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Mobile ad hoc networks for intelligent systems

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ABSTRACT

MOBILE AD HOC NETWORKS FOR INTELLIGENT SYSTEMS

by
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Advances in wireless technology and portable computing along with demands for high user mobility have provided a major promotion toward the development of ad hoc networks. Mobile ad hoc networks feature dynamic topology, self-organization, limited bandwidth and battery power of a node. They do not rely on specialized routers for path discovery and traffic routing. Research on ad hoc networks has been extensively investigated in the past few years and related work has focused on many of the layers of the communications architecture.

This research intends to investigate applications of MANET for intelligent systems, including intelligent transportation system (ITS), sensor network and mobile intelligent robot network, and propose some approaches to topology management, link layer multiple access and routing algorithms. Their performance is evaluated by theoretical analysis and off-the-shelf simulation tools.

Most current research on ad hoc networks assumes the availability of IEEE 802.11. However, the RTS/CTS protocol of 802.11 still leads to packet collision which in turn decreases the network throughput and lifetime. For sensor networks, sensors are mostly battery operated. Hence, resolving packet collision may improve network lifetime by saving valuable power. Using space and network diversity combination, this work proposes a new packet separation approach to packet collision caused by masked nodes

Inter-vehicle communication is a key component of ITS and it is also called vehicular ad hoc network. VANET has many features different from regular MANETs in terms of mobility, network size and connectivity. Given rapid topology changes and network partitioning, this work studies how to organize the numerous vehicular nodes and establish message paths between any pair of vehicular nodes if they are not apart too far away.

In urban areas, the inter-vehicle communication has different requirements and constraints than highway environments. The proposed position-based routing strategy for VANETs utilizes the traffic pattern in city environments. Packets are forwarded based on traffic lights timing sequence and the moving direction of relaying vehicles. A multicast protocol is also introduced to visualize the real time road traffic with customized scale. Only vehicles related to a source node's planned trajectory will reply the query packet. The visualized real time traffic information therefore helps the driver make better decision in route planning when traffic congestion happens.

Nowadays robots become more and more powerful and intelligent. They can take part in operations in a cooperative manner which makes distributed control necessary. Ad hoc robot communication network is still fresh field for researchers working on networking technology. This work investigates some key issues in robot ad hoc network and evaluate the challenges while establishing robot ad hoc networks.

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by
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To My Beloved Parents and My Wife

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CHAPTER 1

MOBILE AD-HOC NETWORKS AND INTELLIGENT SYSTEMS

1.1 Introduction

Mobile wireless networking has been experiencing dramatic development in popularity over the past decade. As VLSI technology advances and computing power increased in the past twenty years, mobile terminals became more and more intelligent, robust and consumed less and less power. Moreover, they are required to handle more and more so-called teamwork. Multihop packet radio networks, or mobile ad hoc networks (MANET), are an ideal technology to establish "instant" communication infrastructure for many military and civilian applications. Every node in MANET is a mobile host as well as a mobile router which is automatically configured to relay messages destined to other nodes. Once an intermediate node is down, a new data delivery path is quickly established without degrading the network performance. There is no central control unit for MANET to allocate resources and all nodes carry out tasks in a cooperative way. In other words, MANET is robust and flexible to link failure.

MANET takes a key role in many critical tasks such as disaster relief, environment monitoring, and surveillance due to their quick deployment and robustness nature. Moreover, some other applications of mobile ad hoc networking technology may include industrial and commercial applications involving mobile data exchange as well as many existing applications for IP-compliant data services within mobile wireless communication networks. The goal of mobile ad hoc networking technology is not only operated as alternatives or enhancement to cellular wireless networks, but to form network routing infrastructures with independent wireless mobile nodes in an ad hoc fashion.

1.2 Related Work

MANET has been extensively investigated in the past few years and related work in MANET has focused on many layers of the communications architecture. Most research results can be categorized according to architectural layers.

1.2.1 Link Layer

The link layer must address a number of important issues related to bandwidth utilization. For example, it must address congestion control, latency, throughput, fairness, and scalability with respect to the number of mobile nodes. Two issues that have been extensively studied at the link layer are the complementary problems of hidden and exposed nodes, and their effect on throughput [Xu and Saadawi 2001].

Hidden nodes are two nodes that, although they are outside the interference range of one another, share a set of nodes that are within the transmission range of both as shown in Figure 1.1.

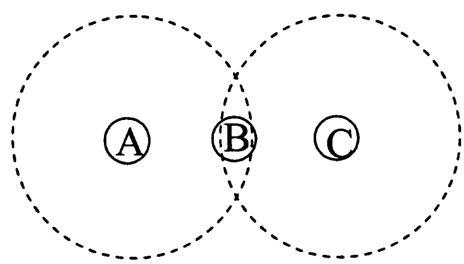

Figure 1.1 Hidden nodes.

Nodes A and C are outside the transmission range of each other. If both attempt to transmit at the same time, they will cause a collision at B. Exposed nodes, on the other hand, are nodes that are within interference range of each other. As shown in Figure 2, although A and C are within interference range of each other, A could transmit to B and C could transmit to D without causing a collision at either B or D. However, since they are within interference range of each other, only A or C would transmit at a time. The effect of hidden nodes on throughput is handled by request-to-send/clear-to-send (RTS/CTS) handshaking. However, exposed nodes are difficult to address and present one of the most important factors in limiting network throughput.

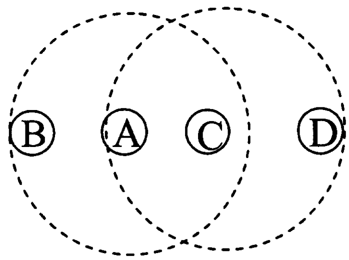

Figure 1.2 Exposed nodes.

One way to increase network throughput is to increase the number of nodes in the network. One study with random mobility notes that an increase in network size while holding traffic load constant yields increased throughput [Perkins, Hughes, and Owen 2002].

1.2.2 Routing Layer

At the routing layer, MANET research has focused on the development of three broad classes of routing protocols, analysis of these approaches under various mobility models, and attempts to manage mobility-related routing issues.

MANET routing protocols, which do not use nodal position data, can be classified as table-driven and on-demand [Royer and Toh 1999]. Table-driven protocols, Destination Sequence Distance Vector (DSDV) for example, are proactive in the sense that each node attempts to maintain a current representation of the network topology. On-demand protocols, on the other hand, are reactive in the sense that routes are requested by source nodes only when needed. Table-driven protocols provide lower message latency because routes are immediately available. However, the overhead required to maintain these routes consumes bandwidth and restricts the scalability of these protocols.

Another class of routing protocols uses position-based information for routing decisions [Mauve, Widmer and Hartenstein 2001]. A location service may then be necessary to find the location of a destination node. These protocols also naturally support geocasting. In location-based multicast, the set of recipients is defined as nodes located in some target region of space. A number of mobility models have been used to analyze routing protocols. Among the most commonly used is the random waypoint model. In this model, nodes move in a random direction for a random amount of time, pause for some period of time, and then choose a different direction. Another approach at a more realistic mobility model is scenario-based mobility, which considers scenarios of people moving at a sporting event, in a disaster area, and at a conference.

Mobility presents a number of problems for MANETs, including short-lived paths between nodes and network partitioning. On-demand routing protocols attempt to manage short-lived paths by using nodal mobility information to predict the stability of routes.

1.2.3 Security

Because MANET lacks a fixed infrastructure and may rely on untrustworthy nodes for the propagation of control and data messages, securing a MANET is very difficult. Research for the security control of MANET has included secure routing protocols, secure transport protocols, and intrusion-detection systems.

Secure routing proposals adopt cryptographic techniques, including hash chains and digital signatures, to ensure the validity of routing messages [Papadimitratos and Haas 2002][Hu, Perrig and Johnson 2002][Zhang and Zhou 2002]. By increasing message size, these protocols limit available bandwidth. However, for stable routes, this additional load may not be significant.

Since the transport of messages may rely on untrustworthy nodes, not only are routing messages subject to corruption, but also data messages are. Secure message transport (SMT) attempts to address this problem by utilizing the redundancy in the network [Papadimitratos and Haas 2002]. SMT cryptographically splits a message into n parts and sends each part over a distinct path. As long as k pieces are received, the message can be decoded. SMT, therefore, requires multiple independent paths between a source and a destination and spares bandwidth.

Intrusion-detection systems for MANET attempt to identify nodes that are acting maliciously by fabricating, dripping, or altering control or data messages [Marti, et al 2000]. In these systems, nodes overhear their neighbors' broadcast in order to ensure that these neighbors are acting appropriately.

1.3 Motivation and Contribution

This research intends to investigate the applications of MANET to intelligent systems and propose innovative ways to topology management, link layer multiple access and routing. Their performance is evaluated by theoretical analysis and off-the-shelf simulation tools. The specific systems studied are intelligent transportation system (ITS), sensor networks, and mobile intelligent robot networks.

One main objective of intelligent transportation systems is to enable safe and smart driving to be feasible while maximizing transportation efficiency. Inter-vehicle communication is a key component of ITS and actually it is also called vehicular ad hoc network (VANET). VANET has many features different from regular MANETs in terms of mobility, network size and connectivity. Due to the inherent nature of quick topology changes, centric control communication is almost impossible and therefore the ad hoc fashion is an attractive choice. Given rapid topology changes and network partitioning, this proposal studies how to organize the numerous vehicular nodes and establish message paths between any pair of vehicular nodes if they are not apart too far away.

Most current research on ad hoc networks assumes the availability of IEEE 802.11. However, as discussed in Chapter 2, it still leads to packet collision which in turn decreases the network throughput and lifetime. For sensor networks, sensors are mostly battery operated. Hence, resolving packet collision may improve network lifetime by saving valuable power.

Nowadays robots become more and more powerful and intelligent. They can take part in operations in a cooperative manner which makes distributed control necessary. Ad hoc robot communication network is still fresh field for researchers working on networking technology.

This proposal is organized as follows; Chapter 2 studies the masked node problem and proposes a new signal separation algorithm using space and network diversities. The performance is evaluated through analytical results and simulations results. Chapter 3 investigates the topology management for inter-vehicle communication and a new position-based clustering approach is introduced. In Chapter 4 a new epidemic routing method is proposed in order to deliver messages between two vehicular nodes if the network is partitioned. Chapter 5 gives a detailed overview of mobile robot communication networks and analyzes the design objectives for future research. At last some conclusions are summarized in Chapter 6.

CHAPTER 2

COMBINING SPACE AND NETWORK DIVERSITY TO RESOLVE MASKED NODE COLLISION IN WIRELESS NETWORK

2.1 Introduction

In wireless ad hoc networks, the most commonly chosen Media Access Control protocol is Carrier Sense Multiple Access (CSMA) due to its simplicity and scalability. However CSMA is susceptible to the hidden node problem, which is caused by limited radio transmission range, and therefore a node cannot communicate with another node which is outside of the receiving range. This results in costly data packet collision and becomes one of the important problems to be resolved in wireless network [Tobagi and L. Kleinrock 1975]. To avoid such expensive collision, IEEE 802.11 wireless network standards proposed RTS/CTS handshaking protocol (CSMA/CA). Note that RTS means Request-To-Send and CTS stands for Clear-To-Send. However, although this RTS-CTS protocol solves the hidden node problem, it leads to other issues, such as masked nodes, which adversely affect the throughput of the network [Carruthers, Ray and Starobinski 2003]. As mentioned before, an exposed node problem inherently occurs in any contention-based multiple access networks and leads to inefficiency in terms of throughput. The RST/CTS protocol apparently cannot solve it while using network allocation vector to assign channels for nodes.

