single-tier VANET system, and have lower lookup latency than the single-tier P2P systems. Moreover, the unstructured P2P approaches are more suitable for single-tier P2P and two-tier VANET/P2P systems because they achieve higher lookup success rates and introduce less lookup latencies than the structured P2P approaches.

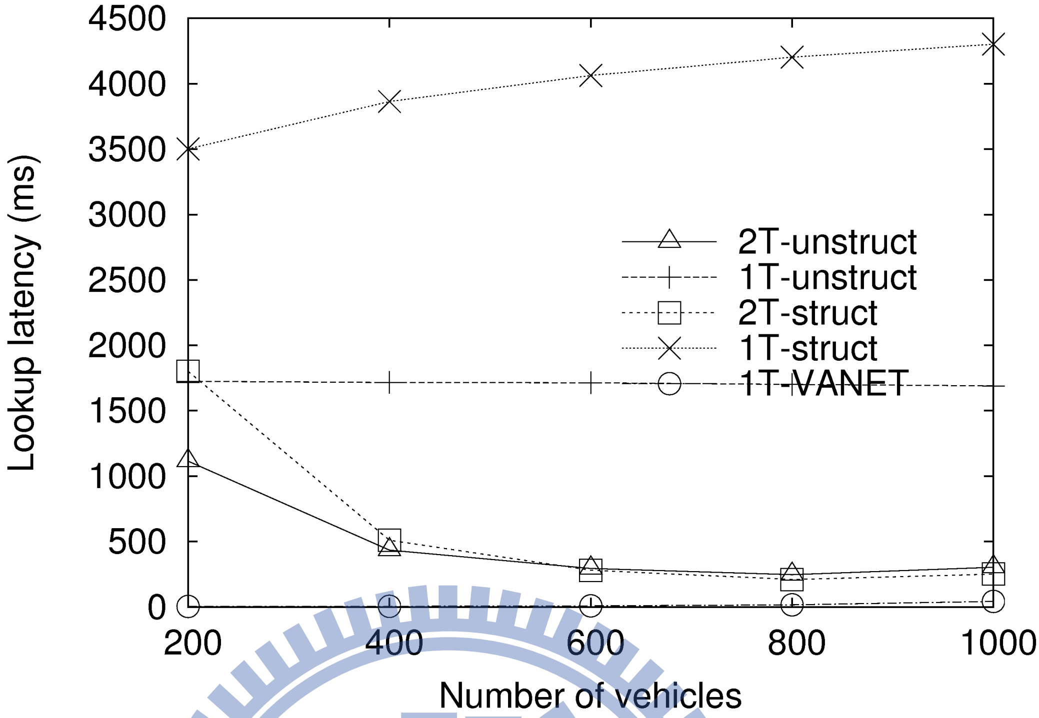


Figure 3.8: Lookup latency for different approaches.

Figure 3.9 and Figure 3.10 shows the average bandwidth usage of VANETs (i.e., IVC lookup) and P2P overlay (i.e., P2P lookup and overlay maintenance in infrastructure network) per vehicle, respectively. The single-tier P2P systems do not consume VANET bandwidth as they only use infrastructure network. On the other hand, the single-tier VANET system utilizes only IVC, and thus does not consume the bandwidth of infrastructure network. As shown in Figure 3.9, the bandwidth usage of VANETs for the single-tier VANET and two-tier VANET/P2P systems significantly increases with the number of vehicles. The number of lookup messages increases in VANETs because more vehicles are involved in the lookups.

Figure 3.10 indicates the bandwidth usage of infrastructure network. The single-tier P2P and two-tier VANET/P2P systems occupy a certain infrastructure network bandwidth in performing the lookup and maintenance of the P2P overlay. The two-tier systems reduce the bandwidth usage of infrastructure network by 40%–60% compared with the single-tier P2P systems because only some vehicles (i.e., superpeers) participate in the P2P overlay and perform the P2P operations. Although the unstructured P2P approach requires more bandwidth for P2P lookups, it still outperforms the structured P2P approach because of less P2P maintenance overhead.

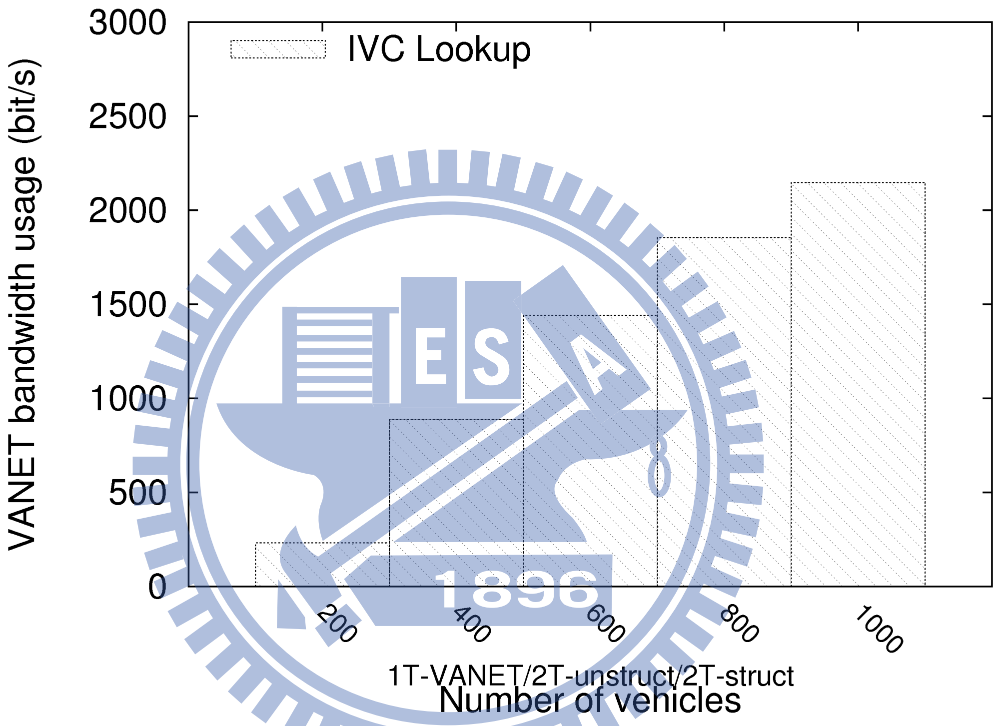


Figure 3.9: VANET bandwidth usage for different approaches.

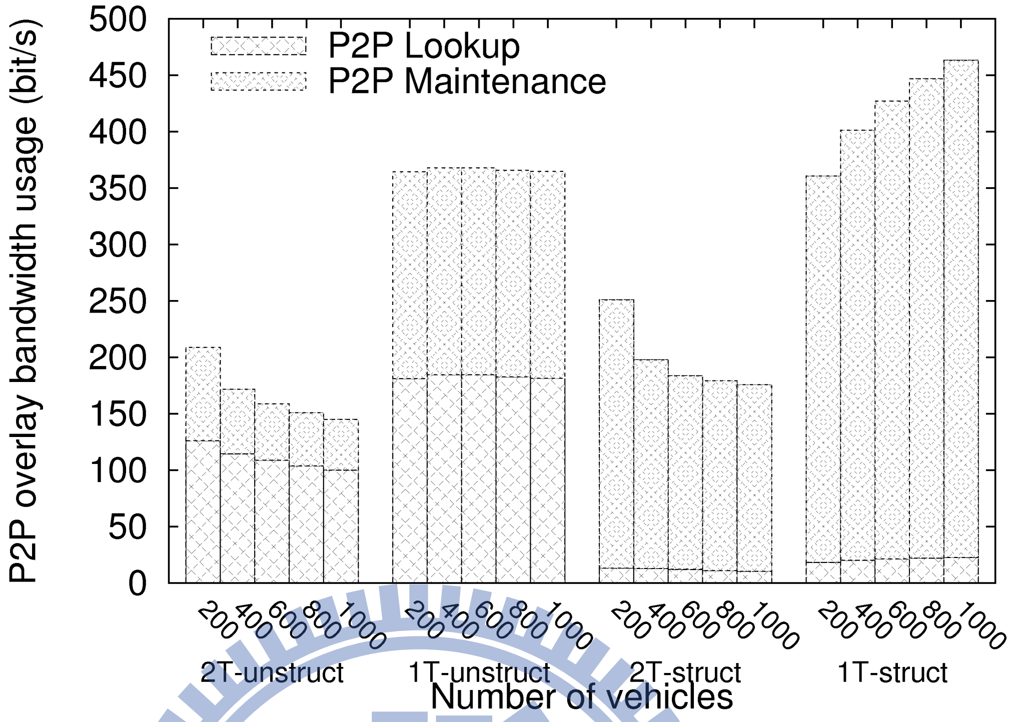


Figure 3.10: P2P overlay bandwidth usage for different approaches.

In the previous simulations, the superpeer election is performed every one second. The message overhead of maintaining the cluster structure decreases when the frequency of superpeer election decreases. When the election is performed every two seconds, the clustering message overhead in VANETs can be reduced while the lookup success rate is almost unchanged. However, if the superpeer election is performed much less frequently (e.g., longer than eight seconds), the lookup success rate decreases. This is because normal peers may move out of range of their superpeers and cannot communicate with their superpeers if the superpeer election is conducted infrequently. Although a vehicle can forward a lookup message to its VANET neighbors, the opportunity to send the lookup messages to the destination via P2P overlay may lose. On the other hand, the lookup latency is reduced slightly with a longer election period because less lookups are resolved through P2P overlay which introduces more lookup latency than VANETs. Figure 3.11 and Figure 3.12 show the simulation results under different superpeer election frequencies, where T_{clus} indicates the clustering period (i.e., superpeer election period).

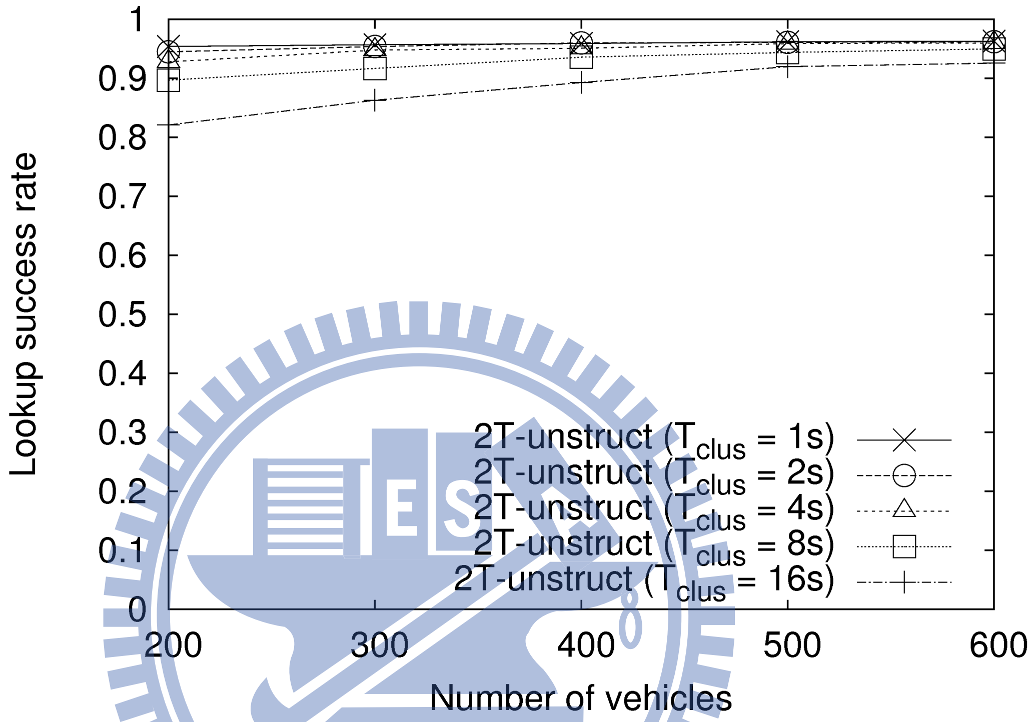


Figure 3.11: Lookup success rate under different clustering periods.

