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A Novel Real-time Traffic Information System Based on Wireless Mesh Networks

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***Abstract*— Probe-vehicle technique is an effective method of collecting real-time traffic information on road networks. A technically feasible and cost-effective wireless communication network is in great demand so that large amounts of traffic data sampled by probe vehicles over a large geographical area can be sent to the Traffic Management Center (TMC). However, how to design such a wireless network forms a major bottleneck of probe system, due to high dynamics of the network. In this paper, we address a Wireless Mesh Network (WMN) architecture which is independent of any existing wire or wireless network, and needs very low communication cost. We describe the architecture of a WMN-based traffic information system, and provide the details of the network protocols. By means of computer simulation, we evaluate the WMN performance, and find that the WMN scheme is low up-front cost, easy network maintenance, robustness and large reliable service coverage for the probe data transmissions.**

I. Introduction

Real-time traffic information is an essential and important factor in such Intelligent Transportation System as congestion management, traffic control, route guidance, traffic accident detection and so on. Using vehicles as probes is a flexible and low-cost way to obtain real-time traffic information. The key idea of using probe vehicles to collect traffic information is that a vehicle running on the road which is a part of the traffic stream is reasonable representative of the behavior of the traffic and has the capability to provide a richer insight into network performance. The trajectory followed by a vehicle is an integral part of the highway travel experience and hence important for a traffic management system [1]. Compared to the conventional stationary detectors (e.g. the inductive loops, radar, and video) which are commonly installed on urban freeways, probe vehicles may provide benefits such as an easier implementation, more precise information and lowered costs for constructing and maintaining the information collection system.

Probe vehicles roam a large scale road networks and rely on a wireless communication network to automatically send traffic reports to the TMC. Since the multi-path delay spread and Doppler shifts associated with the multi-path propagation have significant distortion effects on the performance of the communication system, and network topology changes so frequently when vehicles travel with high speed, wireless transmission techniques form a major bottleneck of the wireless data collection technique.

As various wireless networks evolve into the next generation to provide better services, wireless mesh networks (WMNs) have emerged recently. In this paper, we propose a novel traffic information system based on a WMN to gather real-time speed, location and other sensing data sampled by moving probe vehicles, focusing on wireless communication aspects. We address a WMN architecture which does not depend on any existing wireless cellular network, and needs very low communication cost to deliver the traffic reports of numerous probe vehicles to TMC. In addition, the WMN scheme is low up-front cost, easy network maintenance, robustness and large reliable service coverage for the probe data transmissions.

The rest of the paper is organized as follows. The following section presents the overview of the related works. Section III describes the system architecture. Section IV presents the details of network protocols. Section V evaluates the network performance through computer simulations. Section VI concludes the paper.

II. Related Work

Probe vehicle techniques have long been seen as an effective method of collecting real-time traffic information on road networks. Probe vehicle-based collection of real-time traffic information has potential applications in incident detection, traffic management, the provision of information to influence travel decisions and for longer-term performance monitoring of the road [2].

A. Cellular-based Probe Systems

Wireless cellular technology is one of the most promising technologies for the real-time probe systems, because the necessary infrastructure is already built up in most urban areas. In USA, California Partners for Advanced Transit and Highways (PATH) has been actively involved with research and development of cellular probe technologies since 1999 [3]. Cellular phone tracking technologies are adopted to produce reliable travel time information. In the UK, ITIS Holdings Plc. begins to develop the commercial FVD™System [4] since February 2000. In FVD™, the vehicles equipped with Global Positioning System (GPS), usually make use

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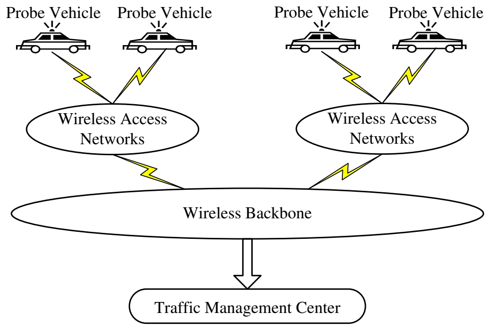

Fig. 1. Lay-out of WMN-based probe system

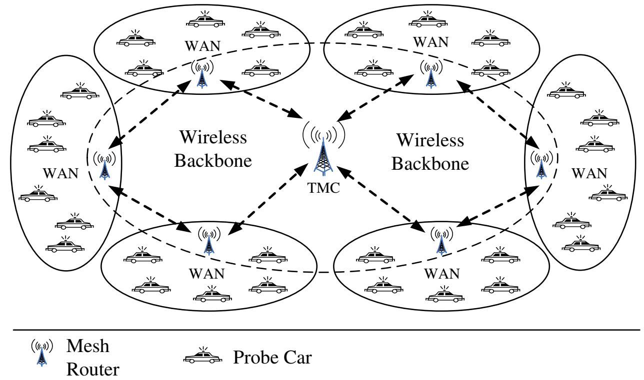

Fig. 2. Communication network architecture of WMN-based probe system

of Global System for Mobile Communication (GSM) or General Packet Radio Service (GPRS) technology to send their current positions and speeds to TMC periodically.