Better approaches to resolving and separating collision were found to improve the throughput and performance of the system [Zhao, Tong and Mergen 2001]. To avoid a masked node problem, the receiver at a given node is designed to extract data from the signals of interested users. The key component to the successful signal separation is the redundancy embedded in the received data packages. Such redundancy can be introduced at the transmitter as well as receiver. The transmitting diversity introduces redundancy into the data packages using techniques mainly at the physical layer (modulation, coding, and spreading) as well as network layers (retransmissions). The spatial diversity is a well-known technique in communication for reliable signal reception over wireless fading channels. The use of antenna array also provides additional degrees of freedom for multipacket reception and collision separation [Paulraz and Papadias 1997]. The multiuser detection [Verdu 1998], by exploiting signal structure embedded in the data packets, is the essence of many signal separation methods. These techniques, such as transmitting diversity, receiving diversity, and multiuser detection, are mainly implemented in the physical layer. In addition, the recent research also uses network resources to provide diversity through selective retransmission [Zhang, Tsatsanis and Banerjee 2000].

Zhang, Tsatsanis and Banerjee's work [2000], employing antenna array at a receiving node, allows the separation of colliding packages when the number of active transmitting nodes is less than the number of the antennas. However, with the increase of the active transmitting nodes, the receiving node cannot extract the data simply using spacial diversity, resulting in collision. Using the proposed scheme, the received packets in collision (previously stored in memory) are combined with future selective retransmissions to enable the separation of colliding packets [Liu and Ge 2004]. This work combines the diversities provided by different protocol layers, investigates the collision detection problem and constructs the steady state model via a Markov chain model. This chapter studies the performance of a network using the proposed Space and Network Diversity Combining method.

2.2 Problem Statement

2.2.1 Hidden Nodes and RTS-CTS Mechanism in IEEE 802.11

If a node is located within the transmission range of the receiver but not of the sender, it does not hear the packet exchange and may start sending packets to the same receiver. This results in costly data packet collision. Such a node is called a hidden node. By using a RTS-CTS handshake mechanism, when node 1 wants to transmit a data packet to node 2, it first sends a small control packet RTS as illustrated in Figure 2.1. Node 2, upon receiving it, replies with another control packet called CTS. The neighboring nodes, in this case, nodes 0 and 3 that hear either RTS or CTS set their network allocation vector (NAV) and defer any of their transmission till this transmission is over. The deferral period is given by the corresponding RTS and CTS. After receiving CTS, node 1 transmits its data packet to node 2 that replies with acknowledgement (ACK). If a node does not get a reply for its RTS or data packet, it enters an exponential back off mode before retransmission.

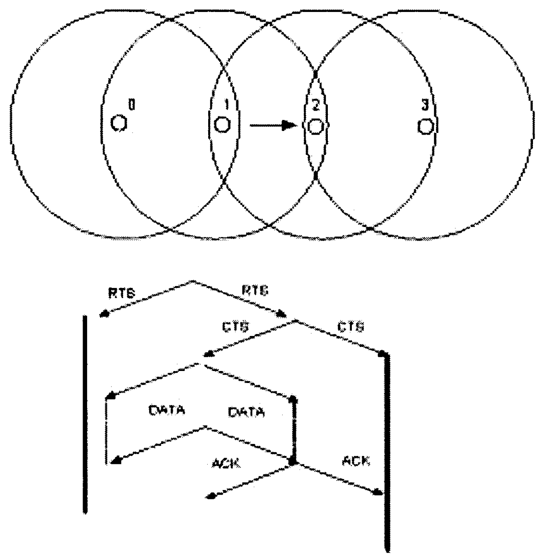

Figure 2.1 RTS/CTS handshaking protocol.

2.2.2 Masked Nodes

RTS-CTS handshake is aimed to solve the hidden node problem with the assumption that every node in the transmission range would hear the RTS or CTS and defer transmission accordingly. However the assumption is not always true. All nodes in this range may not decode RTS or CTS correctly due to other ongoing transmission. If a node receives two or more signals simultaneously, it generally cannot decode them. Such a node is referred to as a masked node, such as node 2 shown in Fig 2.2. Though masked nodes do not cause data packet collision, they lead to data packet or Ack packet collision with an RTS or CTS.

For example, consider a wireless network shown as in Fig. 2.2. Assume that node 3 wants to transmit data to node 4 and they exchange RTS-CTS successfully. Node 2 receives RTS and then set its NAV. Node 0 which cannot hear data transmission from node 3 to node 4, it sends RTS to node 1, and node 1 replies with CTS. Node 0 receives the CTS correctly. However node 2 does not receive and decode this CTS correctly because it is in the deferred mode already. Node 2 will send RTS after its deferral period. This RTS reaches node 1 and collides with the data packet from node 0.

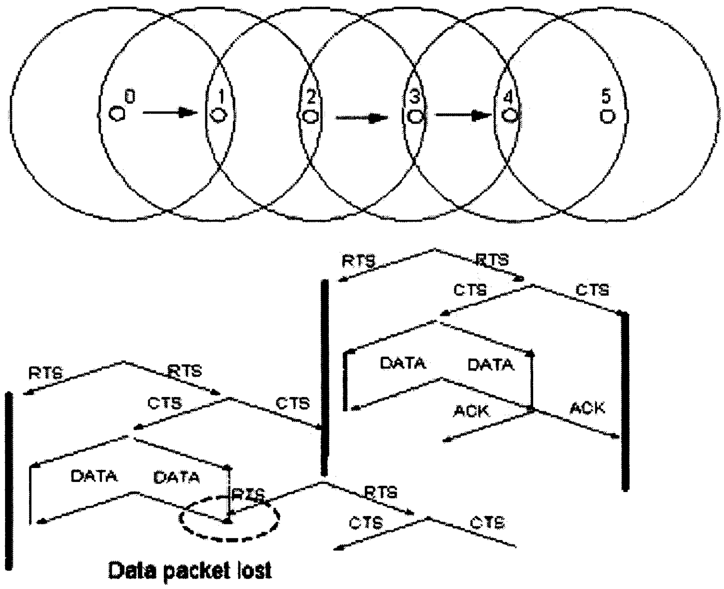

Figure 2.2 Data packet loss scenario due to masked node.

2.2.3 System Model for Packet Collision

Consider a wireless ad hoc network with K active transmitting nodes, each using a slotted random access scheme. Specially, node k transmits a length-N data packet, $d_k(n) = [d_k(n+1), \cdots, d_k(n+N)]^T$ during the n-th time slot. Assume that the receiving node uses an antenna array of M sensors. Within the n-th time slot, the data vector received by the m-th antenna can be modeled as,

$$\mathbf{y}_m(m) = \sum_{k=1}^{K} a_{k,m}(n)\mathbf{d}_k(n) + \mathbf{v}_m(n) \tag{2.1}$$

where $a_{k,m}(n)$ denotes the channel gain (a real-valued Gaussian random variable) between the k-th transmitter (node) and m-th antenna, vector $v_m(n)$ is the real-valued addictive white Gaussian noise at the m-th antenna. The total received data from all M sensors within the n-th time slot, collected in an N×M matrix, can be modeled as

$$
\begin{aligned}
\mathbf{Y}(n) &= [\mathbf{y}_1(n) \ \cdots \ \mathbf{y}_M(n)] \\
&= \begin{pmatrix} d_1(n) & \cdots & d_K(n) \\ \vdots & \ddots & \vdots \\ d_1(n+N) & \cdots & d_K(n+N) \end{pmatrix} \begin{pmatrix} a_{11}(n) & \cdots & a_{1M}(n) \\ \vdots & \ddots & \vdots \\ a_{K1}(n) & \cdots & a_{KM}(n) \end{pmatrix} + \begin{pmatrix} v_1(n) & \cdots & v_M(n) \\ \vdots & \ddots & \vdots \\ v_1(n+N) & \cdots & v_M(n+N) \end{pmatrix} \\
&= \mathbf{D}(n)\mathbf{A}(n) + \mathbf{V}(n)
\end{aligned}
\tag{2.2}
$$

where A(n) is a K × M mixing matrix with $a_k^T(n) = [a_{k,1}(n), \cdots, a_{k,M}(n)]$, k = 1,2,….,K as its rows; the N × K matrix D(n) = [d_1(n),…., d_k(n)] contains K colliding packages; and V(n) = [v_1(n) …v_M(n)] is the noise matrix.

In the network using RTS-CTS protocols, when a collision is detected, the whole packet Y(n) is discarded and the system initiates a retransmission schedule. However, the data matrix Y(n) contains information of all colliding packets. Hence, it should be exploited with the help of additional data transmission for collision resolution. Based on these, this work proposes a collaborative approach to combining the spatial diversity with the network assisted diversity to separate and extract information from received data packets in collision.

2.3 Collision Resolution Through Signal Separation

2.3.1 Space and Network Diversity Combination

In principle, collision resolution is equivalent to signal separation. Consider the case when K transmitting nodes collide in a given time slot n. The receiver is equipped with an array with M receiving sensors. With the network layer knowledge, all transmitting nodes are aware of that a collision with multiplicity K occurs during the time slot n. Therefore, each of the K nodes has to retransmit its information packet L more times in the next L - 1 slots, i.e., slots n + 1,... , n + L -1, [Haykin 1996].

$$L = \left\lceil \frac{K}{M} \right\rceil \tag{2.3}$$

where [•] is the integer part of a fraction.

No other nodes transmit a new packet in the next L-1 slots. The receiver receives a total of L × M copies of the colliding packets with these conventions.

$$Y(n) = D(n)A(n) + V(n)$$

where data *Y(n)* is *N* ×*(ML)* matrix, the channel gain *A(n)* is *K* ×*(ML)* matrix and noise *V(n)* is *N* ×*(ML)* matrix. If the mixing matrix *A(n)* is known or can be estimated, the maximum likelihood estimation of the transmitted packets is

$$\hat{\mathbf{D}}(n) = \arg\min_{\mathbf{D}} \left\| \mathbf{Y}(n) - \mathbf{D}\mathbf{A}(n) \right\|_F^2 \tag{2.4}$$

where $\|\bullet\|_F$ represents the Frobenius norm, and *D* takes all possible finite values. Since *ML*≥ *K*, the least square solution yields [Bersekas and R. Gallager 1992],

$$\hat{\mathbf{D}}(n) = \mathbf{Y}(n)\mathbf{A}^T(n)\left(\mathbf{A}(n)\mathbf{A}^T(n)\right)^{-1} \tag{2.5}$$

2.3.2 Collision Detection and Signal Separation

For a given time slot n, the receiver has to discriminate all the active transmitting nodes. There are 2*J* different possibilities in a J-transmitting nodes system. A unique ID sequence for each node contained in the packet is required in order to enable the receiver to uniquely identify all the active transmitting nodes. Assume that the first Q symbols of each packet of node k is the ID sequence, that is $\overline{d_k} = [d_k(n)]_{1:Q}$, The corresponding received data is,

$$\overline{y_m}(n) = \sum_{k=1}^{K} a_{k,m}(n)\overline{d_k} + \overline{v_m}(n) \tag{2.6}$$

where $\overline{y}_m(n) = [y_m(n)]_{1:Q}$, and $\overline{v}_m(n) = [v_m(n)]_{1:Q}$. From the above data, it is observed that the estimation of $a_{k,m}(n)$ from the received data $\overline{y}(n)$ is related to a least square (LS) problem. Assume that the ID sequences are orthogonal to each other.

$$\overline{d}_k^T \overline{d_l} = \begin{cases} 0 & k \neq l \\ 1 & k = l \end{cases} \tag{2.7}$$

The matched-filter output $z_{k,m}(n)$ associated with $\overline{d_k}$ is

$$z_{k,m}(n) = \overline{d}_k^T \overline{y}_m(n) = a_{k,m}(n) + \overline{d}_k^T \overline{v}(n) \tag{2.8}$$