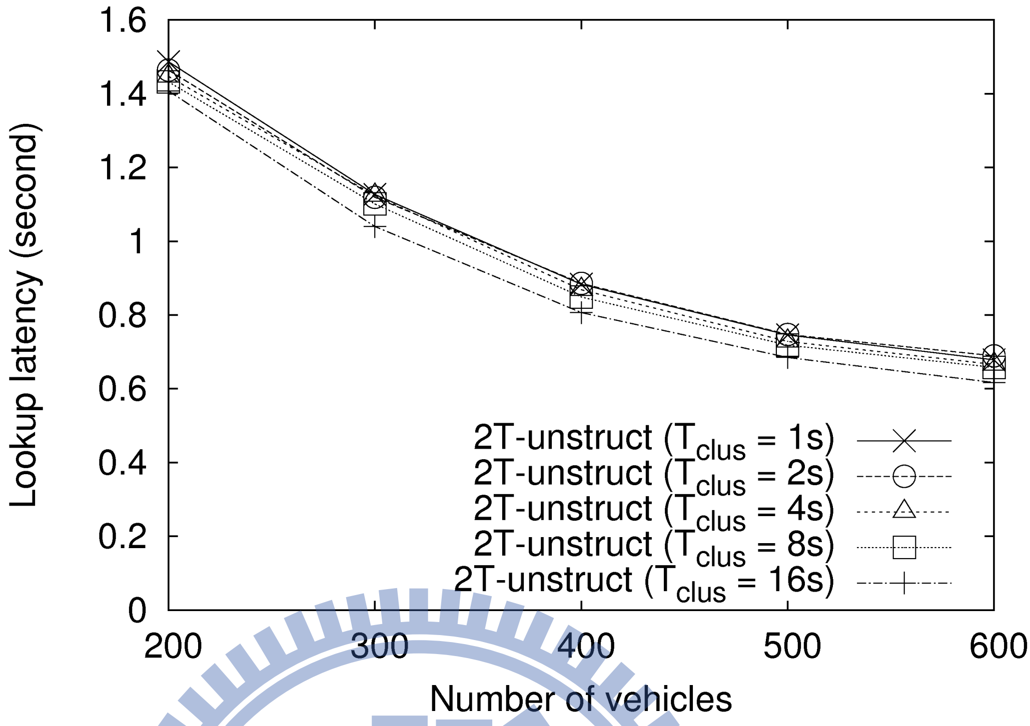


Figure 3.12: Lookup latency under different clustering periods.

The superpeer election is performed periodically to form clusters of vehicles within a range in VANETs. With one-hop clusters, vehicles are elected as superpeers if they have the largest IDs among one-hop neighbors. The one-hop clusters ensure that a normal peer can communicate directly with its superpeer to request a lookup in the P2P overlay. However, because vehicles move and the VANET topology changes, normal peers may not be able to communicate with their superpeers through neighboring nodes especially for a larger cluster size, i.e., a larger number of hops for a cluster. The lookup success rate decreases when the number of hops for a cluster increases. Figure 3.13 and Figure 3.14 show the simulation results under different numbers of clustering hops (i.e., cluster size).

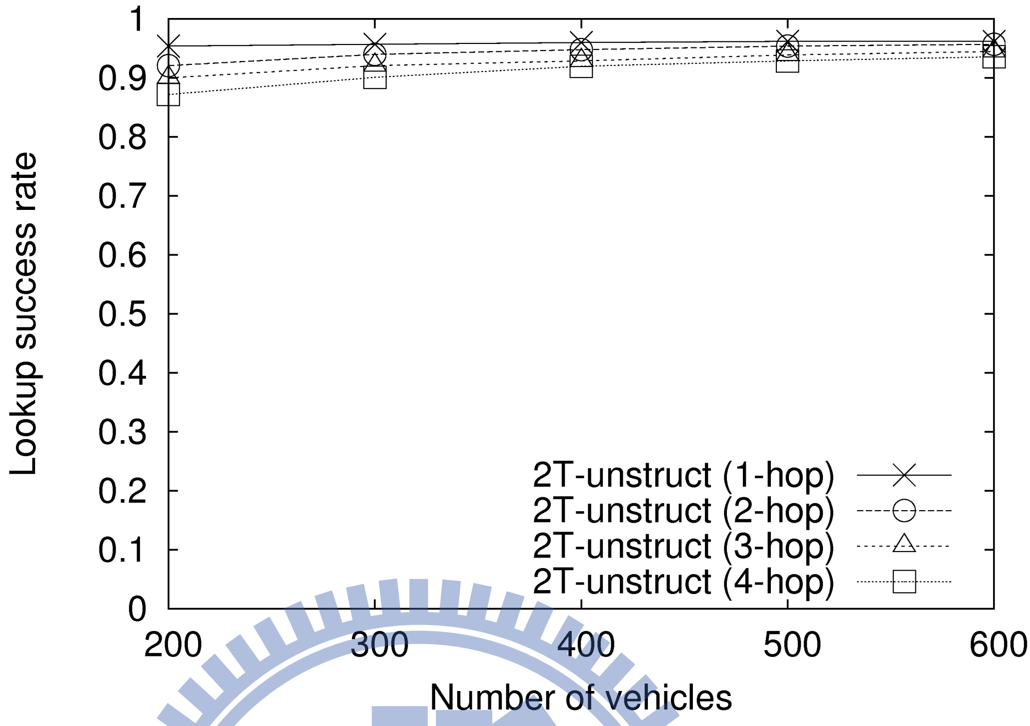


Figure 3.13: Lookup success rate under different clustering hops.

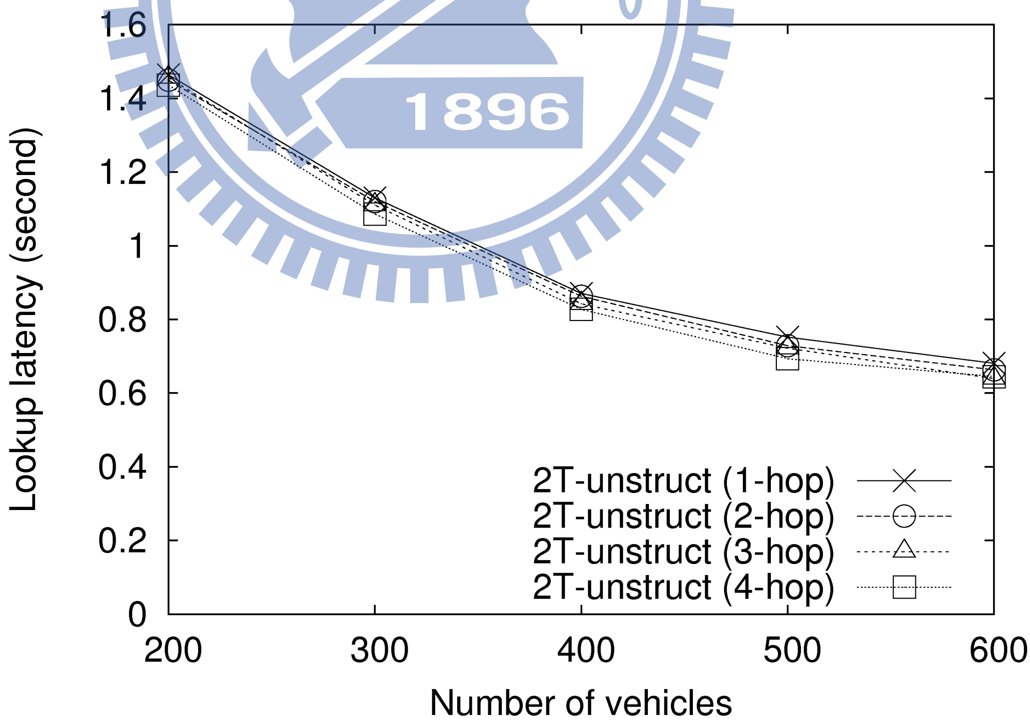


Figure 3.14: Lookup latency under different clustering hops.

3.8 Summary

In this chapter, we propose a two-tier VANET/P2P system to support information retrieval services for the vehicular environment in an effective and efficient manner. When the vehicle density is low, information can be retrieved through lookups performed in the infrastructure-based P2P overlay. Thus, the two-tier system can alleviate the disconnectivity problem of VANETs to maintain a high lookup success rate. In addition, the two-tier system minimizes the bandwidth usage in the infrastructure network. On the other hand, given a sufficient vehicle density, lookups may be resolved rapidly through VANETs, and a short lookup latency can be achieved. Therefore, the proposed two-tier VANET/P2P system can improve success rate compared with single-tier VANET-based systems while reducing lookup latency and bandwidth usage compared with single-tier infrastructure-based P2P systems. Simulation results also reveal that a two-tier unstructured P2P system can tolerate network dynamics and achieve higher performance than a two-tier structured P2P system.

CHAPTER 4 ADAPTIVE TWO-TIER LOOKUP PROTOCOL

In the two-tier VANET/P2P information retrieval system, lookups for information are performed in the low-tier VANETs and high-tier P2P overlay simultaneously. Information can be retrieved with low latency through the VANETs if VANETs are connected, and through the P2P overlay if lookups in the VANETs fail. Therefore, the two-tier system can achieve both low latency and high success rate. However, the two-tier system may introduce high lookup overheads due to lookups performed in both networks. It may cause redundant P2P lookups when lookups can be resolved in connected VANETs. On the other hand, the two-tier system does not consider that an intermediate node in the P2P forwarding path may be able to route the lookup to the destination rapidly through the VANETs. This results in not only losing the chance of performing lookups through the VANETs with lower latency, but also wasting infrastructure network resources in the P2P overlay.

Figure 4.1 shows an example of conventional information retrieval in the two-tier VANET/P2P system. In step 1, a vehicle requests information available in location *D* by broadcasting a lookup in VANETs. The lookup is forwarded toward destination *D* in VANETs, but it cannot reach the destination due to VANET disconnectivity, as in step 2. On the other hand, the lookup can be forwarded to superpeer located in the destination through the P2P overlay, as in step 3 and step 4. However, the lookup can be rapidly routed to the destination by superpeer n_d through VANETs if superpeer n_d redirects the lookup to VANETs when receiving the lookup in step 3. Thus, the lookup forwarded by n_d in the P2P overlay is unnecessary since the lookup through VANETs can be resolved with a lower latency.

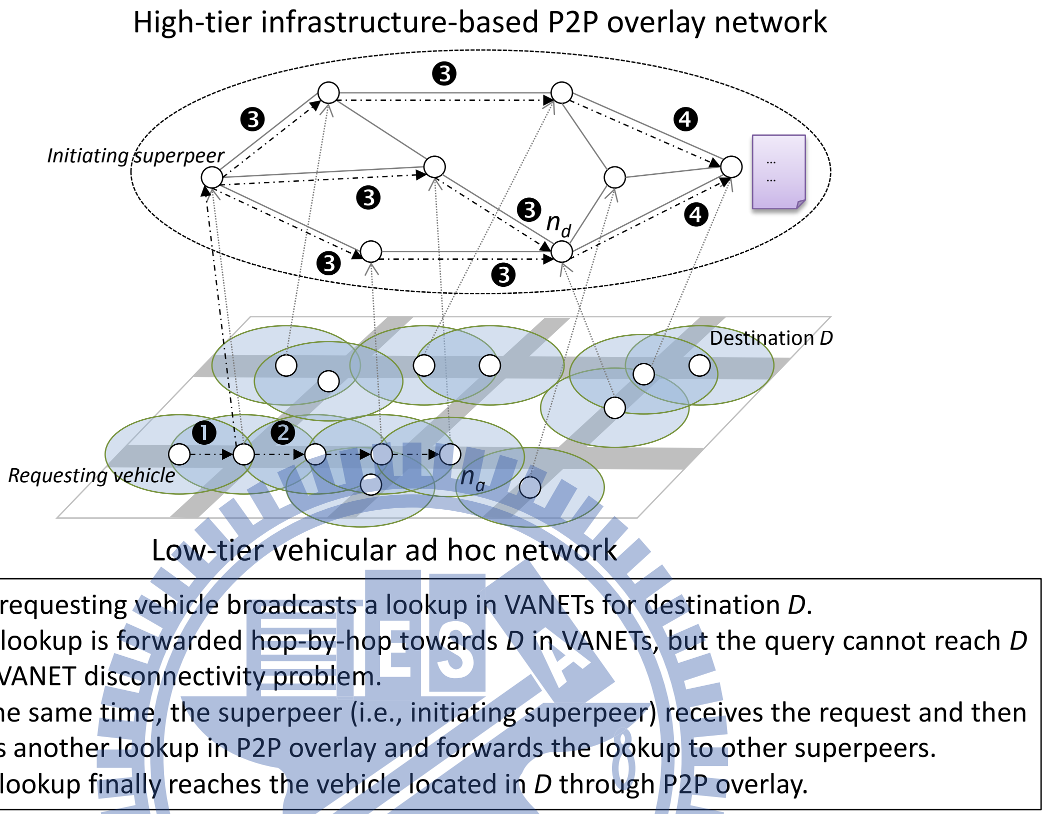


Figure 4.1: Example of conventional information retrieval in the two-tier VANET/P2P system.