However, there are two basic factors to confine the commercial feasibility of the cellular-based systems. One is the cooperation of the wireless carriers to provide corresponding services, such as numerous vehicles' frequent accesses, which may make the cellular system overloaded in hot spot areas. The other is the huge communication cost. That is, each cellular user needs to pay cellular carriers for data transmission and consequently the communication cost is very high due to a large number of sample messages. These two factors motivate us to design a novel wireless communication scheme for probe systems independent of cellular networks.

B. VANET-based Probe Systems

More than ten years ago, Linnartz *et al*. [5] describe a method of collecting real-time traffic data from probe vehicles. The vehicles use ALOHA access protocol to send traffic reports to base stations, connected to a TMC by a wired communications network. ALOHA radio network is in an early stage of development of wireless ad hoc networks, and the wired network infrastructure is necessary for this system.

In the ITS research community, Vehicular Ad-hoc Networks (VANET) have attracted the interests of many automobile manufactures and researchers. Vehicular ad-hoc networking based on Dedicated Short Range Communications (DSRC) is a potential technology for supporting several vehicle applications, such as vehicle-to-vehicle safety, collaborative expedition, distributed passengers teleconference, etc.

DSRC is a general purpose of communications link to transfer information between vehicles and roadside systems. In October 1999, the Federal Communications Commission (FCC) allocated a 75MHz spectrum from 5.850 to 5.925GHz for DSRC-based ITS applications. In August 2003, American Society for Testing Materials (ASTM) published the DSRC Standard as ASTM E2213-03 [6] based on IEEE 802.11a physical layer and IEEE 802.11 Medium Access Control (MAC) layer. Currently, the ASTM E2213-03 standard is being migrated to the IEEE 802.11p standard [7] by Wireless Access for the Vehicular Environment (WAVE) study group within the IEEE 802.11 community. Per the official IEEE 802.11 Work Plan predictions the formal 802.11p standard is scheduled to be published in April 2009.

Though DSRC's communication cost is none, it is difficult to achieve timely and efficient information transmission on top of DSRC VANET [8] [9]. Furthermore, the scalability issue in multi-hop ad hoc networks has not been fully solved. Hence, VANET is not competent for large-scale probe systems.

Different from the flat topological structure of wireless ad hoc networks, Wireless Mesh Networks (WMN) consist of heterogeneous wireless mesh clients and stationary wireless mesh routers. Mesh routers form the wireless backbone by way of self-organization and self-configuration. The mesh routers do not have high mobility as mobile nodes in ad hoc networks, so the wireless backbone is able to provide large coverage, connectivity, and robustness in wireless domain [10]. The mesh backbone communication can be established using long-range high bandwidth communication techniques. Therefore, WMN is the most suitable communication network for the probe-vehicle system over a large geographical area.

III. System Architecture

The traffic information system based on WMN consists of two components: probe vehicles and a WMN, as shown in Figure 1. When travelling in road networks, probe vehicles gather real-time traffic data automatically and transmit the data over WMN to TMC. In our designed system, WMN comprises a wireless backbone and Wireless Access Networks (WAN).

A. Probe-vehicle Terminal

The probe vehicles are equipped with Data Collection Units (DCUs) and vehicular wireless terminals. The DCU is a combination of on-board sensor systems and GPS devices. The sensor system detects the conditions of roads, including road temperature, surface water, light intensity, etc. The GPS devices provide vehicle's latitude, longitude and speed regularly. The wireless terminals send the data from the DCUs to TMC on a minute by minute basis.