Therefore vector $z_m(n) = [z_{1,m}(n), \cdots, z_{K,m}(n)]^T$ forms the sufficient statistic for estimating the node gain $a_m(n) = [a_{1,m}(n), \cdots, a_{K,m}(n)]^T$ for the mth antenna. Therefore,

$$\widehat{a_m}(n) = z_m(n) \tag{2.9}$$

From the estimation of the channel gain, one may compose the mixing matrix *A(n)* and recover the data packets according to (2.9). Define the two hypotheses for user k: $H_{k,0}$ stands for that inactive user k is active and $H_{k,1}$ corresponds to that user k is not active. The probability density of $y_m(n)$ under each hypothesis follows

$$p(\overline{y_m}(n) \mid H_{k,0}) = \frac{1}{2\pi\sigma^2} \exp\left(\frac{-\left|z_{k,m}(n)\right|^2}{2\sigma_v^2}\right) \tag{2.10}$$

$$p(\overline{y_m}(n) \mid a_{km}(n), H_{k,1}) = \frac{1}{2\pi\sigma^2} \exp\left(\frac{-\left|z_{k,m}(n) - a_{km}(n)\right|^2}{2\sigma_v^2}\right) \tag{2.11}$$

and the likelihood ratio is

$$\Lambda(\overline{y_m}(n) \mid a_{km}(n)) = \frac{p(\overline{y_m}(n) \mid a_{km}(n), H_{k,1})}{p(\overline{y_m}(n) \mid H_{k,0})} \tag{2.12}$$

$$= \exp\left(\frac{z_{k,m}(n)a_{km}^*(n) + z_{km}^*(n)a_{km}(n)}{2\sigma_v^2}\right) \bullet \exp\left(\frac{|a_{km}(n)|^2}{2\sigma_v^2}\right)$$

The optimal detector is determined by

$$|z_{k,m}(n)| \underset{H_{k,0}}{\overset{H_{k,1}}{\lessgtr}} T \tag{2.13}$$

The probability of false alarm P_F under the Additive White Gaussian Noise channel and the probability of detection P_D are

$$P_F = \int_T^\infty \frac{x}{\sigma_v^2} \exp\left(-\frac{x^2}{2\sigma_v^2}\right) dx = \exp\left(-\frac{T^2}{2\sigma_v^2}\right) \tag{2.14}$$

$$P_D = \int_T^\infty \frac{x}{\sigma_v^2} \exp\left(-\frac{x^2 + a_{k,m}^2(n)}{2\sigma_v^2}\right) I_0\left(-\frac{a_{k,m}(n)^2}{2\sigma_v^2} x\right) dx = M\left(-\frac{a_{km}(n)T^2}{\sigma_v}, \frac{T}{\sigma_v}\right) \tag{2.15}$$

2.4 Performance Analysis

2.4.1 Markov Chain and Steady State Model for One User

Consider user k in the network. Define the state as the number of data packets in this user's buffer, and the transmission period for one packet as τ. The traffic load follows Poisson distribution with an average λ packets per τ. The buffer size N is limited. If buffer is full, an arrival does not enter the node and leaves instead.

The probability that there are k data packets entering the buffer during time τ is:

$$P(N(t+\tau) - N(t) = k) = \frac{(\lambda\tau)^k}{k!} e^{-\lambda\tau} \tag{2.16}$$

The probability of state i changed into state $i + k$ can be represented by two probabilities. The first is the probability of k packets coming into the buffer and the transmission failing. The second is the probability of $k+1$ packets coming into the buffer and transmission succeeding.

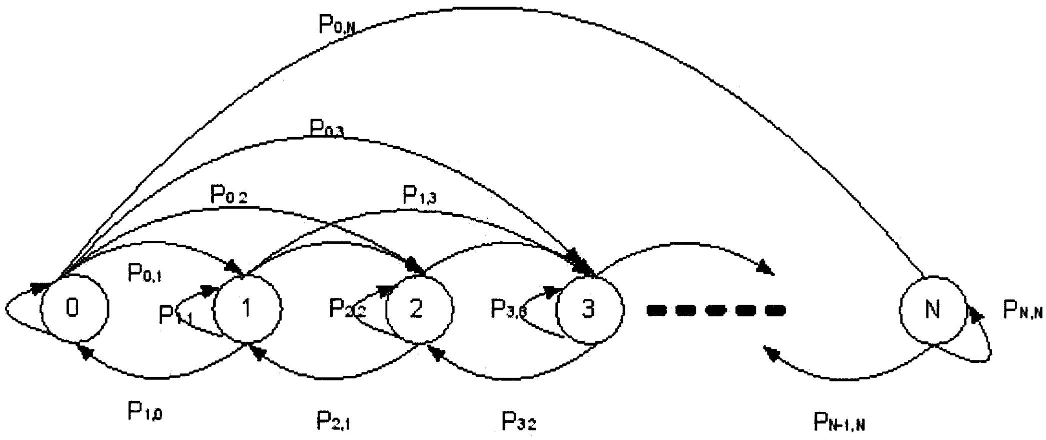

Figure 2.3 A Markov chain model.

$$P_{i,i+k} = \frac{(\lambda\tau)^k}{k!} e^{-\lambda\tau} P_{FT} + \frac{(\lambda\tau)^{k+1}}{(k+1)!} e^{-\lambda\tau} P_{ST} = \frac{(\lambda\tau)^k}{k!} e^{-\lambda\tau}(1-P_{ST}) + \frac{(\lambda\tau)^{k+1}}{(k+1)!} e^{-\lambda\tau} P_{ST} \tag{2.17}$$

where the packet failure probability in transmission is $P_{FT}=1-P_{ST}$, P_{ST} is the successful transmission probability $P_{ST}=(1-P_e)^L$, where L is the length of the packet and P_e is the bit error rate.

Note that the probability of state i changed into state N is

$$\begin{aligned} P_{i,N} &= \sum_{k=N-i}^{\infty} \frac{(\lambda\tau)^k}{k!} e^{-\lambda\tau} P_{FT} + \sum_{k=N-i+1}^{\infty} \frac{(\lambda\tau)^k}{k!} e^{-\lambda\tau} P_{ST} \\ &= \frac{(\lambda\tau)^{N-i+1}}{(N-i+1)!} e^{-\lambda\tau} P_{ST} + e^{-\lambda\tau}[1-\sum_{k=0}^{N-i-1}\frac{(\lambda\tau)^k}{k!}] \end{aligned} \tag{2.18}$$

The probability of state i changed into state $i-1$ equals the probability that no packet comes into the buffer and the transmission is successful

$$P_{i,i-1} = P(i-1 \mid i) = \frac{(\lambda\tau)^0}{0!} e^{-\lambda\tau} P_{ST} = e^{-\lambda\tau} P_{ST} \tag{2.19}$$

The probability that state i does not change $P_{i,i}$ =P(i|i) equals the probability that no packet arrivals and the transmission fails plus the probability that one packet arrives and the transmission succeeds.

$$\begin{aligned} &P_{i,i} = P(i \mid i) = e^{-\lambda\tau}(1-P_{ST}) + \lambda\tau e^{-\lambda\tau} P_{ST}, \\ &\forall i \in \{1, 2, \cdots, N-1\} \end{aligned} \tag{2.20}$$

The system can be modeled as a Markov chain with states 0,1,…, N and the transitional probability $P_{i,j}$. The corresponding transition probability matrix is

$$\mathbf{P} = \begin{bmatrix} P_{0,0} & P_{1,0} & 0 & \cdots & 0 \\ P_{0,1} & P_{1,1} & P_{2,1} & \cdots & 0 \\ P_{0,2} & P_{1,2} & P_{2,2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{0,N} & P_{1,N} & P_{2,N} & \cdots & P_{N,N} \end{bmatrix} \tag{2.21}$$

Define the probability of stationary distribution of the whole system as $\boldsymbol{\pi} = [\pi_0 \cdots \pi_N]^T$, then

$$\begin{cases} \boldsymbol{\pi}\mathbf{P} = \boldsymbol{\pi} \\ \pi_0 + \pi_1 + \cdots + \pi_N = 1 \end{cases} \tag{2.22}$$

and it can be written as

$\mathbf{A}\boldsymbol{\pi} = \mathbf{b}$

where

$$\mathbf{A} = \begin{bmatrix} P_{0,0} & P_{1,0}+1 & 1 & \cdots & 1 \\ P_{0,1} & P_{1,1}-1 & P_{2,1} & \cdots & 0 \\ P_{0,2} & P_{1,2} & P_{2,2}-1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{0,N} & P_{1,N} & P_{2,N} & \cdots & P_{N,N}-1 \end{bmatrix} \tag{2.23}$$

and b=[1 0 … 0]T, then $\boldsymbol{\pi} = \mathbf{A}^{-1}\mathbf{b}$

2.4.2 Throughput Analysis

Consider the traffic in the channel as a flow of collision resolution periods or epochs. An epoch includes one or several consecutive channel slots that are dedicated to the transmission (including the initial transmission and retransmissions) of the data packets from the nodes who are active at the beginning of the epoch. The idle slots, during which no data is transmitted, also compose epochs called idle epochs. Correspondingly, they are called, during which some packets are under transmission, busy epochs. The length of a busy epoch is the number of time slots the channel takes to serve the currently active transmitting nodes. The epoch length is a random variable depending on the number of the active transmitting nodes at the beginning of the epoch. Since π_0 is the probability of a transmitting node's buffer being empty at the beginning of an epoch, one can obtain the probability that one epoch is busy or idle,

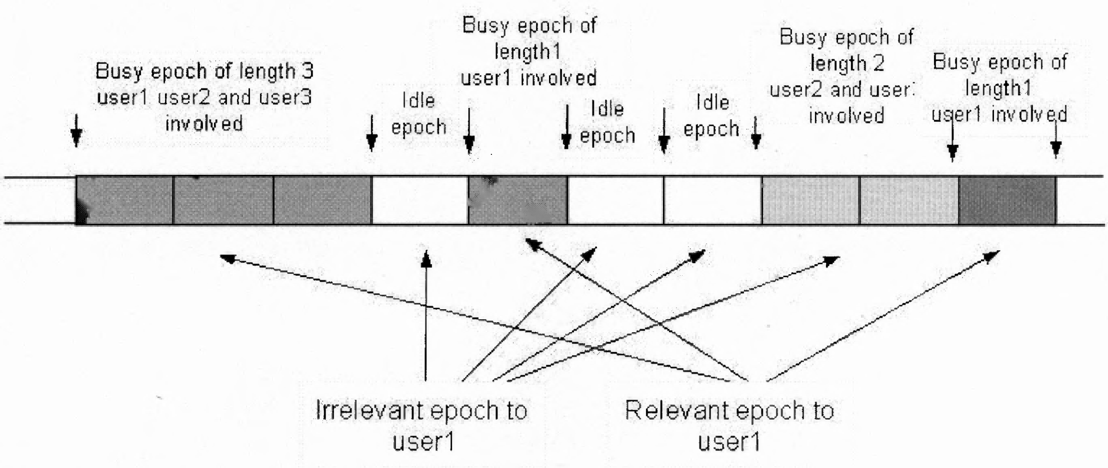

Figure 2.4 Epoch flow and types of epoch.

$$P_{busy}(k) = \binom{J}{k}(1-\pi_0)^k \pi_0^{J-k} \quad P_{idle}(k) = \begin{cases} \pi_0^J & k = 1 \\ 0 & otherwise \end{cases} \tag{2.24}$$

where k = 1,2,..., J is the number of active transmitting nodes and J is the total number of transmitting nodes in the network.