To improve the lookup performance, we propose an adaptive lookup protocol for the two-tier VANET/P2P information retrieval system. The adaptive lookup protocol leverages the reachability of road segments to determine whether information lookups should be performed in low-tier and/or high-tier networks. The reachability indicates whether a road segment can be reached through the low-tier VANETs. We benefit from the reachability information to improve the lookup routing. This chapter presents the adaptive two-tier lookup protocol.

4.1 Reachability Model

Each vehicle locally maintains the reachability of road segments in a reachability database. For a vehicle, a road segment is considered reachable if the vehicle receives messages that have recently traversed the road segment through VANETs. The reachability of road segments for a vehicle is based on two sources of information: (1) The first-hand reachability information that a vehicle can directly observe. For example, a vehicle may receive or forward lookup messages from other vehicles that have traversed several road segments. (2) The second-hand reachability information, for which one vehicle may share its first-hand reachability information with its neighbors. Because vehicles are moving, the reachability information is not always correct. Consequently, reachability information is maintained in a soft-state manner and the information decays over time.

The reachability information is continuously collected and disseminated using various messages transmitted among vehicles in VANETs, such as lookup messages and node information messages. For lookup messages, a lookup query and response consist of the location of the requesting vehicle and responding vehicle. When a vehicle receives a lookup message originating from vehicle n, it updates the reachability regarding the road segment where vehicle n is located. The road segment is reachable because a message from the location can be received. In addition to the road segment where a message is generated, the lookup message may traverse several road segments. The lookup message may contain a list of the traversed road segments, which can be recognized as reachable by the vehicles receiving the message. Piggybacking information of traversed road segments in a transmitted message has been used as an efficient mechanism to collect information along the traversed path [30]. Through these mechanisms, a vehicle can gather first-hand reachability information.

To efficiently maintain and exchange reachability information, a Bloom filter data structure is used [10]. A Bloom filter is a space-efficient data structure that represents a set of elements in order to support membership queries in the set [31]. It consists of a bit array of m bits; all bits are initialized at 0. There are k independent uniform hash functions h_1, h_2, …, h_k, each of which maps an element to one bit in the array. An element x is represented by k bits indexed by $h_i(x)$ where $i = 1, 2, …, k$ in the array. To add an element to the set, the k bits that the element is mapped to are set to 1. A query for element x (i.e., whether x is in the set) checks whether all $h_i(x)$ are set for $i = 1, 2, …, k$. The element is likely to be in the set if the k bits are set. Otherwise, the element does not belong to the set. The use of the Bloom filter in efficient information exchanges has been considered in various applications, such as service discovery [32], cache lookup [33], and query routing in P2P networks [34].

Each vehicle locally maintains a Bloom Filter BF to store the first-hand reachability information of road segments. When receiving a lookup message consisting of road segment s, a vehicle updates the reachability of segment s in its BF by setting the bits $h_i(s)$ to 1 for $i = 1, 2, …, k$. As described in Section 3.2, vehicles periodically broadcast their node information through IVC for superpeer election in the two-tier system. The reachability information locally maintained in a vehicle can be included in the periodic messages to be disseminated to other vehicles. Thus, when a vehicle broadcasts a node information message, it also advertises its reachability information with the message. After receiving the message, other vehicles extract the Bloom filter in the message and aggregate it with their own Bloom filters. Thus, a vehicle can gather second-hand reachability information from its neighbors. Any two Bloom filters can be merged into one by simply performing bitwise OR operations on them. The reachability information can be disseminated over multiple hops through the vehicles that are connected in the VANETs (i.e., they are reachable to each other). Figure 4.2 shows the algorithms for maintaining reachability information using Bloom filters.

AddReachability(*BF*, *s*):

// execute when a vehicle receives a lookup from road segment *s*, add road segment *s* to *BF* with *k* hash functions.

for all $i \in \{1, 2, ..., k\}$ **do**

  $BF[h_i(s)] \leftarrow 1$

end for

AggregateReachability(BF, BF_r):

// execute when a vehicle receives a Bloom filter from its neighbors, aggregate local *BF* with the received BF_r.

$BF \leftarrow BF \cup BF_r$

DecayReachability(*BF*):

// execute periodically to decay *m*-bit *BF*.

for all $i \in \{1, 2, ..., m\}$ **do**

  if ($BF[i]$ == 1) **then**

    with probability *p*, $BF[i] \leftarrow 0$

  end if

end for

Figure 4.2: Algorithms for maintaining reachability information using *m*-bit Bloom filters.

As vehicles are moving, the reachability of road segments continuously changes because of high vehicle mobility and rapid VANET topology changes. The reachability information received at time t_1 may be inaccurate at a later time t_2. To accommodate the network dynamics, the reachability information is maintained as a soft state. A decay mechanism [34] is adopted to reduce confidence in the reachability information. Each vehicle decays its *BF* every T_{decay}. For every T_{decay}, each bit that is set to 1 in *BF* is reset to 0 with probability *p*.

In the Bloom filter, the number of bits set to 1 for a road segment divided by total bits *k* is interpreted as the reachability probability of the given road segment. Let $\theta(s) = |\{i \mid BF[h_i(s)] = 1, i = 1, 2, ..., k\}|$ be the number of 1s in *BF* corresponding to road segment *s*. A larger $\theta(s)$ indicates that the reachability information may have been updated recently, and road segment *s* can be reached with a greater probability. Therefore, we define $\gamma(s) = \theta(s) / k$ as the reachability probability of road segment *s*. The reachability probability measures the probability that the information continues to be accurate and a lookup message can be routed to the destination through the VANETs.

Finally, the reachability collection and dissemination described above are mainly passive schemes. The reachability of road segments can also be discovered using other active mechanisms. For example, a reachability discovery message can be generated by a randomly selected vehicle to discover the reachability in particular locations. The message acts as a one-way lookup query (i.e., no lookup response), and discovers reachability when being forwarded toward a destination. How to select vehicles and destinations to initiate the reachability discovery process is an issue that may depend on vehicle location and current reachability. Active discovery may cause overheads in VANETs.

4.2 Lookup Initiation

In the two-tier VANET/P2P information retrieval system, a normal peer or superpeer can generate a lookup request for information available in a location. When a normal peer generates a lookup request, the request is broadcasted through IVC, and can be received by other vehicles, including the superpeer of the normal peer. The superpeer of the requesting normal peer is responsible for determining whether it should perform the lookup though the VANETs and/or P2P overlay. On the other hand, when a superpeer generates a lookup request, it also determines whether the lookups in the VANETs and P2P overlay are necessary. The superpeer, which determines the lookup procedure in these two instances, is called the initiating superpeer.

Each vehicle locally maintains a Bloom filter *BF* to store the reachability information of road segments. For a lookup for information located in destination *D*, the initiating superpeer determines whether to perform lookups through the VANETs and/or P2P overlay according to the reachability probability of *D* in its *BF*. The two reachability thresholds are defined as γ_l and γ_h to determine the lookup routing. If the reachability probability of *D*, that is $\gamma(D)$, is greater than the high threshold γ_h, that is $\gamma(D) > \gamma_h$, there is a significant chance that the lookup can be routed to the destination through the VANETs. In this situation, the lookup is forwarded to the VANETs to reduce the lookup messages in the P2P overlay. If the reachability probability of *D* is less than the low threshold γ_l, that is $\gamma(D) < \gamma_l$, it is occasionally possible that the lookup can be routed to the destination through the VANETs. In this situation, the lookup to the P2P overlay should only be forwarded to avoid a lookup failure, and to reduce the lookup messages in the VANETs.

However, when the reachability probability of *D* is between the high threshold and low threshold, that is $\gamma_l \leq \gamma(D) \leq \gamma_h$, the decision to forward the lookup to either the P2P overlay or VANETs is uncertain. This is mainly because the accuracy of the reachability information maintained in the Bloom filters is not guaranteed. The inaccuracy of reachability information can be caused by four reasons. First, the reachability information may be out-of-date because of the dynamics of a vehicular network. The second reason is the false positives in the Bloom filter. A false positive occurs when the bit positions corresponding to a road segment are set by other road segments, which are also mapped to the same bits. The hash function design and the size of the Bloom filter influence the possibility of false positives in the Bloom filter. The third reason is the false negatives in the Bloom filter. For every decay period, i.e., T_{decay}, we decay all bits in the Bloom filter instead of the correspondent bits of road segments one segment by one segment. Therefore, hash collisions (i.e., the bit positions corresponding to a road segment are also shared by other road segments) will not introduce additional decays on the bits mapped by several road segments. However, false negatives may occur because the bits in the Bloom filter may reset to 0 due to a number of decays over time. The decay mechanism is adopted to reduce the confidence of the reachability information. As vehicles are moving, the reachability of road segments continuously changes. Therefore, to accommodate the VANET dynamics, the reachability information is maintained in a soft-state manner. The false negatives make the adaptive lookup protocol to be more conservative and to forward lookup queries through P2P overlay instead of possible connected VANETs. As a result, lookup latency may not be reduced significantly. Fourth, even when the reachability information is correct, the lookup over the VANETs may not succeed because of network congestion. If the reachability probability of D is between the high and low thresholds but the lookup message is only forwarded to the VANETs, the lookup messages may not successfully reach the destination and may introduce a lookup failure. However, if the lookup is only forwarded to the P2P overlay, an opportunity to reduce latency is lost if the message can be routed to the destination through the VANETs. Therefore, when the reachability probability of D is between the high and low thresholds, lookups in both the P2P overlay and VANETs should be performed to gain latency improvement without introducing lookup failures. This design may introduce redundant P2P and/or VANET messages, which are used to compensate for the dynamics in a vehicular network, communication loses in the VANETs, and false positives in the Bloom filter. Therefore, if the reachability probability is greater than the low threshold, that is $\gamma(D) \geq \gamma_l$, the lookup is forwarded to the VANETs. If the reachability probability is less than the high threshold, that is $\gamma(D) \leq \gamma_h$, the lookup is forwarded to the P2P overlay. In situations where a vehicular network is stable, there is no congestion or packet loss in the VANETs, and false positives in the Bloom filter rarely occur, the low and high thresholds may be set to the same value. In this situation, lookup latency and lookup overheads can be minimized while a high lookup success rate can be achieved. Moreover, if the high threshold is set to 1 and the low threshold is set to 0, the proposed lookup protocol reverts to the lookup scheme which is very similar to the conventional two-tier lookup protocol. In the proposed protocol, $0 \leq \gamma_l < \gamma_h \leq 1$ is suggested. The low and high thresholds are design parameters that should be adjusted according to situations in a real environment. A discussion on the selection of parameters in the simulation section is presented. Protocol 1 in Figure 4.3 shows the pseudo-code to initiate a lookup.

Protocol 1. Lookup initiation

Notation:

D: Destination road segment

BF: Local Bloom filter

if the current vehicle serves as a normal peer **then**

    Broadcast lookup message in VANETs and request its superpeer for P2P lookup

else // the current vehicle serves as a superpeer and generates a lookup or receives a request from its normal peer

    $\gamma \leftarrow \text{GetReachability}(BF, D)$

    if $(\gamma \geq \gamma_l)$ **then**

        Broadcast lookup message in VANETs

    end if

    if $(\gamma \leq \gamma_h)$ **then**

        for each P2P neighbor n_i **do**

            Forward lookup to n_i in P2P overlay

        end for

    end if

end if

GetReachability(*BF*, *s*):

// execute to get reachability probability of road segment *s* from *BF*.

$\theta \leftarrow 0$

for all $i \in \{1, 2, ..., k\}$ **do**

    $\theta \leftarrow \theta + BF[h_i(s)]$

end for

Return θ / k

Figure 4.3: Lookup initiation for the normal peer and initiating superpeer.

4.3 Lookup Forwarding

When receiving lookup messages from other superpeers in the P2P overlay, a superpeer may have to continue to forward the lookup messages if it does not have the required information. If a lookup forward is necessary, it determines whether a lookup should be continuously forwarded in the P2P overlay or be adaptively redirected to the VANETs according to the reachability information. If $\gamma(D) \leq \gamma_h$, then it continues to forward the lookup to the neighbor, which is closest to *D*, as the conventional lookup forwarding in the P2P overlay. If $\gamma(D) \geq \gamma_l$, then it redirects the lookup to the VANETs by broadcasting the lookup through IVC.

The lookup forwarding in the VANETs also exploits reachability information. When a vehicle receives a lookup message in the VANETs, it may reply with the requested information if it has it. Otherwise, it forwards the lookup in the VANETs using geographic forwarding scheme if $\gamma(D) \geq \gamma_l$. Protocol 2 in Figure 4.4 shows the pseudo-code to forward a lookup.