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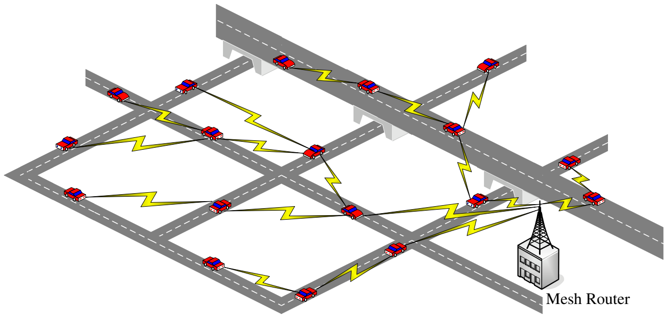

Fig. 3. Application scenario of WAN

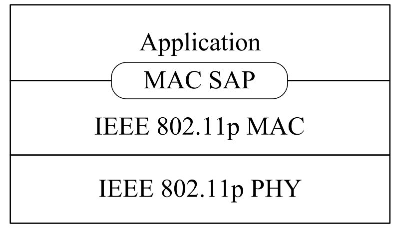

Fig. 4. Client protocol stack

B. Wireless Mesh Networks

Figure 2 depicts the communication network architecture of the system. The WMN consists of two types of nodes: mesh routers and mesh clients. In our system, probe vehicles act as mesh clients.

WANs are formed dynamically by mobile probe vehicles equipped with vehicular wireless terminals through wireless links without using the existing network infrastructure or centralized administration. As shown in Figure 3, the probe vehicle detects the real-time traffic environmental data, and the data are routed hop by hop through other probe vehicles until they reach the nearest mesh router.

WAN is essentially a type of wireless sensor networks with a multi-hop infrastructureless architecture, in which probe vehicles serve as mobile sensors and mesh routers serve as sink nodes. The sinks (mesh routers) communicate with TMC via wireless backbone, which can provide more distant, more reliable, and faster data transmission than wireless sensor or ad-hoc networks. Actually, the mesh routers are used as a gateway to wireless backbone. The mesh routers are equipped with two types of radios. One is for WAN communication to perform the traffic information collection from probe vehicles in routers' surrounding area. And the other is for backbone communication to perform routing of the gathered data supplied by WANs to TMC.

In our technical scheme, the wireless backbone adopts IEEE 802.16 standard as mesh networking technology, and WANs adopt IEEE 802.11p standard as vehicular wireless terminal technology. Note that the mesh routers should be installed on top of roofs of tall buildings because of obstacles (buildings) in the city.

IV. Network Protocol

A. Vehicular Protocol Stack

The protocol stack used by probe vehicles is given in Figure 4. The protocol stack consists of the application layer, medium access control layer (MAC) and physical layer (PHY).

The PHY shall be implemented in accordance with IEEE 802.11p [7] based on orthogonal frequency division multiplex (OFDM) technology. This layer deals with all issues involved in the transmission of raw bits on one of the seven channels approved to be used with DSRC. The MAC shall be implemented in accordance with IEEE 802.11p [7] based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol. This layer coordinates the channel access in a distributed manner.

The MAC service is provided to the application layer via a service access point (SAP) across which defined primitives are exchanged. The application layer mainly carries out two tasks. One is to receive the data from DCUs periodically. And the other is to route the data packets to the nearest mesh router.

Routing approach in a WAN is a challenging task due to the high dynamics of such a network. However, there also exist some advantages in the system to simplify the routing approach. First of all, all the nodes can get their current geographic position through the equipped GPS devices. Furthermore, the destination nodes, i.e. mesh routers, are stationary and evenly distributed in the city, so each node is able to obtain the destinations' position in its surrounding area. Hence, the application layer can utilize the position-based routing protocols [12] [13] to greedily route packets toward mesh routers. Position-based routing bases forwarding decisions on position information. This type of routing protocols does not need to install states in mobile nodes to find a path, set up a path, and maintain a path as traditional routing protocols do (e.g. [14] and [15]).

In order to send data packets to the nearest mesh router as soon as possible, probe vehicles require information on the current geographic position of the mesh router in order to include it in the packet header and support the routing decision. Besides, each node should periodically broadcast beacon messages so that the position of its one-hop neighbors is obtained to forward packets.

A message from the application layer to MAC shall be packed into MAC Service Data Unit (MSDU), and an illustration of frame body is shown in Figure 5. The MSDU frame body comprises seven fields in a fixed order:

1) The equipment type, where 1 represents a probe vehicle and 0 represents a mesh router.
2) The MAC address of a neighbor, which is selected as the next hop to forward the data packet.
3) The node's MAC address.
4) The node's current geographic position.
5) The MAC address of the associated mesh router, which is the closest mesh router to the node.
6) The geographic position of the associated mesh router.
7) The traffic information, including its own collected

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TABLE I

NEIGHBOR LIST.