Define the throughput as

$$R = \frac{\text{average length of busy epoch}\bullet(1\text{-P}_e)}{\text{average length of (busy or idle) epoch}} \tag{2.25}$$

Then

$$R = \frac{\sum_{k=1}^{J} k \binom{J}{k} (1-\pi_0)^k \pi_0^{J-k} \cdot (1-P_e(k))}{\sum_{k=1}^{J} k \binom{J}{k} (1-\pi_0)^k \pi_0^{J-k} + 1 \cdot \pi_0^J} \tag{2.26}$$

2.4.3 Delay Analysis

From the viewpoint of a particular transmitting node, two types of epochs (Fig. 2.4) can be distinguished: relevant epochs, in which a data packet belonging to this node is being transmitted, and irrelevant epochs, in which no packet belonging to this node is being transmitted. The lengths of two types of epochs, denoted by l_r and l_i, obey different distributions,

$$P_{lr}(L) = \binom{K-1}{J-1} (1-\pi_0)^{K-1} \pi_0^{J-K} \qquad 1 \le K \le J \tag{2.27}$$

$$P_{li}(L) = \{ \begin{array}{ll} \pi_0^{J-1} + (J-1)(1-\pi_0)\pi_0^{J-K} & K = 1 \\ \binom{K}{J} (1-\pi_0)^K \pi_0^{J-K-1} & 1 \le K \le J-1 \end{array} \tag{2.28}$$

where L = K in Network Diversity Multiple Access scheme, and for SNDC approach L is chosen according to the definition in 2.3.

A transmitting node's buffer can also be modeled as an M/G/1 queue with vacation, in which the relevant and irrelevant epochs play the role of the service time and vacation time respectively. According to the property of the M/G/1 queue with vacation, the average system delay (including the waiting time in the buffer and the transmitting time in the channel) for a data packet can be expressed as

$$D = \bar{l}_r + \frac{\lambda \overline{l_r^2}}{2(1-\lambda \bar{l}_r)} + \frac{\overline{l_i^2}}{2\bar{l}_i} \tag{2.29}$$

where packet arrival is a Poisson process with rate λ, $\bar{l}_r$, $\overline{l^2}$, $\bar{l}_i$ and $\overline{l_i^2}$ are the first and second moments of the relevant and irrelevant epoches, respectively, and can be computed from their distribution.

2.5 Simulation

To observe the performance of the SNDC method, this work compares it with the NDMA method through simulation. Consider a slotted data communication system. Its total number of users is J = 32, and users' ID sequences are selected from the Jth order Hadamard matrix. The length of the ID sequence is Q = 32. The number of the receiving antenna is M = 2. The user packets are of fixed length N = 424 bits (equal to the length of an ATM cell).

Two groups of experiments are carried out. In the first one, the number of active users is fixed K = 5, the SNR change for different approaches. In the second one, the simulation is carried under four SNR cases: (a) 5dB, (b) 10dB, (c) 20dB and (d) 30dB. Under each scenario, the number of active users in system changes. Figure 2.5 shows the simulation result of bit error rate versus signal to noise ratio. In this case, it is observed that the SNDC approach significantly outperforms the NDMA method for the same SNR. The delay performance is shown in Figures 2.6-2.7 as a function of the traffic load. The analytical and simulation results demonstrate that SNDC is better than NDMA in terms of their delay performance. Both are much better than TDMA and ALOHA. The analytical results of throughput versus total traffic load according to (20) are shown in

Figure 2.8. The simulation results as shown in Figure 2.8 shows the throughput versus total traffic load, J as SNR changes from 5dB to 30dB. Under each case, the system was run for time equivalent to 10000 channel slots. The performance of the proposed method is better than NDMA, especially in low SNR. It is also observed that the simulation results are in good agreement with the analytical ones.

2.6 Summary

A new cross-layer design approach for diversity combination is presented in this chapter. The proposed collision resolution scheme to multiple access in wireless network is based on the combination of space and network assisted diversity. The diversity is fully exploited by the receiver for collision resolving and package separation. The collision packets can be separated so that the masked node problem is nicely solved. It is demonstrated that this approach can extract the useful information from colliding packets. Both analytical and simulation results conclude that the proposed SNDC method outperforms NDMA in terms of throughput and delay performance.

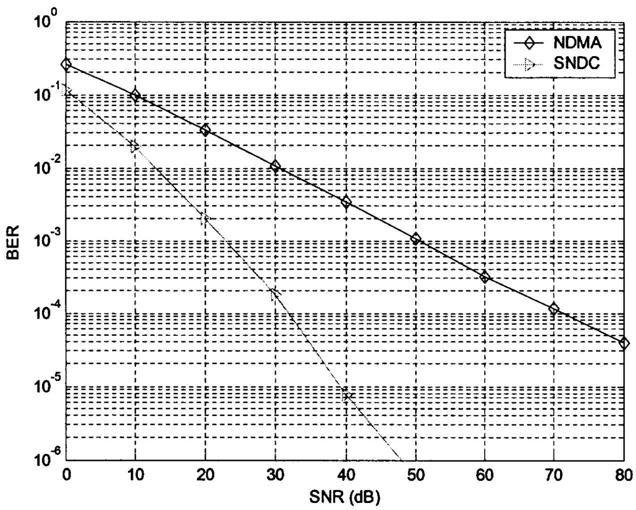

Figure 2.5 Performance comparison between different collision resolution approaches. System parameters: J = 32, M = 2, and the number of active users K = 5.

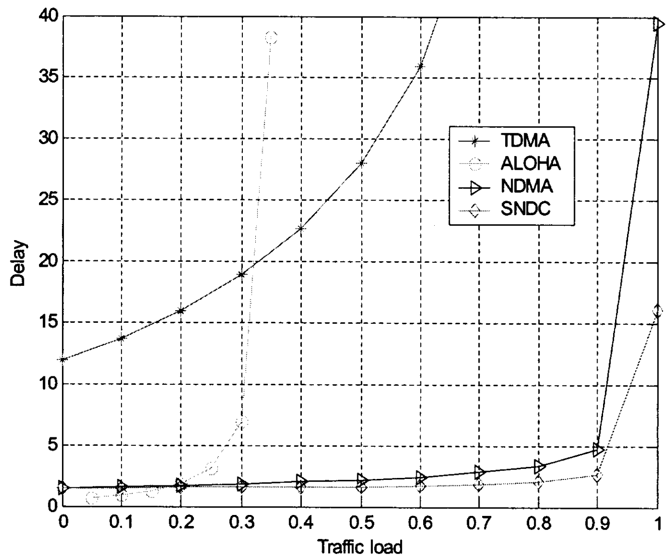

Figure 2.6 Analytical performance comparison (delay vs. traffic load).

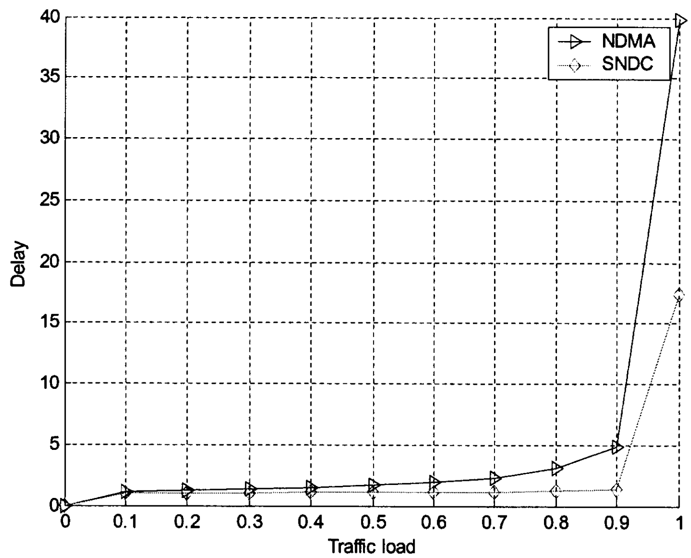

Figure 2.7 Simulation performance comparison (delay vs. traffic load).

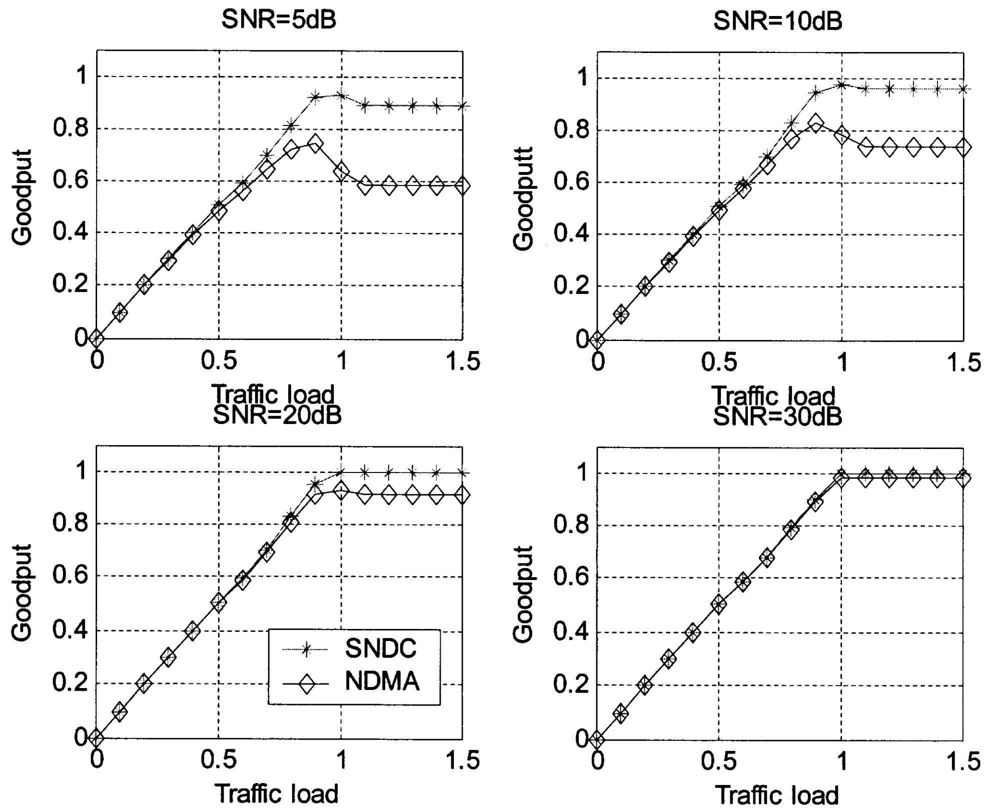

Figure 2.8 Simulation results: throughput vs. traffic load (J = 32, M = 2). (a) SNR=5 dB (b) SNR=10dB (c) SNR=20dB (d) SNR=30dB.

CHAPTER 3

A POSITION-BASED CLUSTERING TECHNIQUE FOR AD-HOC INTER-VEHICLE COMMUNICATION

3.1 Introduction

The increasing availability of wireless technologies presents a great chance for the automotive industry. Vehicles are no longer isolated systems since their communications with the outside world enable completely new types of applications. In recent years, intelligent transport systems (ITS) have been investigated and many kinds of technologies have been developed for ITS [Aoki and Fuji 1996][Nakao et al 1999][Kamijo 1999]. The inter-vehicle communication is one of the four communication systems defined in ITS system architecture [U.S. DOT 1999]. The inter-vehicle communication enables each driver or each vehicle to communicate with other vehicles at any location at any time. They can extend the horizon of a driver and automated systems, which will benefit from the inter-vehicle communication in terms of safety and efficiency of the road traffic.

In vehicle-to-vehicle communication, network topology may change randomly and rapidly at unpredictable times because vehicle positions constantly change. Therefore, centralized control by a base station is not feasible, and autonomous decentralized control is required. Ad hoc networks formed by rapidly deployable, short range wireless devices, such as those based on IEEE 802.11 wireless LAN standard, are well suited for moving vehicles. Their deployment on individual vehicles doesn't require any infrastructure; also, ad hoc routing adapts to node mobility. Ad-hoc networking in the vehicular environment was investigated [Jeremy 2004][Kosch 2001][Hannes 2001]. The ad-hoc connection of vehicles within a limited area can make message dissemination more flexible because of its self-organizing property. Two passing cars can exchange data (single hop), or data can pass several other cars when they act as routers/relays (multihop). With this principle, highly efficient accident warning systems are possible; cars involved in an accident can send warning messages back over a pre-defined number of other vehicles, thus avoiding motorway pileups and enhance the traffic safety.