Protocol 2. Lookup forwarding in the P2P overlay and VANETs

Notation:

D: Destination road segment

BF: Local Bloom filter

Dist(n_i): Distance from vehicle n_i to destination *D*

REQ: Requested information

DB: Local information database

n_S: Sending vehicle from which a lookup message is received

// execute when a vehicle receives a lookup message from vehicle n_s in the P2P overlay.

if $REQ \in DB$ **then**

  Reply information back to the initiating superpeer

  Return

end if

$\gamma \leftarrow \text{GetReachability}(BF, D)$

if $(\gamma \geq \gamma_l)$ **then**

  Broadcast lookup message in VANETs

end if

if $(\gamma \leq \gamma_h)$ **then**

  For all P2P neighbors $n_i \neq n_s$, pick n_j with the smallest $Dist(n_j)$

  Forward lookup to n_j in the P2P overlay

end if

// execute when a vehicle receives a lookup message from vehicle n_s in the VANETs.

if $REQ \in DB$ **then**

  Reply information back to the requesting vehicle

  Return

end if

$\gamma \leftarrow \text{GetReachability}(BF, D)$

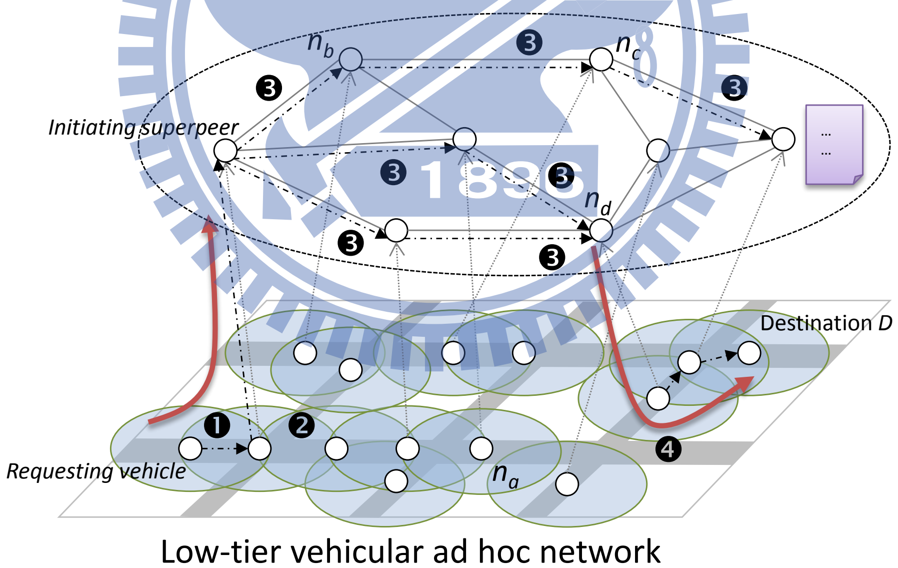
if $(\gamma \geq \gamma_l)$ **then**

  Use geographic forwarding scheme to forward lookup message toward D in the VANETs

end if

Figure 4.4: Lookup forwarding in the P2P overlay and VANETs.

Figure 4.5 shows an example of the adaptive lookup protocol applied to the scenario shown in Figure 4.1 After receiving a request, the initiating superpeer decides not to perform a lookup in the VANETs according to its reachability probability of the destination (i.e., $\gamma(D) < \gamma_l$). It initiates a lookup in the P2P overlay. The lookup performed in the P2P overlay can reach the destination through superpeers n_b, n_c, and n_d. Moreover, when superpeer n_d receives the lookup in the P2P overlay, it redirects the lookup to the VANETs because the reachability probability of D is greater than γ_h. Thus, the lookup can be forwarded to the destination through the VANETs, resulting in a rapid lookup process.



❶ The requesting vehicle broadcasts a lookup in VANETs for destination *D.*
❷ The initiating superpeer decides not to perform VANET lookup according to the reachability information.
❸ The initiating superpeer performs lookup in the P2P overlay.
❹ The P2P lookup is redirected to the VANETs by superpeer n_d with a high reachability probability of *D* and finally arrives *D.*

Figure 4.5: Example of the adaptive lookup protocol in the two-tier VANET/P2P system.

In this chapter, we use a two-tier VANET/P2P system based on the unstructured P2P overlay (i.e., Gnutella) to present the proposed adaptive lookup protocol. The proposed lookup protocol is independent of the P2P lookup mechanism (i.e., the P2P overlay) because it routes lookups between VANETs and the P2P overlay. Thus, the proposed protocol can be applied to any two-tier VANET/P2P system with a structured or unstructured P2P overlay. Moreover, single-tier infrastructure-based P2P systems (e.g., PeerTIS [3] as described in Section 2.3) can also benefit from the proposed protocol if they integrate VANET communications. If these systems add intervehicle communication interfaces to establish VANETs and use both P2P overlay and VANETs simultaneously, they then become two-tier P2P systems. According to the results shown in Section 3.7, two-tier structured P2P systems can reduce the lookup latency and overhead of a P2P overlay more than single-tier structured P2P systems. However, because vehicles are moving, a structured P2P overlay becomes unstable because of frequent updates to the logical locations of vehicles in the structured P2P overlay. Conversely, two-tier unstructured P2P systems can tolerate these network dynamics and achieve much higher performance than two-tier structured P2P systems. Therefore, we use a two-tier unstructured P2P system based on Gnutella to illustrate the proposed adaptive lookup protocol.

4.4 Performance Evaluation

This section presents the simulation results to evaluate the performance of the proposed adaptive lookup protocol in the two-tier VANET/P2P system using a traffic simulator and network simulator.

4.4.1 Setup

The performance of the adaptive lookup protocol in the two-tier VANET/P2P system is evaluated using a traffic simulator and network simulator. The open-source and micro-scope traffic generator is used, namely the Simulation of Urban MObility (SUMO) [28], to generate vehicle mobility traces that are then imported into the network simulator. This simulation uses a 5000 m × 3500 m real road map of Chicago, United States, obtained from OpenStreetMap [35]. The number of vehicles varies from 200 to 500. The maximum vehicle speed is set to 13.9 m/s (i.e., 50 km/h).

The two-tier VANET/P2P information retrieval system is implemented in the QualNet network simulator [29]. Each node in QualNet represents one vehicle and travels according to the mobility traces. The low-tier vehicular network is simulated by IEEE 802.11a with a two-ray path loss, Rayleigh fading, and lognormal shadowing. The radio range is 350 m. We assume that the high-tier infrastructure-based wireless network is Mobile WiMAX or UMTS which can provide a reliable communication means between vehicles. All the vehicles are equipped with both intervehicle and infrastructure-based wireless communication interfaces. The simulation parameters are summarized in Table II.

Table II: Simulation parameters.

Parameter	**Value**
Channel frequency	5 GHz
Propagation model	Two-ray
Fading model	Rayleigh
Shadowing model	Lognormal
Propagation distance	350 m

Antenna model	Omnidirectional
Transmission power	20 dBm
PHY model	802.11a
MAC model	802.11 DCF

In the VANETs, vehicles periodically broadcast messages to exchange information with neighboring vehicles for superpeer election and information sharing. If the superpeer election is performed less frequently (e.g., longer than eight seconds), a lookup request issued by a normal peer may not be received by its superpeer because the normal peer has moved out of range of its superpeer. In addition, normal peers may not be able to communicate with their superpeers through neighboring nodes especially for a larger cluster size, i.e., a larger number of hops for a cluster. The lookup success rate decreases when the number of hops for a cluster increases. In the simulation, the superpeer election is performed every 1 s to form one-hop clusters. Through infrastructure-based wireless communication, superpeers construct the high-tier P2P overlay based on the unstructured Gnutella model. In the Gnutella overlay, each node maintains eight neighbors, and the neighbor connections are maintained every 10 s.

We use a traffic information system as an example to demonstrate the efficiency of the information retrieval service. Vehicles can share, collect, and query traffic information in the system. Each vehicle continuously broadcasts its current speed and collects speed information from neighboring vehicles. Based on the collected speed information of a road segment, a vehicle derives the average speed as traffic condition for the road segment. Each vehicle generates a lookup request for the traffic information of a randomly chosen road segment every 10 s. Vehicles located on the destination road segment reply with the estimated average speed when receiving the lookup query. The lookups in VANETs are propagated in a multi-hop manner and the TTL value is set to 20. On the other hand, the TTL value for lookups in the P2P overlay is set to seven. Each scenario is run for 200 s.

The Bloom filter has 2000 bits and the number of hash functions is five. The size of the Bloom filter and the hash functions are carefully chosen to minimize false positive errors in the Bloom filter. In VANETs, however, network dynamics have a much more serious influence on the accuracy of reachability information than the size of the Bloom filter. Therefore, we use a sufficiently large Bloom filter and consider other design factors.

We evaluate the performance of the two-tier system using the conventional lookup mechanism (2T-CON) and the proposed adaptive lookup mechanism (2T-ADP) in terms of lookup success rate, lookup latency, VANET lookup overhead, and P2P lookup overhead, defined as follows.

- Lookup success rate is defined as the ratio of the number of successful lookups to the total number of lookup requests generated by vehicles. A lookup is successful if a requesting vehicle can receive responses containing the required information.
- Lookup latency is the average latency for a successful lookup. It measures the elapsed time between the time that a lookup request is generated and the time that the corresponding response is received by the requesting vehicle.
- VANET lookup overhead measures the average number of lookup messages transmitted in the low-tier VANETs per second.
- P2P lookup overhead measures the average number of lookup messages transmitted among the superpeers in the high-tier P2P overlay per second.

Because the two-tier VANET/P2P system must be maintained regardless of the lookup protocol used, both the conventional and the adaptive lookup protocols can be assumed to introduce the same amount of maintenance messages (i.e., messages for maintaining clustering and the P2P overlay). Thus, maintenance messages are not considered.

4.4.2 Results in a Stationary Scenario

First, we simulate a stationary scenario where each vehicle stays at the same location during the entire simulation time. This configuration eliminates the effects of the dynamics of VANETs and thus can verify the design of the Bloom filter and the correctness of the reachability information. Since the VANETs in each simulation run are stable, we set a low decay probability p to 0.2 and the decay timer T_{decay} to 1 s to evaluate the performance. We simulate this ideal case in order to understand how much performance improvement that the adaptive lookup protocol can achieve by fully utilizing the reachability information.

As described previously, the values of low and high thresholds (i.e., γ_l and γ_h) are decided depending on the confidence in the reachability information. In the stationary scenario which we also minimize the false positive errors in the Bloom filter, we have more confidence in the reachability probability of a road segment. Moreover, a low value of γ_l would consume more bandwidth of VANETs without apparent benefits on performance. Therefore, we set both γ_l and γ_h to be 0.5. Finally, we increase γ_h to 0.7 but keep $\gamma_l = 0.5$ to investigate the impact of γ_h on the performance.

Figure 4.6 shows the results of lookup success rate. The conventional lookup mechanism can reach a stable success rate over 95% for information retrieval in the two-tier system. The results also show that even in the stationary scenario, the success rate cannot reach 100% because certain packet losses may occur because of the wireless network congestion and wireless channel interference. When the vehicle density is low, the adaptive lookup protocol can achieve the same success rate as the conventional lookup mechanism. When the vehicle density increases, however, more lookup messages would be generated by vehicles, resulting in VANET congestions. A lookup message may not reach the destination through the VANETs and cause a lookup failure. If both thresholds are set to the same value (i.e., $\gamma_h = \gamma_l$), the success rate of the adaptive lookup protocol decreases a little bit. This is mainly because if the reachability probability of the destination is higher than γ_l (i.e., it is also higher than γ_h in this case), the lookup is only forwarded in the VANETs. In this case, the success of a lookup only relies on the lookups in the VANETs, but a VANET lookup may lose due to the network congestion issue under a high vehicle density. On the other hand, if γ_h is set to be higher than γ_l, lookups are sent to both P2P and VANETs when the reachability probability is between γ_h and γ_l. These additional P2P lookups can compensate for these losses in the VANETs and thus we can maintain a high lookup success rate.