Neighbor's MAC address	Equip. Type	Geo-position	Timer
MAC - A	1	Position-A	1 min.
MAC - B	0	Position-B	2 min.
MAC - C	1	Position-C	1.5 min.

TABLE II

MESH-ROUTER LIST.

Mesh router's MAC address	Geo-position	Timer
MAC - D	Position-D	2 min.
MAC - E	Position-E	2 min.
MAC - F	Position-F	1 min.

data and forwarded data for other nodes.

The beacon messages contain all the fields except the second and seventh fields, and are not forwarded, because they are only intended to inform the neighbors.

Routing in the application layer requires two lists' support, i.e. neighbor list and mesh-router list, which are shown in Table I and Table II, respectively. When a node receives a neighbor's packet, the application layer extracts each of the fields from the MSDU, and place (or update) the neighbor's equipment type, MAC address and geographic position in the corresponding position in the neighbor list. And the corresponding timer is started from zero at the same time. If there do exist mesh routers in the neighbor list, the application layer will select a closest one as its associated mesh router (destination), and send the packet to the router. Otherwise, the application layer will select a closest one from its mesh-router list as its associated mesh router (destination), and forward the packet to the neighbor that is closest to its associated mesh router in the neighbor list. Note that if a timer exceeds a specified threshold (say 3 min.), which implies that the topology information is out of date, the corresponding entry will be removed from neighbor or mesh-router list.

The following three steps are the receive procedure:

1) The frame body of MSDU is provided to the application layer via MAC SAP.
2) The application layer extracts each of the fields, places the neighbor's equipment type, MAC address and geographic position in the corresponding position in the neighbor list, and places the MAC address and geographic position of the neighbor's associated mesh router in the mesh-router list. Both timers in neighbor and mesh-router lists are started from zero.
3) The application layer checks the MAC address in the field of next-hop address with its own MAC address. If these two addresses are the same, it will invoke the transmit procedure to forward the field of traffic information. Otherwise, it will wait for the arrival of next packet.

Client?	Next hop address	MAC address	Geo-position	Associated Mesh router's MAC address	Associated Mesh router's geo-position	Traffic information

Fig. 5. The structure of MSDU frame body

The following three steps are the transmit procedure:

1) The application layer waits for the arrival of three types of messages, i.e., the beacon messages, the real-time data from its DCU and forwarded data of neighbors.
2) The application layer fills all the fields of MSDU.
3) MSDU is transmitted to MAC via MAC SAP and MAC broadcasts it.

B. Mesh Router Stack

The protocol stack used by mesh routers is given in Figure 6. Since mesh routers serve as the gateways between WANs and wireless backbone, they integrate two protocol stacks. At the side of WANs, the PHY and MAC shall be implemented in accordance with IEEE 802.11p PHY and MAC [7]. At the side of wireless backbone, the PHY and MAC shall be implemented in accordance with IEEE 802.16 PHY and MAC [11].

Within wireless backbone, TMC serves as a Mesh base station (BS) and mesh routers serves as Mesh subscriber stations (SS). The bridge functionalities in mesh routers gather traffic data supplied by WANs, and make use of User Datagram Protocol (UDP) and Internet Protocol (IP) on top of IEEE 802.16 MAC to forward the data to TMC.

V. PERFORMANCE EVALUATION

We use computer simulation to evaluate the performance of WMN-based probe system in terms of arrival ratio and delay of data packets. The OPNET simulation tool is employed to simulate a bi-directional traffic road, whose length is 20 kilometers in each direction, with various number of probe vehicles running on it. As IEEE 802.11p is undergoing revision, IEEE 802.11a is adopted as DSRC technology instead of 802.11p in the simulation. The transmission range of DSRC is 1000 meters, and the transmission range of mesh routers is 5 kilometers. The probe vehicles broadcast a beacon message per 5 seconds, and send the traffic information per 30 seconds. We increase the number of probe vehicles gradually from 5 to 60 in the road. And two kinds of speeds, i.e. 20km/h and 60km/h, are involved.

We use the following scenarios for simulation:

Scenario 1: There is only one mesh router in the road.