An ad hoc network structure can be flat [Broch et al 1998] or hierarchical [Bettstetter and Krausser 2001]. In flat structures, all nodes carry the same responsibility and have the global knowledge of whole networks. Flat structures are not bandwidth efficient in large networks because control messages have to propagate globally throughout the network. The scalability gets worse when the number of nodes increases. On the contrary, in hierarchical structures, the detail of the network topology information is only exchanged among local cluster members, and aggregated (reduced) information is distributed between neighboring clusters in the higher hierarchy level [Bettstetter and Krausser 2001]. In other words, topological changes are confined to a local area and are hidden from the rest of the network. There are three main advantages of organizing the nodes into clusters and routing packets hierarchically. First, efficient spatial and frequency reuse can improve network throughput and link utilization [Gerla and Tsai 1995]. Secondly, the size of a routing table in each node is reduced [Awerbuch 1990][Peleg 1989] [Bettstetter and Krausser 2001]. Thirdly, the communication overhead for distributed routing is reduced [Baker 1984]. A minor advantage of organizing the nodes into clusters is that less overhead is incurred for tracking mobile users [Awerbuch 1990].

Several heuristic clustering techniques have been proposed to choose cluster heads in an ad hoc network. These are lowest-ID, highest-degree and node-weight heuristics. However they cannot be deployed directly in ad hoc vehicular networks since their design objectives are not for high-mobility vehicular networks. For example, vehicles leave and enter highways randomly and rapidly, the computation task then causes a huge amount of communication overheads for each node to perform the heuristic technique based on the highest-degree algorithm. Cluster heads may frequently change their relative position on highways, then the size and stability of clusters change unpredictably if lowest-ID and node-weight heuristics are used. On the other hand, vehicles on (one way) highways have almost the same direction within a certain area. Therefore, their geographical location and velocity information are helpful when they are evenly divided into non-overlapping clusters along highways. [Stojmenovic 2001] demonstrated that better performance could be achieved if the geographic position of the network nodes is known.

This chapter proposes a new clustering technique, position-based hierarchical clustering (PHC), which incorporates position information into a novel hierarchical clustering technique. Each node knows its own position through a global positioning system (GPS). The cluster structure is determined by the geographic position of nodes. Each cluster has one node as the cluster head. Not only is the election of cluster heads based on nodes' position, but also the association and dissociation of clusters are determined by each node's position. The predefined maximum distance between the cluster head and its members then controls the cluster size. It enables nodes to move during cluster setup and maintenance. Furthermore, it allows asynchronous operation for cluster head election. A vehicular ad hoc network can be considered as a one-dimension network by taking the number of lanes into account. This work performs some mathematical analysis of PHC's performance under certain assumptions. The simulation results show that PHC gains better stability of the cluster structure, and needs smaller communication overhead for maintaining the cluster structure than the existing approaches do.

3.2 A Position-based Clustering Technique

3.2.1 Overview

Clustering is a technique to group nodes in a network into logically separated entities called clusters. This work assumes that each node is assigned a distinct ID, which is greater than zero. For the clustering purpose, each node maintains a small amount of information of itself and its neighboring nodes. Periodically, a node broadcasts the information which is referred to as its cluster information. It includes five fields:

i : node ID,

H : cluster head ID,

i_N: ID of the next node along the path from the node to its cluster head,

P : node position,

R : distance between the cluster head and next neighbor along the path from the node to its cluster head. They are denoted by a 5-tuple (i, H, i_N, P, R).

Cluster size may limit radio efficiency and throughput. Hence, the cluster radius is defined in order to organize the nodes within the given maximum distance, L, into a cluster. The parameter L will be referred to as the cluster radius. When a node moves away from its cluster head and the distance between the node and its cluster head is larger than the cluster radius, L, it joins a new cluster if it can find an existing cluster head within L; otherwise, a new cluster is formed with the node as the cluster head. When the distance between two cluster heads is detected to be less than or equal to a predetermined threshold, D ($D \leq L$), the cluster with less members is dismissed. Each of the nodes in the dismissed cluster finds a new cluster to join. Figure 3.1 is an example network of clustering vehicles. Nodes A, B and C are cluster head nodes. Obviously, some nodes (node i) can hear A and B simultaneously but obey the previous convention.

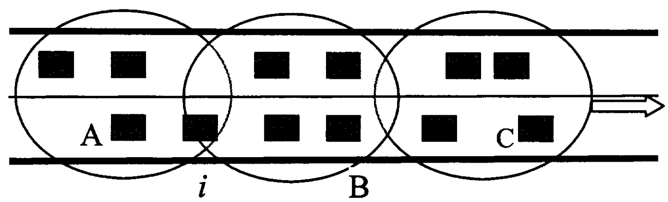

Figure 3.1 An illustration of clustering ad hoc vehicle network.

3.2.2 Registration

When node i is powered up, it sets its cluster information to be (i,0,0,P,0) indicating that it is at its registration phase. It then searches for its neighboring nodes. If there is at least one node, it sends its cluster information to all of them. Upon receiving the cluster information of node i, each neighboring node adds i as one of its neighbors. Each neighboring node that detects the existence of i also sends its cluster information to node i.

When i receives the cluster information from all of its neighboring nodes, it checks whether there is any registered neighboring nodes which is not in the registration phase. If yes, it tries to find a cluster such that the distance between the cluster head and itself is minimum and is less than or equal to the cluster radius, L. If such a cluster is found, it joins the cluster and updates its cluster information. It then sends its clustering information to all of its neighboring nodes. Upon receiving the cluster information of *i*, each neighboring node updates its maintained information.

If *i* finds that (1) it has no neighboring node, (2) none of its neighboring nodes belongs to a specific cluster, or (3) it cannot find a cluster head that is within the cluster radius L, it forms a new cluster with itself as the cluster head and sets its cluster information to be (*i*,*i*,0,P,0). Node *i* then sends its clustering information to all of its neighboring nodes if any.

When *i* detects the existence of a new neighbor, node j, and finds j is at its registration phase, *i* replays its cluster information to j. Meanwhile *i* adds j as a new neighbor and updates its information if j decides to join this cluster. If j is not at its registration phase and both *i* and j belong to the same cluster, node *i* updates its cluster information and sends its new cluster information to all of its neighboring nodes. Otherwise, nothing else needs to be done.

3.2.3 Information Forwarding

Generally, there are different strategies a node can use to decide to which neighbor a given packet should be forwarded. Assume that each vehicle has a fixed transmission range and cannot adapt the signal strength of a transmission to the distance between two nodes. Hence define that a node that makes the most progress towards (is closest to) the cluster head is the next hop for any node in the cluster. It is illustrated in Figure 3.2, where S and H denote the source and cluster head, respectively. The circle with radius r indicates the maximum transmission range of S. in the example the next node of S would be node C.

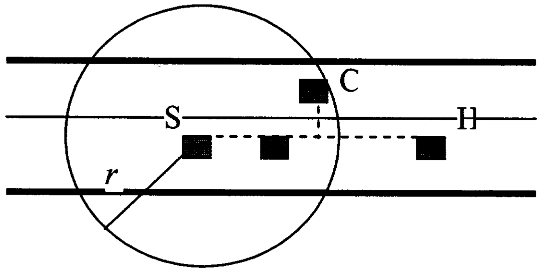

Figure 3.2 An illustration of MFR.

This strategy is called as most forward within r (MFR) [Takagi and Kleinrock, 1984], and the idea is to minimize the number of hops a node has to reach a cluster head.

3.2.4 Information Update

When node *i* receives the new cluster information from an existing neighbor node j, it updates the cluster information of j in its routing table. If j is the next node on the path from node *i* to the cluster head, *i* checks whether the new cluster information of j is the same as the original one. If at least one of the fields of the new cluster information of j (excluding the position field) is different from that of the original cluster information, *i* calculates the distance between itself and all cluster heads known to it. If the distance between node *i* and its current cluster head is d, then:

(1) if $[R(j) + |P(j)-P(i)|] \leq d \leq L$, nothing needs to be done.
(2) if $d \leq \{L$ and $[R(j) + |P(j)-P(i)|]\}$, *i* finds the closest head and updates its cluster information.
(3) if $L \leq d$, *i* tries to find the nearest cluster head and joins the cluster. If *i* cannot find any cluster to join, it forms a new cluster with itself as the cluster head. If its cluster information changes, *i* sends the information to all of its neighboring nodes.

3.2.5 Cluster Reconfiguration

If the distance between two cluster head nodes is detected less than the dismiss threshold D, the cluster with fewer members is dismissed to reduce communication overheads while its members join a new cluster. Each node of this cluster launchs a new registration stage to join other clusters. The threshold determines the rate of cluster reconfiguration and also depends on the radio transmission range. It makes no sense when the distance between two cluster heads is less than the cluster diameter, 2L. An example of reconfiguration is illustrated in Figure 3.3.

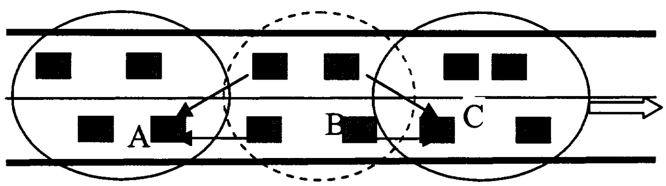

Figure 3.3 An Illustration of clustering ad hoc vehicle network.

The nodes currently belonging to cluster head B now launch new registration processes to join the proceeding or following clusters since the distance between B and C is less than the dismiss threshold D. Some nodes who are closer to head A will join the following cluster while others including B will join the proceeding cluster.

A problem may arise when a node needs to know which cluster head is in front of or behind it. GPS receivers can provide not only coordinates but also their first order derivatives. Figure 3.4 shows an example. Node 1 can get two vectors to node 2 and 3 at its current position. If the angle of two vectors is θ, then:

$\theta < 90^{\circ}$, 2 and 3 are in front of 1 ; and
$\theta \geq 90^{\circ}$, 2 (or 3) is in front of 1 and 3 (or 2) is behind 1.

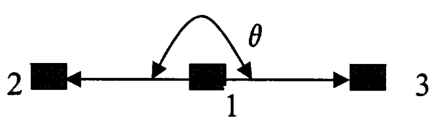

Figure 3.4 Using GPS signals to determine vehicle moving directions.

3.2.6 Positional Errors

Consider a node i that thinks it is located at position p_i but is actually located at $p_i^{'}$. This could happen if node i gets its positions from GPS and there is an error in the position measurement it receives from the GPS. Node i then advertises its position as p_i, and all packets to node i are addressed to position p_i even though i is actually located at $p_i^{'}$. It is referred to p_i as the network position of the node since this is what the routing algorithm uses, and $p_i^{'}$ as the actual position of node i.

Suppose that the error between the actual position and network position is δ, i.e., $\| p_i - p_i^{'} \| < \delta$. If node i is at network position p_i and node j is at network position p_j, the actual distance between i and j is $\| p_i^{'} - p_j^{'} \| < \| p_i - p_j \| + 2\delta$. When a node j receives a packet for position p_i, it can use the bound on $\| p_i^{'} - p_j^{'} \|$ to decide on its course of action. If the packet gets stuck at j, then j may initiate a route discovery, or it may do local flooding in an area of radius $\| p_i - p_j \| + 2\delta$ around it.

It is possible that node i joins the original cluster that has been dismissed. In this case, its calculated distance to the cluster head increases until it is greater than R or i receives the new cluster information of a neighbor node and finds that it can join a different cluster. Eventually, i joins a different cluster or forms a new cluster with itself as the cluster head. Therefore, each of the nodes which belong to a dismissed cluster joins a different cluster or forms a new cluster.