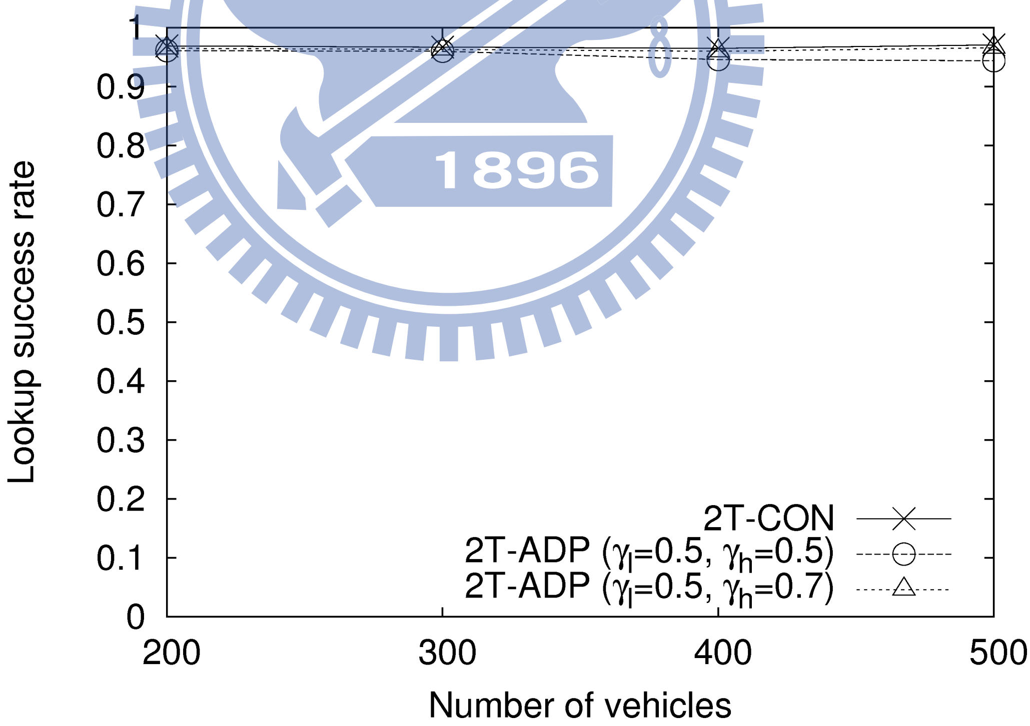


Figure 4.6: Lookup success rate in a stationary scenario.

The results of lookup latency are shown in Figure 4.7. For both the conventional and adaptive lookup mechanisms, the lookup latency decreases with the increasing number of vehicles because the VANET connectivity increases and thus the required information can be retrieved rapidly through lookups performed in connected VANETs. Moreover, the adaptive lookup protocol can redirect a lookup to the low-tier VANETs as soon as the reachability probability of the destination is high enough. When the vehicle density increases, the lookup latency can be reduced by up to 18%. The γ_h does not affect the lookup latency because the lookups redirected to the VANETs are determined according to γ_l.

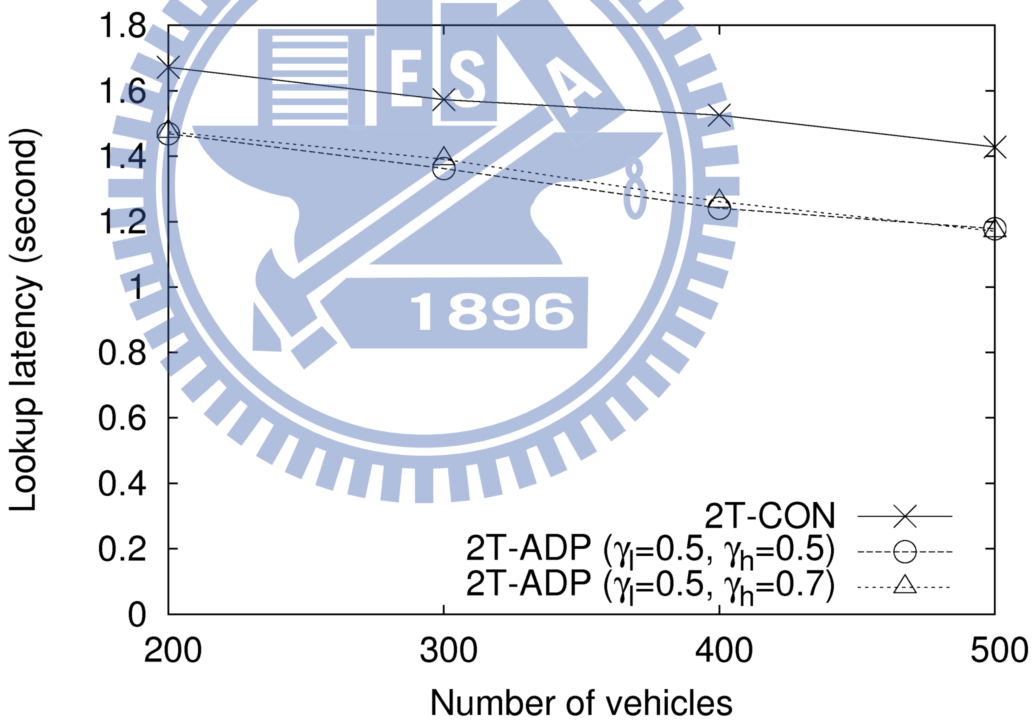


Figure 4.7: Lookup latency in a stationary scenario.

Figure 4.8 and Figure 4.9 show the results of lookup overhead in the VANETs and P2P overlay, respectively. The lookup overhead in both VANETs and P2P overlay can be reduced by using the adaptive lookup protocol. The adaptive lookup protocol uses γ_l to avoid unnecessary lookups in the VANETs and thus the VANET lookup overhead can be reduced. The impact of different values of γ_h on the VANET overhead is negligible because γ_h is mainly used to determine whether P2P lookups need to be continuously forwarded in the P2P overlay. On the other hand, to increase γ_h also increases the P2P lookup messages but it can compensate for the lookup losses in the VANETs to maintain a high lookup success rate. Furthermore, the adaptive lookup protocol can still reduce the P2P lookup overhead compared to the conventional lookup mechanism because P2P lookups are not required when the reachability probability is greater than γ_h.

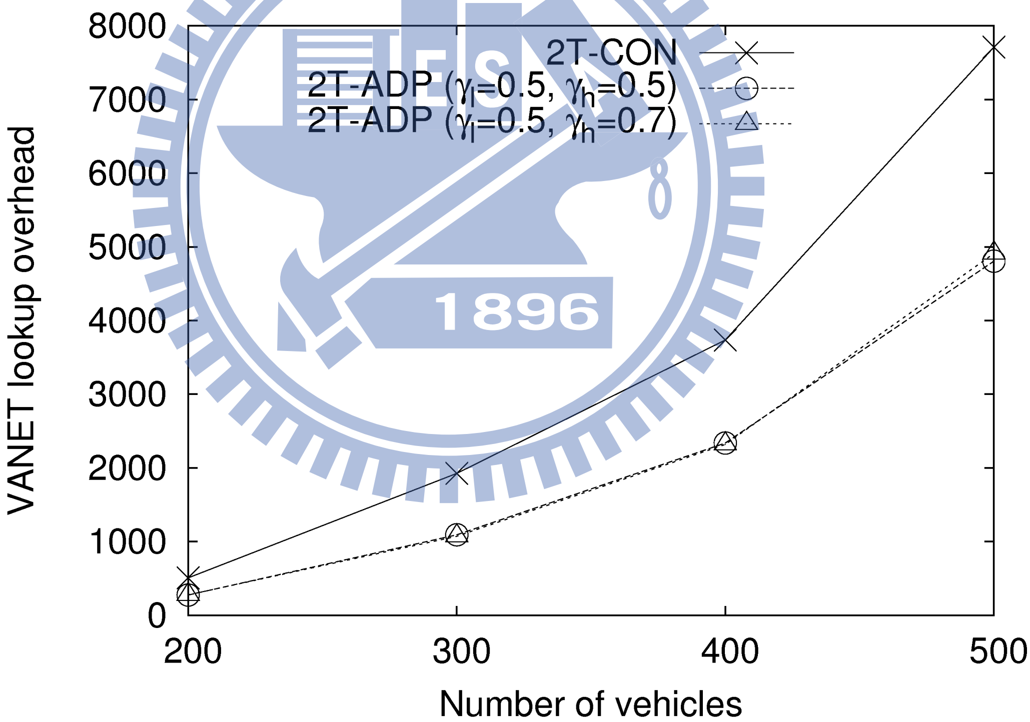


Figure 4.8: VANET lookup overhead in a stationary scenario.

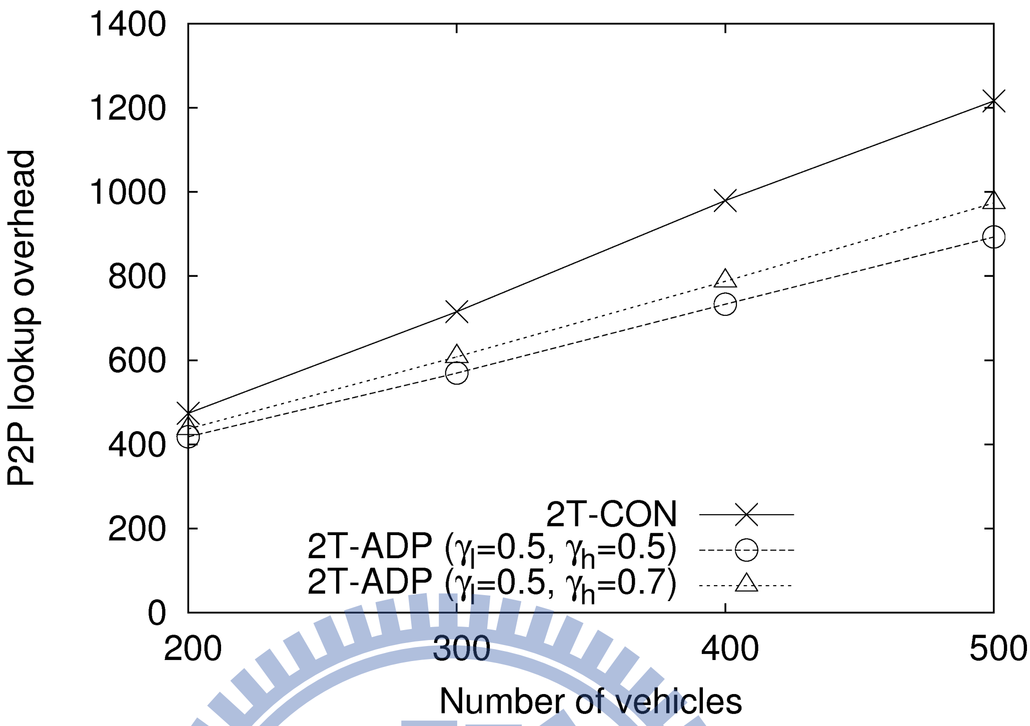


Figure 4.9: P2P lookup overhead in a stationary scenario.

The results of the stationary scenario indicate that the proposed mechanism to collect and maintain the reachability information of road segments is efficient and reachability information of road segments is accurate. The reachability information helps the adaptive lookup protocol reduce the lookup latency, P2P overhead, and VANET overhead. The same success rate as the conventional lookup mechanism can be achieved by setting a higher value of γ_h. The simulation results also reveal that some duplicated lookups over both VANETs and P2P are helpful to compensate for VANET congestions and packet losses.

4.4.3 Results in a Mobility Scenario

The second scenario we investigate is a mobility scenario where vehicle movements are generated by the traffic simulator. Contrast to the stationary scenario, the reachability of road segments in a mobility scenario continuously changes and the reachability information may become out-of-date when vehicles move on the roads. As a result, the lookup routing may fail when inaccurate reachability information is referred. Therefore, we investigate the capability of the adaptive lookup protocol to adapt to network dynamics (i.e., vehicle mobility). The reachability information is maintained in a soft-state manner by employing the decay mechanism. The adaptive lookup protocol determines lookup forwarding according to current reachability information and the reachability thresholds. We first examine the improvement that the decay mechanism can contribute to the accuracy of the reachability information in a dynamic vehicular network and then evaluate the impact of the reachability thresholds on the lookup performance.

In the presence of VANET changes, reachability information must be updated frequently to ensure accuracy. The decay mechanism uses the timer T_{decay} and probability p to decay the reachability information over time. The two decay parameters have a similar effect on the reachability information of road segments. A smaller T_{decay} and a larger p lead to a faster decay of reachability information. Therefore, in this study, the timer T_{decay} is fixed, but the probability p is varied to decay the reachability information when propagating the Bloom filters. In the simulation, we first investigate whether a large p can improve the accuracy of the reachability information. Both γ_l and γ_h are first set to 0.5 in this simulation while we increase p from 0.2 to 0.5.