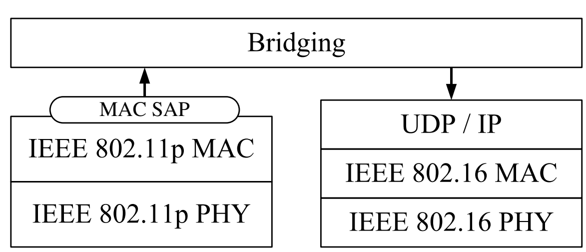

Fig. 6. Mesh router protocol stack

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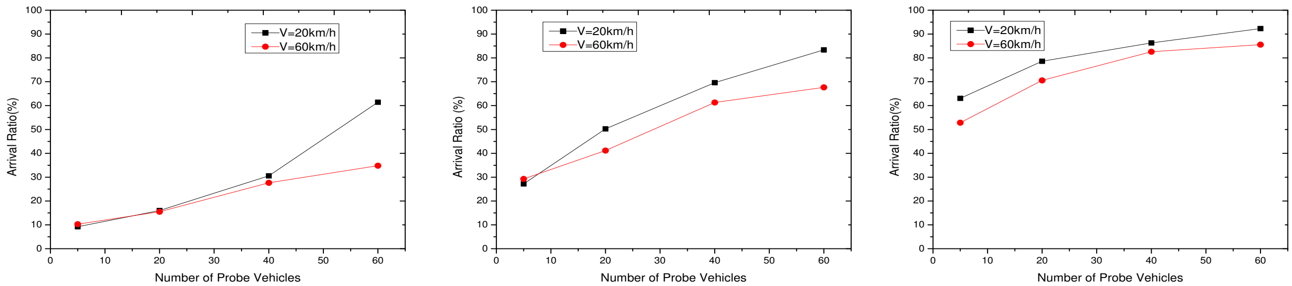
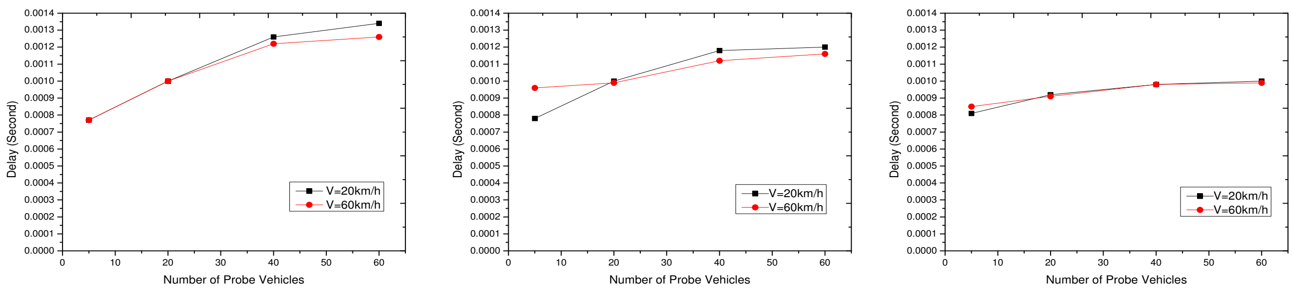


(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Fig. 7. Arrival ratio of data packets



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Fig. 8. Delay of data packets

Scenario 2: There are three mesh routers distributed in the road.

Scenario 3: There are six mesh routers distributed in the road.

In Figure 7, the arrival ratios of data packets are plotted against the number of probe vehicles under the three scenarios. Similarly, in Figure 8, the delays of data packets are plotted against the number of probe vehicles under the three scenarios. It is obvious that the network performance of WMN grows up as the number of vehicles increases, which is the result of connectivity enhancement. And the speed of vehicles has little impact on the network performance.

Actually, Scenario 1 is a pure VANET, so packet loss ratio is quite high. When the number of mesh routers increases, i.e., the wireless backbone is involved, the arrival ratios of data packets are improved greatly.

The delays of data packets are always about $1ms$ in the three scenarios, which is sufficient for the system requirement. However, the arrival ratio of packets seems to be not very satisfied. The main reason is that IEEE 802.11a is primarily designed for indoor WLAN applications, but the system environment is drastically different from the indoor low-mobility environment and its influences on the DSRC PHY performance are non-trivial. If IEEE 802.11p is adopted as DSRC technology, the network performance should be improved.

According to the simulation results, the system designers can obtain and adjust the corresponding parameters, including the number probe vehicles and mesh routers, to achieve the required arrival ratio and delay of data packets.

VI. Conclusion

In this paper, we propose a novel traffic information system based on a WMN to gather real-time speed, location and other sensing data directly from moving probe vehicles. We describe the system architecture and the design details of network protocols. The network performance is evaluated through computer simulations.

In the future, we are going to use more realistic vehicle mobility traces to study the network performance, and deploy a hardware-based testbed with 30 probe vehicles over Tsinghua campus.

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