The main function of a cluster head is to construct and maintain a cluster as long as possible. Frequent changes of cluster heads not only result in significant overheads in network while dismissing old clusters and reconstructing new clusters, but also cause instable network architecture. Therefore, stability is critical for clustering technology. Choosing cluster heads optimally is an NP hard problem if the number of nodes is quite large [Dasagni et al 1997]. But in a highway network, each cluster can be limited, e.g., 30 to 50 members due to both computation and bandwidth limitation. Then the computation is affordable. The next section presents the mathematical analysis of PHC's performance by assuming that all vehicles are evenly distributed in a certain zone and vehicles entering and leaving the zone are balanced.

3.3 Overhead and Stability Analysis

3.3.1 Model

Assume that the spatial position of vehicles in a highway is confined to single dimension (line). But in general, a two-lane highway network has different performance from that of a one way four-lane highway network because of the influence of traffic capacity. Therefore, a cluster is modeled with a rectangle whose length is 2L, twice the cluster radius. First, define some notations:

v average velocity of vehicles

n the number of lanes

r, the efficient radio range

Δt time headway (time between two following vehicles passing a reference point)

N average number of nodes in a cluster

d_e the effective distance between two vehicles

Traffic patterns depend on the traffic density, i.e., the number of vehicles per kilometer. For small density one can assume that vehicles are moving independently of each other. At high densities, the complex interactions between neighboring vehicles make modeling of such a dynamical system a challenge. Several vehicle spacing models are depicted in [Reijmers and Prasad 1998]. Assume that their movements are independent and then their spacing is also independent. Thus an exponential distribution (ED) model is used due to its memoryless property.

Exponential distribution: $F(x) = \lambda e^{-\lambda x}$ $(0 \leq x)$

$$\mu = \frac{1}{\lambda}$$

where x is the spacing, and μ is the mean.

3.3.2 Cluster Radius

Because

$$d_e = (v \cdot \Delta t) / n \tag{3.1}$$

and,

$$N = \frac{2Ln}{d_e} \tag{3.2}$$

hence,

$$N = \frac{2Ln^2}{v \cdot \Delta t} \tag{3.3}$$

$$L = \frac{N \cdot v \cdot \Delta t}{2n^2} \tag{3.4}$$

Because Δt is a random variable, so is N. In [Kato 2002], the distribution of time headway on highways is given. The typical mean time headway is 2 ~ 4 s. From (4), one can learn that the cluster radius is determined by the average velocity of vehicles, the number of nodes in a cluster and the number of lanes. If the average velocity increases, the space between two vehicles must also increase to ensure driving safety. Then a larger cluster radius is needed. On the other hand, when the number of lanes is doubled, the cluster radius needs to be reduced four times. It is also easy to understand the relationship intuitively. More lanes lead to larger traffic capacity and more members of a cluster if the vehicle density is fixed. To guarantee certain level of available radio bandwidth, the cluster radius has to be reduced so that effective spatial and frequency reuse can be achieved.

3.3.3 Communication Overhead for Creating Topology

Consider a network with M nodes. In Link State Routing (LSR), each node generates one Link State Protocol (LSP) packet, and every other node has to forward it once. Therefore, the total amount of communication overhead generated by LSR is

$$C_{LSR}=M^2 \tag{3.5}$$

In PHC, the network is partitioned into C clusters. Assuming that the nodes are distributed evenly throughout the network, each cluster has (M/C) nodes. The amount of communication overhead of a node for creating a cluster becomes $(M/C)^2$ per cluster or $C(M/C)^2= M^2/C$ in the network. Moreover, each cluster has to forward all cluster's LSP once.The amount of communication overhead of cluster LSP's becomes MC. So, the total amount of communication overhead generated by PHC is

$$C_{PHC}= M^2/C +MC \tag{3.6}$$

It can be shown that C_{PHC} is always smaller than C_{LSR}, for $2<C<M/2$. The number of clusters affects the communication overhead generated by PHC. The minimum C_{PHC} is

achieved when $\frac{dC_{PHC}}{dC} = 0$ (it is a value as $\frac{d^2C_{PHC}}{dC^2} = \frac{2M^2}{C^3} > 0$). Therefore, the optimal number of clusters to achieve the minimum C_{PHC} is

$\frac{dC_{PHC}}{dC} = M - \frac{M^2}{C_{opt}^2} = 0$ Assuming that M is an integer, then

$$C_{opt} = \sqrt{M} \tag{3.7}$$

and the minimum C_{PHC} is

$$C_{PHC} = 2M^{3/2} \tag{3.8}$$

3.3.4 Dismiss Threshold

In this proposal, a cluster is dismissed only when its cluster head is dismissed and therefore other nodes are reconfigured. When the distance between two cluster head nodes is less than or equal to the dismiss threshold D, clusters are reconfigured. Hence the probability of cluster reconfiguration is:

$$P(d < D) = \int_0^D \lambda e^{-\lambda x} dx = 1 - e^{-\lambda D} \tag{3.9}$$

The mean value of the given exponential distribution is 1/λ.Therefore, from the definition of the effective distance it can be proved that:

$$\lambda = \frac{n}{v \cdot \Delta t} \tag{3.10}$$

From 3.9 and 3.10, it can be proved that

$$P(cluster\_reformation) = 1 - e^{-\frac{nD}{v \cdot \Delta t}} \tag{3.11}$$

At last, the probability is

$$P(cluster\_reformation) = 1 - e^{-\frac{ND}{2Ln}} \tag{3.12}$$

According to 3.12, one can expect that a larger dismiss threshold leads to a higher rate of cluster head changes and higher probability of cluster reconfiguration. On the contrary, if L increases, the probability decreases. Since the dismiss threshold is related to the transmission range, the probability of cluster changes is also related to the transmission range. Larger transmission provides longer distance for cluster heads to detect each other and therefore more frequent cluster reconfigurations occur. The next section shows the simulation results to demonstrate this conclusion.

3.4 Simulation Results

Extensive simulations are performed to study the characteristics of the proposed clustering technique. The network used in the simulations consists of 100 vehicles moving in a highway with 10 km length. The packet length including the position information is 75 Bytes. The traffic density is 5 veh/km per lane. The time headway is 2 seconds and the effective radio transmission range is 250m.

This research first compare the mean cluster radius with different average cluster size when the average velocity changes. Figure 3.5 shows that different average velocities affect the cluster diameter as discussed previously.

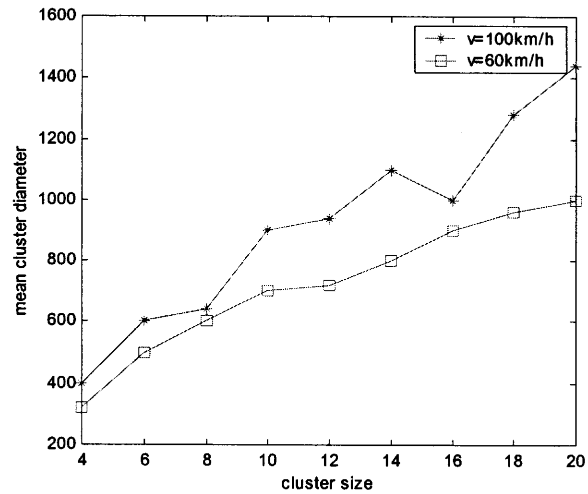

Figure 3.5 Mean cluster diameter (2 lanes).

Then simulations as shown in Figure 3.6 indicate that the number of lanes has significant influence on the cluster diameter due to higher traffic capacity.

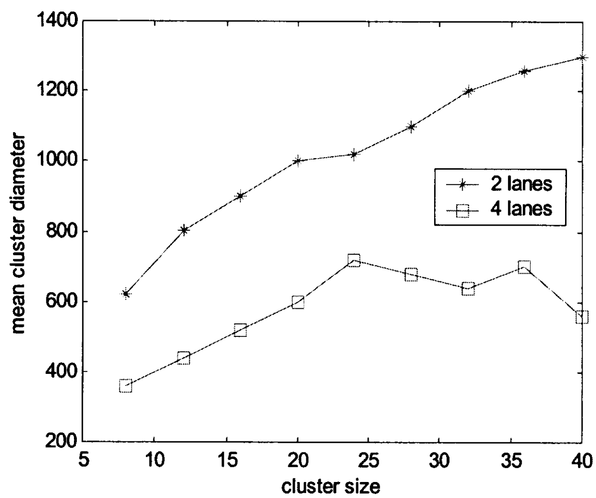

Figure 3.6 Mean cluster diameter (70km/h).

One can also conclude that the mean cluster diameter is not strictly linear with cluster size as Equation (3.4) indicated. The main reason is that the movements of vehicles are not independent in the simulation experiments.

A good clustering algorithm should be stable to radio motion, i.e., it should not change the cluster configuration too drastically when a few nodes are moving and the topology changes rapidly. The dismiss threshold D determines whether a cluster should be dismissed or not and it is critical for cluster reconfigured rate. It is desirable that a clustering technique incurs low cluster reconfiguration rate. Figures 3.7 and 3.8 show the cluster reconfiguration rates of the proposed technique for various values of cluster radius, L, and cluster dismiss threshold, D.

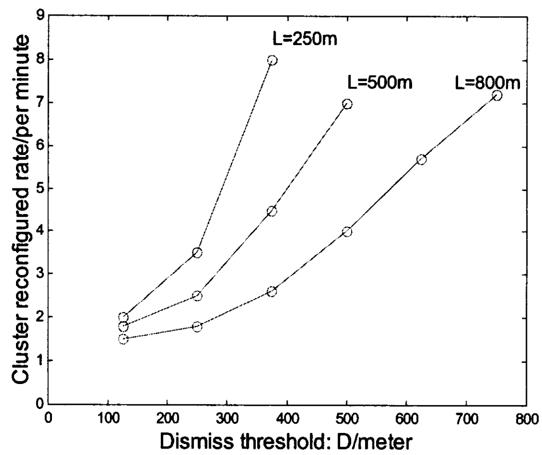

Figure 3.7 Cluster reconfigured rate.

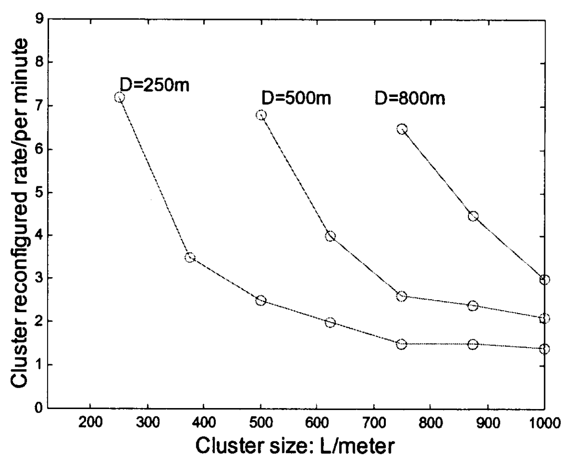

Figure 3.8 Cluster reconfigured rate.

From Figures 3.7-3.8, the following observations are made. For a fixed value of the cluster radius, L, the cluster reconfiguration rate increases as the cluster dismiss threshold, D, increases. There are two reasons for this phenomenon. First, increasing the cluster dismiss distance increases the probability that the distance between two cluster heads becomes less than or equal to the cluster dismiss threshold. As a result, the probability of a cluster being dismissed also increases. Secondly, increasing the cluster dismiss thresholds decreases the probability that a member of the dismissed cluster successfully finds a neighboring cluster to join.

For a fixed value of the cluster dismiss threshold, D, the cluster reconfigured rate decreases as the cluster radius, L, increases. There are two reasons for this. First, when the cluster radius is larger, the members of the dismissed clusters have higher probability of finding neighboring clusters to join, resulting in the lower probability of forming one or more new clusters. Second, when a node moves away from its cluster head such that the distance from its cluster head is greater than L, larger cluster radius results in higher probability for the node to find a cluster head within L; therefore, the probability of forming a new cluster is lower.