Figure 4.10 depicts the results of lookup success rate. In a mobility scenario, the conventional lookup mechanism still achieves a high success rate as in the stationary scenario. For the adaptive lookup protocol, however, VANET changes cause a significant decrease in lookup success rate when a low p is used. A low p implies that reachability information of road segments will remain valid for a long period. The estimation of the reachability probability of a road segment is over-optimistic. As a result, a lookup redirected to the VANETs may not reach the destination due to the over-estimated reachability probability of the destination. Therefore, p should be increased to decay the confidence in reachability information according to the dynamics of a vehicular network. When p increases, reachability information refreshes frequently and the reachability information becomes more reliable and accurate. As can be seen from Figure 4.10, the lookup success rate by applying the adaptive lookup protocol can be improved when p increases. However, when $\gamma_h = \gamma_l$, the adaptive lookup protocol still cannot achieve the same success rate as the conventional lookup mechanism. As we discussed previously, a P2P lookup redirected to the VANETs may not be able to reach the destination when VANET congestion occurs under a high vehicle density. Such lookup failures can be alleviated by increasing γ_h and the simulations will be discussed later. Another improvement is to incorporate broadcast storm mitigation techniques, such as that in [19], into the adaptive lookup protocol to mitigate the collision and congestion occurring in dense VANETs. This improvement can be a direction of future research.

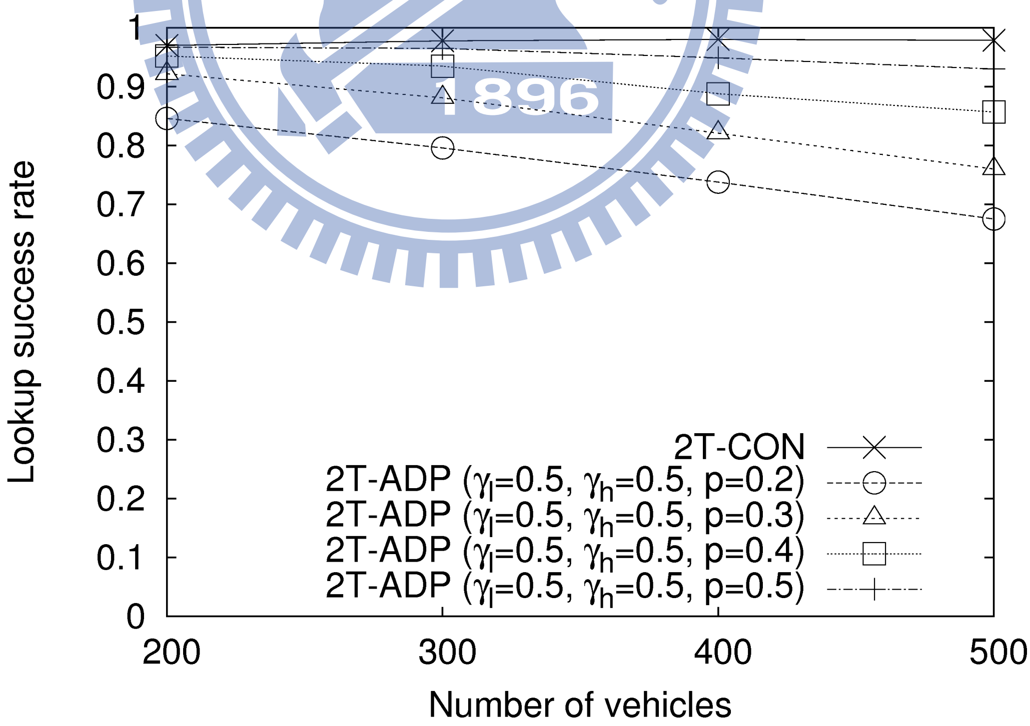


Figure 4.10: Lookup success rate in a mobility scenario.

The results of lookup latency are shown in Figure 4.11. In a mobility scenario, the connectivity of VANETs increases when the number of vehicles increases. The required information can be obtained through rapid lookups performed in the VANETs. As a result, the time required to retrieve information in the two-tier system decreases with increasing number of vehicles for both the conventional and adaptive lookup mechanisms. Moreover, the adaptive lookup protocol can further reduce the lookup latency by exploiting reachability information. A lookup can be redirected to the low-tier VANETs and reaches the destination rapidly when the reachability probability of the destination is high enough. When p is set to a small value, the reachability information will be kept for a period, and the reachability probabilities of road segments increase. Therefore, the adaptive lookup protocol prefers to forward lookups in the VANETs and gains the reduction of lookup latency for a small p. Although the lookup latency increases with p, the adaptive lookup protocol can still reduce lookup latency compared to the conventional lookup mechanism.

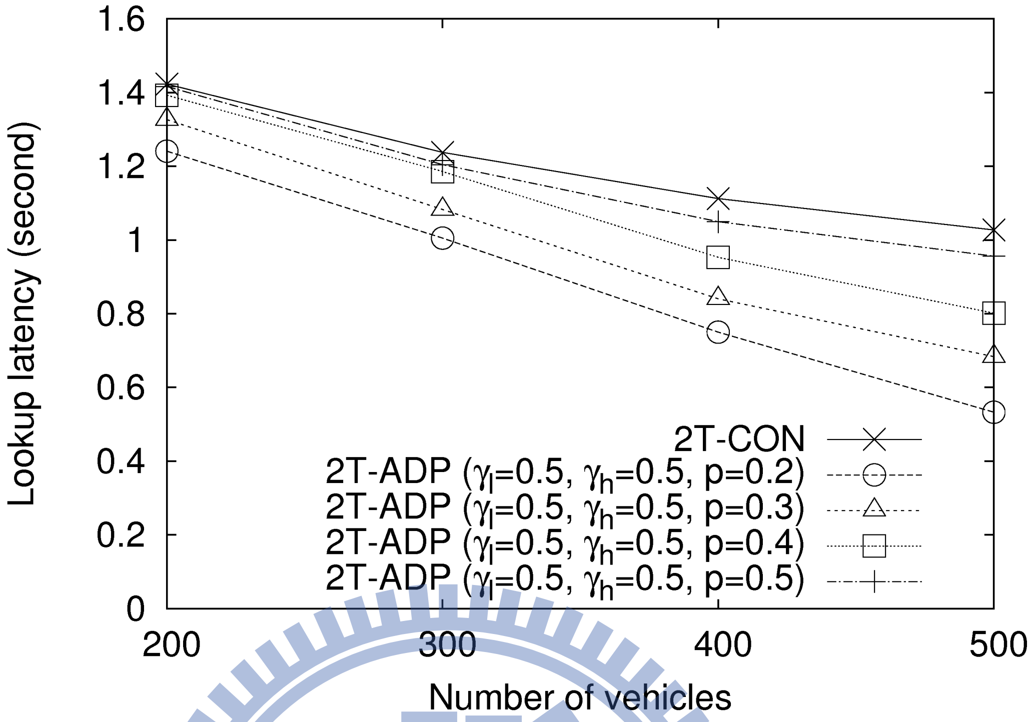


Figure 4.11: Lookup latency in a mobility scenario.

The results of lookup overhead in the VANETs and P2P overlay are shown in Figure 4.12 and Figure 4.13, respectively. For a small *p*, the adaptive lookup protocol introduces more VANET lookup overhead because the protocol is optimistic to the VANET reachability and forwards more lookups in the VANETs. On the other hand, a larger *p* increases P2P lookup overhead because reachability probability is more likely to be low, and thus the adaptive lookup protocol prefers to forward lookups in the P2P overlay to avoid lookup failures. As can be seen from Figure 4.13, even with a large *p*, P2P lookup overhead can still be reduced by avoiding unnecessary P2P lookups once the reachability probability is high enough.

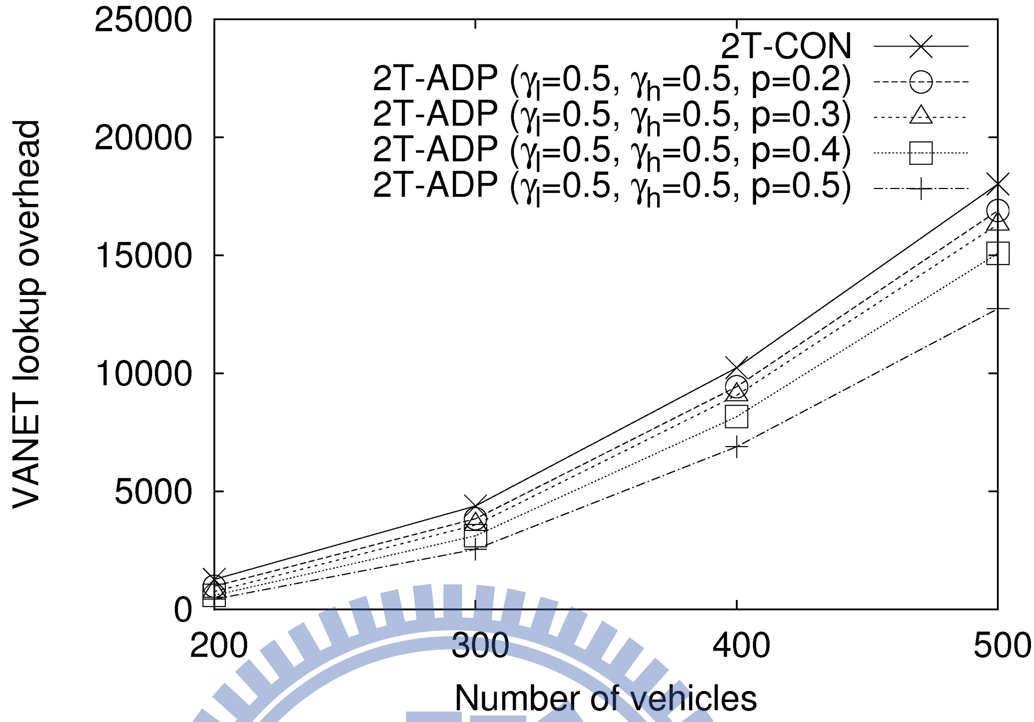


Figure 4.12: VANET lookup overhead in a mobility scenario.

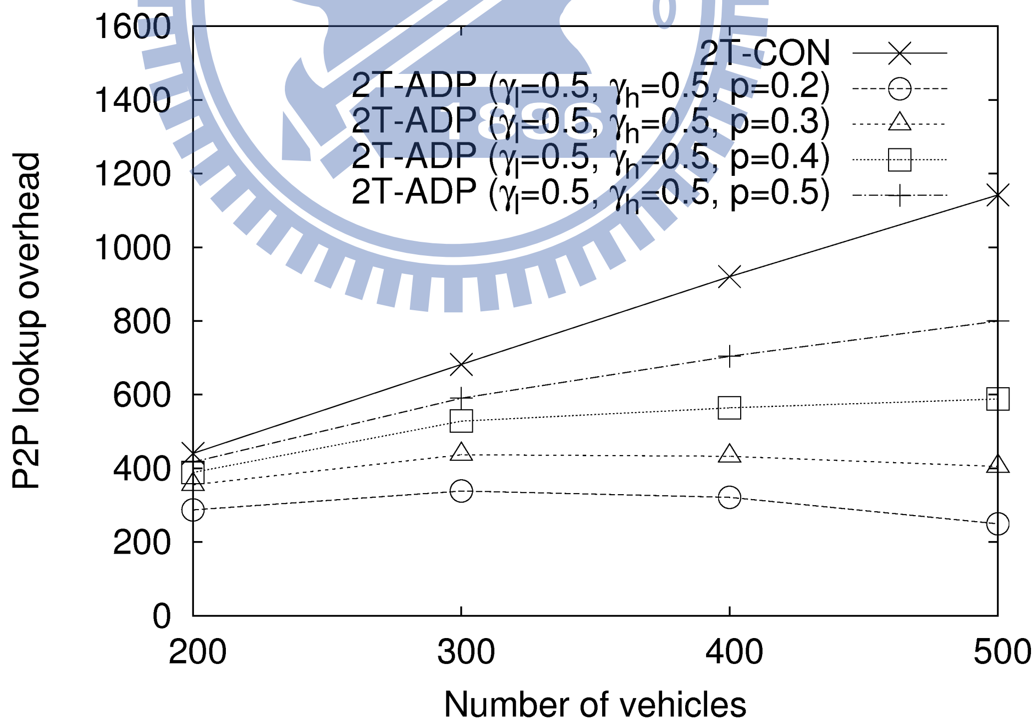


Figure 4.13: P2P lookup overhead in a mobility scenario.