The average aggregate link throughput versus transmission range is shown in Figure 3.9.

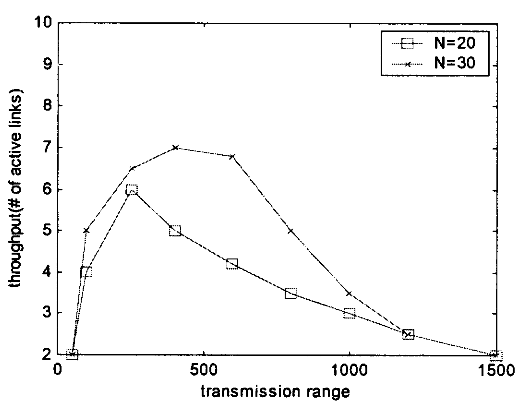

Figure 3.9 Link Throughput.

The results confirm that there exists a tradeoff between transmission range and throughput. For relatively smaller transmission range, the graph consists of several isolated subgraphs, with good spatial reuse but poor connectivity. Too small transmission range, however, leads to decrease in throughput since most of the clusters contain only one node, and no links. As the transmission range grows, the proposal has better connectivity but less efficient spatial reuse, and thus lower throughput.

3.5 Summary

In this chapter, a new clustering technique for ad hoc vehicle networks is proposed. The cluster structure is controlled by geographical position information. There is a cluster head in each cluster and its members are within the cluster radius. The dismiss threshold controls the cluster reconfiguration. Simulations show that this new technique has great flexibility and stability.

Thus it investigated the clustering technique in a one-way highways, but two-way highways are more common in real cases. Obviously, clusters interferences are higher in two traffic streams of opposite direction. Future research should include the influence in terms of available bandwidth and capacity. Studies of extreme cases such as sparse and jammed traffic should also be included in future work.

CHAPTER 4

AN EPIDEMIC ROUTING STRATEGY FOR VEHICULAR AD HOC WIRELESS NETWORKS

4.1 Introduction

In Chapter 3, a new topology management scheme is proposed to reduce communication overheads in vehicular ad hoc networks. There are many potential applications for inter-vehicle communication networks. Such applications are a combination of telecommunication and computation, such as route planning using GPS signals or remote diagnostics using data from sensors built into vehicles. A number of interesting applications are possible in such networks as categorized into three groups.

a) Internet-based applications such as Web browsing E-mail and video streaming can be enabled in a general way by equipping cars with access points for existing portable devices like notebooks or Personal Data Assistants. The connectivity to the Internet at large can be achieved via gateway nodes placed along the highway.

b) Geographic position aided applications provide location information for the points of interest of users. For example, a directory may provide real-time driving directions, or the listing of local services such as gas stations and businesses.

c) Cooperative group applications may be collaboratively run by groups of nearby nodes, and thus match the ad hoc routing model best. For example, vehicles may engage in chat, exchanging short messages, sharing multimedia files, and video-conferencing. Services can likely be offered when an "information vendor" driving along the highway, carrying a library of music files for download. Vehicles belonging to highway-service crews can announce themselves, automatically informing drivers about the oncoming road work areas. Disabled or crashed vehicles may use acceleration sensors to trigger automatic advertisements of an accident, as pointed out in [Briesemeister 2000]. Morris [2000] points out additional localized applications like collaborative road congestion monitoring, route planning, and fleet tracking.

Above applications heavily rely on robust and efficient routing protocols. However, disseminating messages among fast moving vehicles is always challenging because the inter-vehicle communication network exhibits very different characteristics from other MANETs as explained before.

With ad hoc networks deployed on moving vehicles, network partitions due to limited radio range become inevitable when the traffic density is low such as at night, or when only a limited number of vehicles carry wireless devices. A key question to ask is whether it is possible to deliver messages in spite of partitions. By taking advantage of the predictable node movement on highway, one may create opportunities to route messages in a store-and-forward fashion.

This chapter proposes and tests the hypothesis that the motion of vehicles on a highway can contribute to successful message delivery, provided that messages can be relayed—temporarily stored at moving nodes while waiting for opportunities to be sent further. This work intends to test this hypothesis by simulating the movement of vehicles on a highway via CORSIM, simulating an ad hoc network over the vehicles via Network Simulator, and measuring the performance of the network as traffic density decreases. To the authors' knowledge, no such research work has been done and reported in the literature.

In Section 4.2, some related works are reviewed. Section 4.3 introduces a new packet forwarding scheme for ad hoc wireless networks. Section 4.4 is the framework of simulation environment both for communication and transportation. Section 4.5 presents and discusses the experimental results. The chapter finishes with conclusions and future research direction in Section 4.6.

4.2 Routing Challenges and Mobility Models

Forwarding packets within a vehicular MANET is extremely difficult while their average velocity is much higher than that of low-mobility nodes in regular MANET. The idea of using node mobility to improve network performance has been extensively investigated. In general, these proposals mainly aim at optimizing routing protocols, network throughput, message delay, connectivity and energy conservation. [Hartenstein 2001] proposed a position-aware protocol for inter-vehicle communications in the highway environment, and investigated multihop connectivity for high and low traffic density using accurate vehicles' position information which was time-varying. Briesemeister [2000] proposed a multicast protocol for the highway environment, and measured the fraction of nodes to which aggressively forwarded messages were successfully delivered in a fixed amount of time.

Grossglauser [2001] started from a model with random node movements, and showed that the motion led to constant throughput as the network size increased. Bana [2001] proposed a Space Division Multiple Access (SDMA) for robust ad hoc vehicle communication networks. The idea is to divide the geographical space into many non-overlapped smaller places and to allocate each neighboring zone different bandwidth division of time slots or frequency division.

Dolil [1989] proposed that base stations located along highways stored and delivered packets to vehicles using microcells. Li [2000] examined a scenario in which the mobile nodes were under their control, so that the trajectories could be modified to reduce delay.

Xu [2001] introduced a geographical adaptive fidelity algorithm to reduce energy consumption in ad hoc networks. By identifying nodes that are equivalent from a routing perspective and turning off unnecessary nodes, it can consume significantly less energy than conventional routing protocols do.

In the context of inter-vehicle communication, research always includes two aspects of related issues: transportation and wireless networking. Therefore, accurate modeling traffic of highways is required and inevitable. Hartenstein [2001] and Briesemeister [2000] used simple highway models thus their results cannot reflect real traffic environment. Additionally, power consumption is no longer a critical problem for a vehicle driving on highways because of continuously being charged vehicular batteries. Then, research should focus on basic communication performance. Due to the high mobility of highway traffic, any position-based routing protocols have trouble in disseminating accurate geographic location information in a real time way. Hence their conclusion is not always reasonable.

The chapter studies inter-vehicle communications on the basis of an authoritative transportation simulation tool, TSIS 5.0. Many traffic parameters, such as traffic density, highway lanes, and average vehicle travel time and mileage, can be easily set or acquired. The work, hence, reflects nearly real transportation environment. Moreover, the proposal does not require accurate geolocation information, which is required by some existing routing algorithms. In other words, the scheme will function properly with an existing routing protocol with or without geolocation requirements. Hence, the results of this paper render a valuable and significant guide for future research and design of ad hoc inter-vehicle communication.

4.3 Epidemic Best-effort Forwarding

4.3.1 Definition

In ad hoc vehicular wireless networks, each node is a router acting for forwarding packets to its appropriate neighbors. In case of low density, the network could be partitioned due to disconnectivity. If a vehicle fails to relay packets to its next hop, packets arriving from other one-hop neighbors will be dropped at the node according to the previous proposals. Then this data transmission is failed and future retransmission will be necessary.

This section suggests that each packet is buffered at this node once it is stuck and waits for future opportunities to be forwarded. Messages without the next hops can remain on intermediate nodes for certain pre-determined time, depending on applications, hoping that physical movement of network nodes eventually creates a forwarding opportunity. For example, in a geographic routing protocol such as those in Karp [2000] Li [2000] coupled with this kind of forwarding, messages is not dropped, but instead held and then forwarded greedily as soon as a new neighbor node closer to the destination is detected. A packet is dropped only in two cases. The buffer is full or the period of a packet staying within the buffer exceeds certain threshold. Figures 4.1 and 4.2 give two examples of this scheme where r is the radio transmission range. Figure 4.1 shows that a proceeding vehicle A cannot forward packets received from its following neighbors within one hop to its proceeding next hop neighbor because no vehicle ahead is within A's communication radius. In such situation, packets received at node A must be temporarily stored and forwarded until A is close enough to a proceeding vehicle so that they are within its radio range.

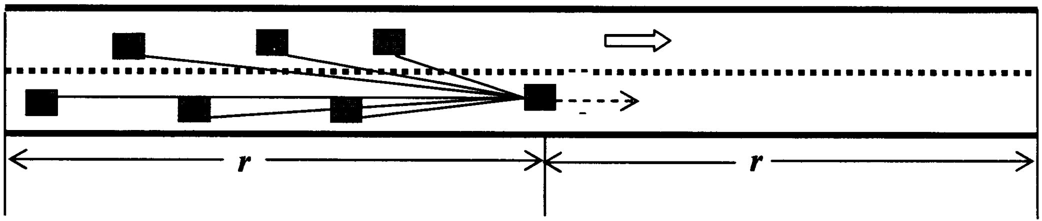

Figure 4.1 Node A can forward packets from its following neighbors.

On the other hand, A's next hop is not necessarily its proceeding neighbor. Its following neighbor could also be A's next hop if a connection is launched by A's proceeding neighbor and the destination is some hops away behind A. Figure 4.2 illustrates such scenario. Again, node A may succeed in delivering stored packets to its following neighbors by taking advantage of relative speeds.

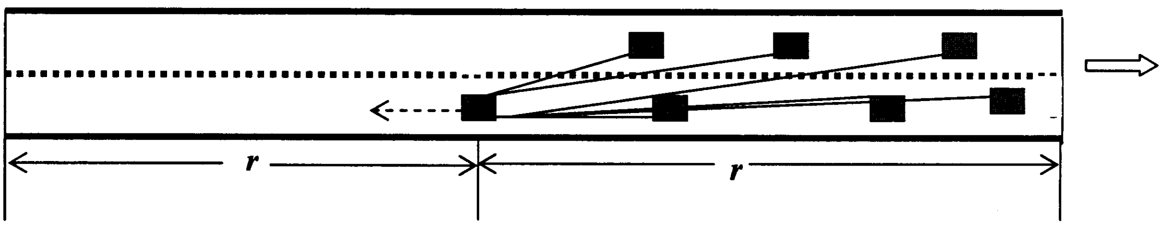

Figure 4.2 Node A can forward packets from its proceeding neighbors.

This best-effort forwarding strategy is similar to the forwarding principle in wireline IP networks. The idea here is based on an assumption that there are relative speeds among moving vehicles. Hence, one vehicle may eventually reconnect to its proceeding/following node if they are getting closer, or its following/proceeding neighbors become its proceeding/following neighbors and then probably make the network connected again. Whatever situation it is, the possibility of successful transmission of messages is expected to be higher.

As stated above, vehicles could be distributed unevenly due to the existence of relative speeds even though the traffic density may be moderate. Then the whole network might possibly be partitioned into isolated small groups whose members have similar group mobility characteristics, such as average velocity, direction and common reference point (e.g., clusterhead in a cluster-based ad hoc network [Bechler 2004]). In Figure 4.3 group A and B have the same moving directions but different average velocity. Successful message delivery between group A and B depends on the probability that one of the edge nodes could eventually get closer with its corresponding receiver. This probability is P_d, service capture probability.