The Bloom filter is a probabilistic data structure that cannot guarantee the accuracy of information. Simultaneously, because of the dynamic nature of VANETs, it is more appropriate to use probabilistic information in the dynamic vehicular environment. Therefore, this approach does not attempt to maintain the exact reachability information, but instead, relies on the probabilistic information maintained in the Bloom filter to determine if a lookup message can be delivered to the destination through VANETs. The results based on stationary vehicles eliminate the effects of dynamics of VANETs, and can verify the quality of the Bloom filter and the accuracy of the reachability information. Moreover, the results of the mobility scenario demonstrate the effectiveness of the reachability information and the benefit of the proposed approach in a dynamic vehicular environment.

Next, we investigate the impact of the reachability thresholds (i.e., γ_l and γ_h) on lookup performance in a mobility scenario. As discussed previously, γ_l should not be set to a low value to achieve a desired performance while a large γ_h can compensate for lookup failures caused by VANET congestions. We mainly focus on the effect of γ_h. Therefore, we keep γ_l = 0.5 and increase γ_h to 0.7 and 0.9. Furthermore, we set *p* to 0.4 since it exhibits an acceptable performance in the mobility scenario we considered.

Figure 4.14 shows the results of lookup success rate. When γ_h increases, the success rate can be improved and achieve performance similar to that of the conventional lookup mechanism. These results are similar to that shown in the stationary scenario. When the reachability probability is between γ_l and γ_h, lookups are performed in both the VANETs and P2P overlay. The additional P2P lookups can compensate for possible lookup failures occurred in the VANETs. The results of lookup latency are shown in Figure 4.15. When the same *p* is used and the vehicle density is low, the lookup latency remains stable regardless of the values of γ_h used by the adaptive lookup protocol. On the other hand, when the vehicle density increases, the lookup latency may increase slightly with γ_h because more information can be obtained through P2P lookups with longer latencies.

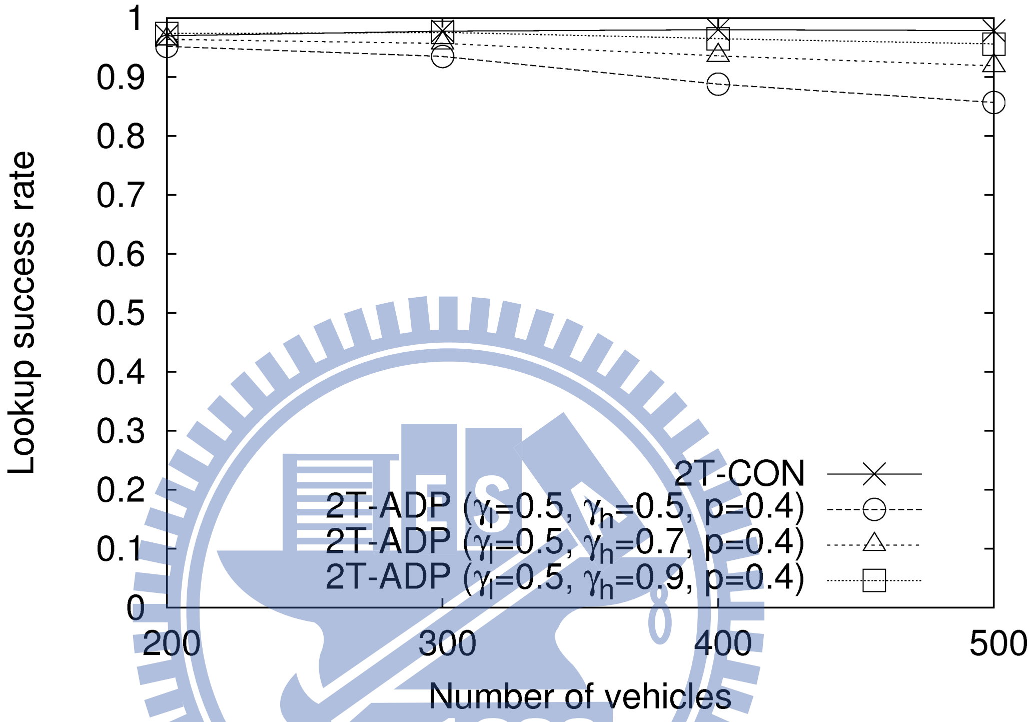


Figure 4.14: Lookup success rate in a mobility scenario.

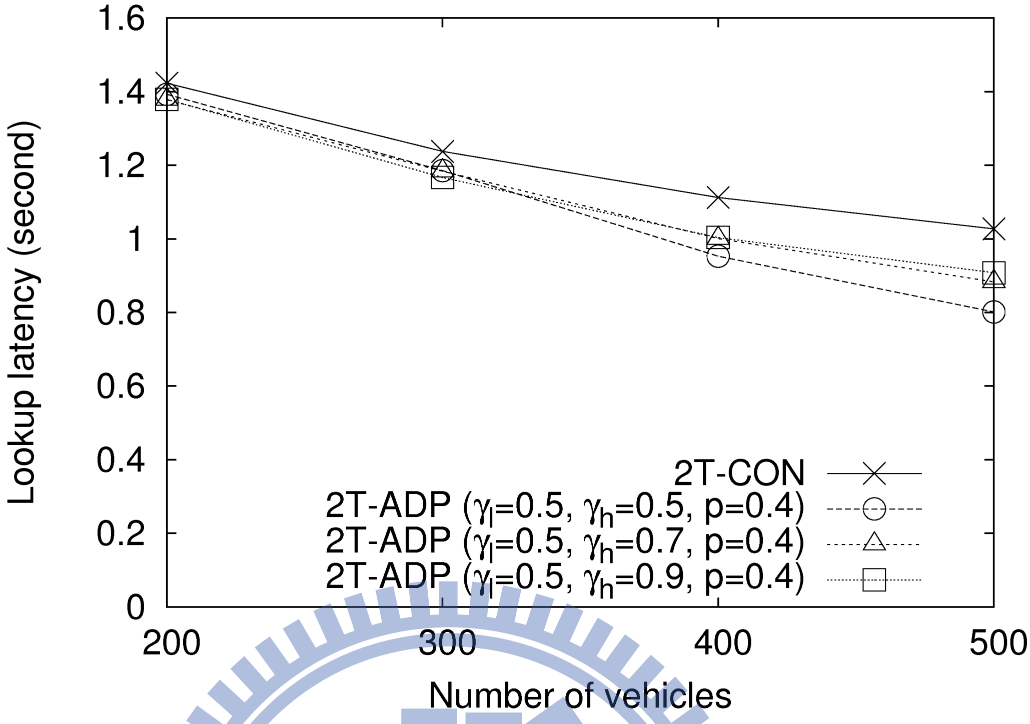


Figure 4.15: Lookup latency in a mobility scenario.

As can be seen from Figure 4.14 and Figure 4.15, the proposed protocol would prefer to forward lookups in VANETs to exploit the VANET reachability when the density increases. Thus, the lookup latency can be reduced with an increased density. However, increased messages may cause network congestion and contention in VANETs, resulting in a degradation of lookup success rate. To alleviate VANET congestions, broadcast storm mitigation techniques, as mentioned previously, can be used. Furthermore, we can rely on the designs of the proposed protocol to improve the performance. First, when more and more lookup messages are forwarded in high-density VANETs, the network congestion occurs. The reachability of VANETs which is estimated based on the number of messages a vehicle can receive from VANETs may decrease. If the reachability of VANETs is not higher than γ_l, the lookups are not forwarded in VANETs according to the design of the protocol. Therefore, the total number of VANET messages is not significantly increased in dense traffic areas because the low threshold avoids unnecessary lookups in the areas without sufficient VANET reachability. Second, we can set a higher γ_h when the lookup success rate decreases. When the reachability of VANETs is lower than γ_h, vehicles send lookups to P2P overlay to compensate for the lookup losses in VANETs. Although the P2P lookup message increases, the proposed protocol can improve the lookup success rate, and the number of P2P message is still less than that of the conventional two-tier lookup mechanism.

The results of lookup overhead in the VANETs and P2P overlay are shown in Figure 4.16 and Figure 4.17, respectively. When γ_h increases, the P2P lookup overhead increases because a large γ_h uses more P2P lookups to compensate for the lookup losses in the VANETs. The P2P lookup overhead still can be reduced even when a large γ_h is used. Particularly, when γ_h = 0.9, a success rate of more than 95% is achieved and the P2P overhead can be reduced by 20%. On the other hand, the VANET lookup overhead may slightly increase because more P2P lookups are performed and some of them may be redirected by superpeers to the VANETs when the reachability probability is high enough.

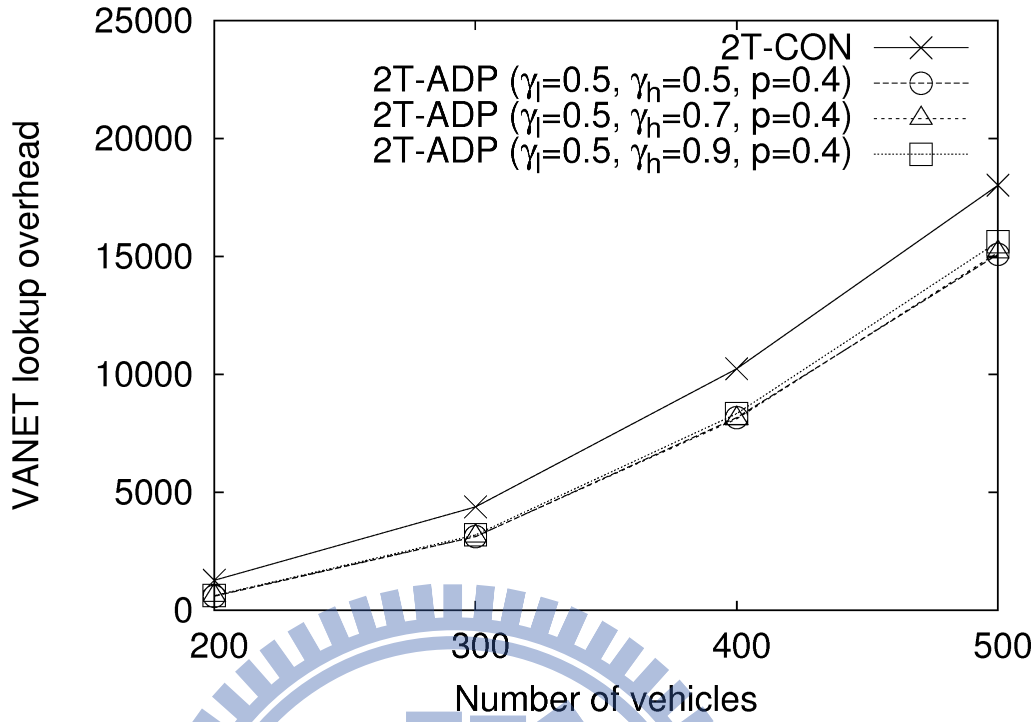


Figure 4.16: VANET lookup overhead in a mobility scenario.

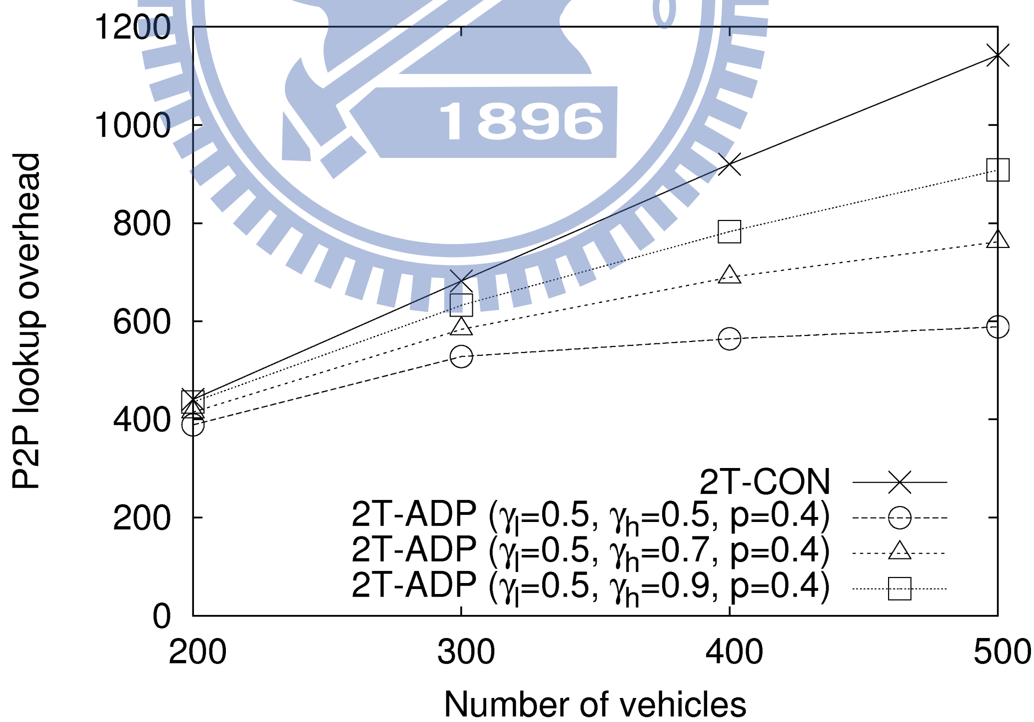


Figure 4.17: P2P lookup overhead in a mobility scenario.

4.5 Summary

In this chapter, we propose an adaptive lookup protocol for the two-tier VANET/P2P system to improve the efficiency of information retrieval. The proposed protocol uses a Bloom filter, which is a space-efficient data structure, to collect reachability information of road segments; therefore, adaptive routing of queries between low-tier and high-tier networks according to reachability probability can be employed. The results in Section 3.7 show that the two-tier VANET/P2P system can improve lookup success rate compared to the single-tier VANET systems and reduce lookup latency and message overhead compared to the single-tier infrastructure-based P2P systems. In this chapter, we further demonstrate that the adaptive lookup protocol outperforms the original lookup mechanism presented in Chapter 3. The results show that compared to the conventional two-tier lookup mechanism, the adaptive lookup protocol can reduce lookup latency and overhead while achieving a high success rate in information lookups. Therefore, an information retrieval system based on the two-tier VANET/P2P architecture (e.g., traffic information system) can benefit from the adaptive lookup protocol to retrieve information in a more efficient manner than other single-tier systems.

CHAPTER 5 CONCLUSION AND FUTURE DIRECTIONS

In this dissertation, we have classified and investigated various single-tier systems, and proposed a two-tier VANET/P2P system for information retrieval in a vehicular environment. The two-tier system exploits both VANET and P2P technologies. Vehicles form low-tier VANETs via IVC while a portion of vehicles establish a high-tier P2P overlay through infrastructure-based communication. Information can be shared among vehicles and retrieved through lookups preformed in the low-tier VANETs and high-tier P2P overlay. We analyzed design issues of different system architectures and compared their performance through the SUMO traffic simulator and QualNet network simulator. Simulation results reveal that the two-tier VANET/P2P architecture achieves much higher lookup success rates than single-tier VANET-based systems and outperforms single-tier infrastructure-based P2P systems in terms of success rate, latency, and maintenance cost. Open research issues for the new two-tier VANET/P2P architecture such as adaptive lookup and routing in between VANET/P2P networks, superpeer election and redundancy, and others are also identified and should be further studied.

We further proposed an adaptive lookup protocol to improve the performance of information retrieval in the two-tier VANET/P2P system. The adaptive lookup protocol exploits reachability information of road segments to perform lookups between low-tier and high-tier networks. To efficiently maintain the reachability information in a dynamic vehicular environment, the Bloom filter and probabilistic information are used to determine the lookup forwarding. Simulation results show that the proposed adaptive lookup protocol significantly improves the performance of lookup latency while it can also achieve a high lookup success rate similar to the conventional approach. Although the improvement may lead to an increase in message overhead in VANETs, the proposed protocol can significantly reduce P2P message overhead in the infrastructure-based network by 20%–33%. It is particularly important and valuable for the two-tier VANET/P2P system to make full use of VANETs and to efficiently use the resources of the infrastructure-based wireless communication. We have investigated the effects of the protocol designs on the lookup performance under various network scenarios. Since vehicle density (i.e., network condition) varies in areas and over time, one future enhancement could consider different and/or dynamic thresholds in various areas (e.g., urban or rural area) and during different times (e.g., rush hour or nighttime) according to the vehicle density and network condition that vehicles observe or estimate.

The proposed two-tier VANET/P2P system provides an infrastructure to share and retrieve information in the vehicular environment. This infrastructure can also be used to implement high-level applications and services such as route planning. For example, the route planning application determines what information (i.e., traffic conditions) it needs, performs lookups for the necessary traffic information, and then suggests a suitable route to the driver based on the obtained traffic reports. A possible implementation of the route planning application is to send a number of lookup queries to nearby road segments and areas along the path from the source to the destination. The performance of an application depends on the number of lookup queries it generates and the lookup latencies required to obtain the necessary information. Information can be retrieved in the two-tier VANET/P2P system with a high success rate, low latency, and low overhead. Moreover, compared with the conventional two-tier lookup mechanism, the adaptive lookup protocol further reduces the lookup latency, VANET overhead, and P2P overhead for each lookup query, and achieves a high lookup success rate. Therefore, the adaptive lookup protocol is likely to improve the performance of high-level applications. Because of various implementations of applications, the discussion of more application scenarios and an evaluation of high-level services are topics for future research.

BIBLIOGRAPHY

[1] Ioan Chisalita and Nahid Shahmehri, “A peer-to-peer approach to vehicular communication for the support of traffic safety applications,” in *Proc. Intelligent Transportation Systems*, Sept. 2002, pp. 336–341.

[2] Lars Wischhof, André Ebner, Hermann Rohling, Matthias Lott, and Rüdiger Halfmann, “SOTIS – a self-organizing traffic information system,” in *Proc. VTC2003-Spring*, vol. 4, Apr. 2003, pp. 2442–2446.

[3] Jedrzej Rybicki, Björn Scheuermann, Markus Koegel, and Martin Mauve, “PeerTIS: A peer-to-peer traffic information system,” in *Proc. ACM VANET*, Sept. 2009, pp. 23–32.

[4] Che-Liang Liu, Chih-Yu Wang, and Hung-Yu Wei, “Cross-layer mobile chord P2P protocol design for VANET,” *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 6, no. 3, pp. 150–163, 2010.

[5] Panos Papadimitratos, Arnaud de La Fortelle, Knut Evenssen, Roberto Brignolo, and Stefano Cosenza, “Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation,” *IEEE Communications Magazine*, vol. 47, no. 11, pp. 84–95, Nov. 2009.

[6] Mihail L. Sichitiu and Maria Kihl, “Inter-vehicle communication systems: A survey,” *IEEE Communications Surveys & Tutorials*, vol. 10, no. 2, pp. 88–105, Second Quarter 2008.

[7] Tamer Nadeem, Sasan Dashtinezhad, Chunyuan Liao, and Liviu Iftode, “TrafficView: Traffic data dissemination using car-to-car communication,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 3, pp. 6–19, July 2004.

[8] Eng Keong Lua, Jon Crowcroft, Marcelo Pias, Ravi Sharma, and Steven Lim, "A survey and comparison of peer-to-peer overlay network schemes," *IEEE Communications Surveys & Tutorials*, vol. 7, no. 2, pp. 72–93, 2005.

[9] Kashif Dar, Mohamed Bakhouya, Jaafar Gaber, Maxime Wack, and Pascal Lorenz, "Wireless communication technologies for ITS applications," *IEEE Communications Magazine*, vol. 48, no. 5, pp. 156–162, May 2010.

[10] Burton H. Bloom, "Space/time trade-offs in hash coding with allowable errors," *Communications of the ACM*, vol. 13, no. 7, pp. 422–426, July 1970.

[11] Lars Wischhof, André Ebner, and Hermann Rohling, "Information dissemination in self-organizing intervehicle networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 1, pp. 90–101, Mar. 2005.

[12] Sandor Dornbush and Anupam Joshi, "StreetSmart traffic: Discovering and disseminating automobile congestion using VANETs," in *Proc. VTC2007-Spring*, Apr. 2007, pp. 11–15.

[13] Kevin C. Lee, Seung-Hoon Lee, Ryan Cheung, Uichin Lee, and Mario Gerla, "First experience with CarTorrent in a real vehicular ad hoc network testbed," in *Proc. Mobile Networking for Vehicular Environments*, May 2007, pp.109–114.

[14] Alok Nandan, Shirshanka Das, Giovanni Pau, Mario Gerla, and M.Y. Sanadidi, "Co-operative downloading in vehicular ad-hoc wireless networks," in *Proc. WONS*, Jan. 2005, pp. 32–41.

[15] Marios D. Dikaiakos, Andreas Florides, Tamer Nadeem, and Liviu Iftode, "Location-aware services over vehicular ad-hoc networks using car-to-car communication," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 8, pp. 1590–1602, Oct. 2007.

[16] Marios D. Dikaiakos, Saif Iqbal, Tamer Nadeem, and Liviu Iftode, “VITP: an information transfer protocol for vehicular computing,” in *Proc. ACM VANET*, Sept. 2005, pp. 30–39.

[17] Christian Lochert, Björn Scheuermann, Murat Caliskan, and Martin Mauve, “The feasibility of information dissemination in vehicular ad-hoc networks,” in *Proc. WONS*, Jan. 2007, pp. 92–99.

[18] Brad Williams and Tracy Camp, “Comparison of broadcasting techniques for mobile ad hoc networks,” in *Proc. ACM MobiHoc*, June 2002, pp. 194–205.

[19] Nawaporn Wisitpongphan, Ozan K. Tonguz, Jayendra S. Parikh, Priyantha Mudalige, Fan Bai, and Varsha Sadekar, “Broadcast storm mitigation techniques in vehicular ad hoc networks,” *IEEE Wireless Communications*, vol. 14, no. 6, pp. 84–94, Dec. 2007.

[20] Gnutella protocol specification v4.0.

[21] Ion Stoica, Robert Morris, David Liben-Nowell, David Karger, M. Frans Kaashoek, Frank Dabek, and Hari Balakrishnan, “Chord: a scalable peer-to-peer lookup protocol for Internet applications,” *IEEE/ACM Transactions on Networking*, vol. 11, no. 1, pp. 17–32, Feb. 2003.

[22] Fan Li and Yu Wang, “Routing in vehicular ad hoc networks: A survey,” *IEEE Vehicular Technology Magazine*, vol. 2, no. 2, pp. 12–22, June 2007.

[23] Yatin Chawathe, Sylvia Ratnasamy, Lee Breslau, Nick Lanham, and Scott Shenker, “Making Gnutella-like P2P systems scalable,” in *Proc. ACM SIGCOMM*, Aug. 2003, pp. 407–418.

[24] Peng Fan, James G. Haran, John Dillenburg, and Peter C. Nelson, “Cluster-based framework in vehicular ad-hoc networks,” in *Proc. ADHOC-NOW*, Oct. 2005, pp 32–42.

[25] Zhigang Wang, Lichuan Liu, MengChu Zhou, and Nirwan Ansari, “A position-based clustering technique for ad hoc intervehicle communication,” *IEEE Transactions on Systems, Man, and Cybernetics–Part C: Applications and Reviews*, vol. 38, no. 2, pp. 201–208, Mar. 2008.

[26] Alan D. Amis, Ravi Prakash, Thai H.P. Vuong, and Dung T. Huynh, “Max-min d-cluster formation in wireless ad hoc networks,” in *Proc. INFOCOM*, Mar. 2000, pp. 32–41.

[27] Sylvia Ratnasamy, Paul Francis, Mark Handley, Richard Karp, and Scott Shenker. “A scalable content-addressable network,” *ACM SIGCOMM Computer Communication Review*, vol. 31, no. 4, pp. 161–172, Oct. 2001.

[28] SUMO. [Online]. Available: http://sumo.sourceforge.net

[29] QualNet. [Online]. Available: http://www.scalable-networks.com/products/qualnet

[30] Josiane Nzouonta, Neeraj Rajgure, Guiling Wang, and Cristian Borcea, “VANET routing on city roads using real-time vehicular traffic information,” *IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp.3609–3626, Sept. 2009.

[31] Andrei Broder and Michael Mitzenmacher, “Network applications of Bloom filters: A survey,” *Internet Mathematics*, vol. 1, no. 4, pp. 485–509, 2005.

[32] Steven E. Czerwinski, Ben Y. Zhao, Todd D. Hodes, Anthony D. Joseph, and Randy H. Katz, “An architecture for a secure service discovery service,” in *Proc. MobiCom*, Aug. 1999, pp. 24–35.

[33] Evangelos Papapetrou, Evaggelia Pitoura, and Kostas Lillis, “Speeding-up cache lookups in wireless ad-hoc routing using Bloom filters,” in *Proc. PIMRC*, Sept. 2005, vol. 3, pp. 1419–1423.

[34] Abhishek Kumar, Jun Xu, and Ellen W. Zegura, “Efficient and scalable query routing for unstructured peer-to-peer networks,” in *Proc. INFOCOM*, Mar. 2005, vol. 2, pp. 1162–1173.

[35] OpenStreetMap. [Online]. Available: http://www.openstreetmap.org/