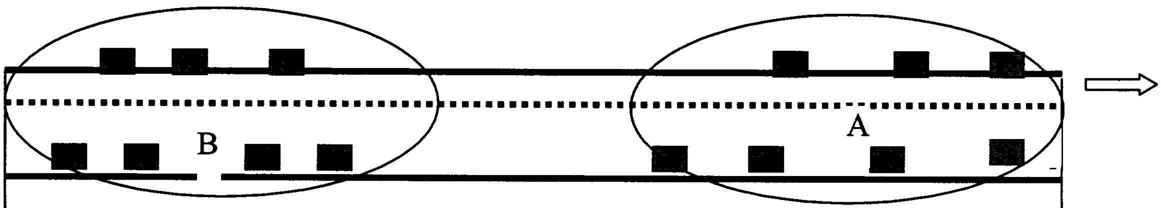

Figure 4.3 Isolated groups along a highway.

Obviously, P_d is determined by many factors, such as traffic time, average speed, driver behavior, and even the type of car. Eventually, it is up to the traffic density. For very high density, it is almost impossible for vehicles to keep their gaps beyond one direct communication radius. Therefore, P_d is always 1 and the idea then makes no sense. This chapter only concerns about the low traffic density scenario, which makes this idea useful for relaying message along a highway.

Apparently, both transportation and communication issues have significant impacts on the performance of this proposal. To focus on communication essence, the work uses a standard simulation tool to provide real transportation scenario and pay main attention on related performance, e.g., proper buffer sizes under different network load, throughput improvement, relationships among throughput, buffer length and average delay. In the next section, mathematical analysis is conducted to examine the basic requirement and performance of this scheme.

4.3.2 Analysis

Assume that the buffer size of each vehicle is K and the number of its neighbor is N that equals $r \cdot l \cdot d$, where l is the number of lanes and d is the density of vehicles per lane (vehicles/km). Note that only radius is calculated here because another half of neighbors should be empty according to Figures 4.1 and 4.2.

It is reasonable to assume that that packet arrival is a Poisson process and packet arrival rate from every vehicle is λ. The service time, however, is not deterministic because it is mainly determined by traffic density. For moderate density, the service capture probability is fixed and the service time is deterministic, so the best-effort scheme can be modeled as an M/D/1/k queuing system. For low density, a node cannot transmit packets from its buffer immediately if its next hop node is unavailable. In some moderate density cases, one node may not start immediate forwarding either. For instance, this happens when the traffic is not evenly distributed and there is a gap between node A and its next hop. If the gap is long enough (beyond one-hop radius), A cannot relay packets even though the overall traffic density is high. The service rate depends on service capture probability, thus is treated as a random variable and it is called modulated service rate.

Generally, the traffic on highways could be thought of as Poisson distribution [Chien 2001][Feller 1971]. To simplify the analysis, assume that the service time is the product of P_d and μ which follows exponential distribution. Hence the average service rate at each node is μP_d.

Apparently, this model is a hybrid M/M/1/K finite waiting space queuing system. Therefore, calculate related parameters as followings:

Average number of packets $L_s = \frac{\rho}{1-\rho} - \frac{(K+2)\rho^{K+2}}{1-\rho^{K+2}}, \quad \rho = \frac{N\lambda}{\mu P_d}$

Average number of packets in buffer $L_q = L_s + \frac{1-\rho}{1-\rho^{K+2}} - 1$

Average waiting time of each packet $W_q = \frac{L_q}{N\lambda(1-\rho^{K+1}p_0)}$

where $p_0 = \frac{1-\rho}{1-\rho^{K+2}}$

For the case of high density and high packet generation rate, λ/μ is close to 1. Typical r is about 200m to 500m and traffic density is 160 cars/km. Then N falls into the range between 201 and 401. If ρ>>1, and usually, K>>1, then it is easy to learn that Lq $\approx$ K and Wq $\approx$Lq / Nλ. When ρ is close to 1, it can be proved that this conclusion still stands. Intuitively, when the network load is large enough then the buffer size would grow linearly.

Even though a buffer can create chances of successful data delivery, one cannot expect that its size is unconstrained. Larger buffer size may also result in longer delays. There is a trade-off between network throughput and packet delay. This purpose is to find out the relationship between the network load, λ, the throughput and the buffer utilization under different circumstances (μ).

4.4 Simulation Environment

The simulation environment consists of two parts. The first part is a traffic microsimulator that produces accurate movement traces of vehicles traveling on a highway. The second is a network simulator that models the transport of messages among the vehicles. This work uses the following traffic scenario. A single packet is sent by each car entering the highway. The destination of a packet is chosen to be 10km away in the entering car's direction; however, if no such car happens to be within 10km away, then no packet is sent. The best-effort delay and conventional delays are obtained on the highway traces, for radio range r=250m. The time period for caching each packet is set to 10 seconds.

4.4.1 Traffic Microsimulator

CORSIM (Corridor Simulator) used in this work is a microscopic traffic simulator developed by the Federal Highway Administration . CORSIM models the behavior of human drivers by approximating a set of common driver decisions [Chien 2001], such as slowing down or changing the lane in the vicinity of slower vehicles ahead. These decisions cause the acceleration and orientation of vehicles to change, resulting in realistic movement patterns.

There are three inputs to the simulator: highway geometry, free-flow speed, and input rate. The geometry in this simulation is basically the same as depicted in Figure 4.4. It is a straight highway segment with two directions, each composed of multiple lanes.

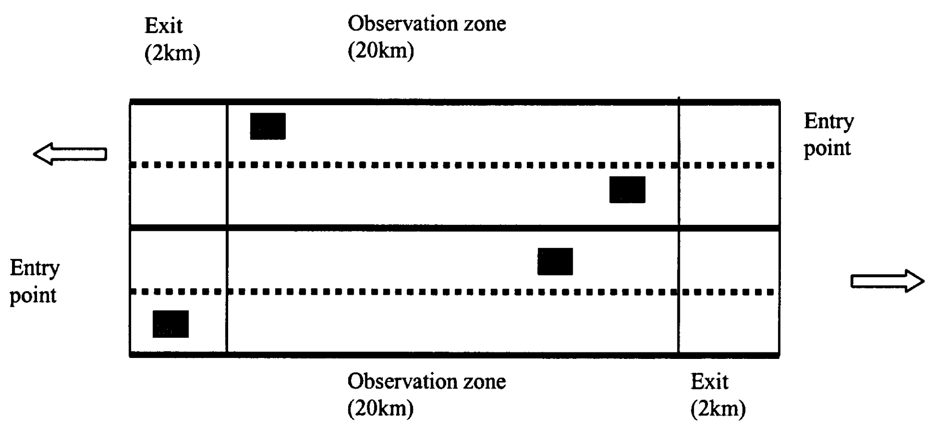

Figure 4.4 An illustration of highway geometry used in the traffic simulator.

The free-flow speed parameter is the mean speed that travelers achieve when they move unconstrained by other vehicles or obstacles. The actual free-flow speeds assigned to vehicles are distributed normally around that mean, with a default standard deviation of 12.8km/h. The free-flow speed parameter used in this simulation is 100km/h.

The input rate parameter controls the period at which the simulator generates new vehicles. At the end of each period, a new vehicle is placed at one of the entry points as indicated in Figure 4.4, but only if enough room is available. In case of congestion, no new vehicles are generated.

Vehicles near the entries move into the observation zone normally or uniformly according to the process of vehicle generation. Only when they reach the sections under observation are their positions recorded. Once they leave these sections, vehicles are removed from the simulation.

The output of each simulation is a trace of vehicle positions taken at one-second intervals. Each of simulation lasts 30000 simulation seconds and about 20000 vehicles are used at each time. The simulations ran a total of 150 simulations with different random seeds, for highways with one to five lanes on each side. Then totally around 3,000,000 vehicles are examined. The average vehicle densities observed in the 150 simulation runs are summarized in Table 4.1.

Table 4.1 Summary of the Highway Traces Obtained from CORSIM and Used to Drive Network Simulations.

Numbers of Lanes	Lowest density (cars/km)	Highest density (cars/km)
1	3.1	79
2	3.1	172
3	3.2	273
4	3.2	336
5	3.5	325

4.4.2 Network Simulator

This work simulates a wireless network over vehicles driven by the traces summarized in Table 1. Assume that the wireless devices installed on vehicles all have the same fixed radio range r. This simulator uses the default routing protocol, i.e., Ad hoc On Demand Distance Vector (AODV) and default radio propagation model, i.e., omnidirectional antenna, 802.11 MAC. It maintains a network connectivity graph, and positions and age of the messages in transit. Messages are propagated greedily each timestep, by hopping to the neighbor closest to the destination. This amount of information is sufficient for the purpose of finding the delay due to mobility status.

Under the conventional forwarding, the simulations measure the average amount of time a sender S waits before a direct route to a destination D becomes available. One can obtain this time directly from the movement traces as a half of the average duration of network partitions between S and D, and calculate it as the conventional delay. Note that such delay is a lower bound only observable in an ideal network with perfect routing information (either local or global) – in practice, route computation may be affected by additional factors, such as timing information of a particular routing protocol. For example, suppose that the network uses a geographic routing algorithm. Then, even though a destination D becomes reachable from source S due to the movement of some nodes, the messages from S will not reach D until the new topology information is learned using beaconing between neighbors.

With best-effort forwarding, messages are not dropped until the buffer is filled. Hence, one can measure the average time messages spent in the network. This value is called the best-effort delay.

4.5 Simulation Results

This section begins with describing the experimental setup, and follow with a set of measurements. This work measures performance as average delay required to traverse a certain fixed distance. The observation zone includes 2 lanes in one way and the number of a node's neighbors is 30, which reflects low or moderate density cases according to Table 1.

4.5.1 Comparing Best-effort and Conventional Delays

Figure 4.5 shows the behavior of measured best-effort and conventional delays as the density of vehicles on the highway increases. At the high densities, both delays are close to zero since the likelihood that a destination is unreachable is very low. However, conventional delay rises more sharply than best-effort delay as the density falls, indicating that mobility succeeds in helping the delivery of best-effort messages. The significance of this result lies in showing that a network taking advantage of node mobility can operate in lower densities while maintaining same average delay.

4.5.2 Buffer Utilization vs. Traffic Load

According to the above discussion, the buffer usage is determined by the packet arrival rate λ and the modulated service rate. Assume that a node can make full use of available bandwidth once it can send packets to its neighbors. So the modulated service rate is the product of service capture probability and deterministic service rate. Based on different network load, the method records the used buffer size of a node during each time slot. Then the simulation repeat calculation along 10000 time slots to get the average buffer usage of this node. The process is repeated for every node within the observation zone and finally the average buffer usage per node of this network versus the network load is plotted in Figure 4.6. Theoretically, buffer size is unlimited and can be increased linearly along with the network load after certain points. However, the actual network load is limited at the same time [Grossglauser 2001]. Moreover, only finite buffer length is practical. Figure 4.5 shows that when the network load is greater than certain point, the buffer size grows rapidly so that it is impossible to implement it.

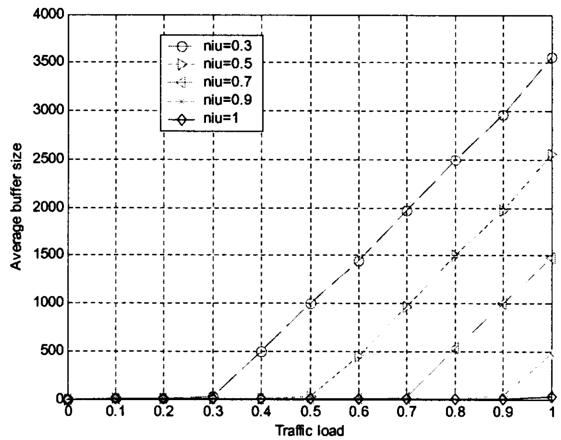

Figure 4.5 The traffic load vs. the average per node buffer length.

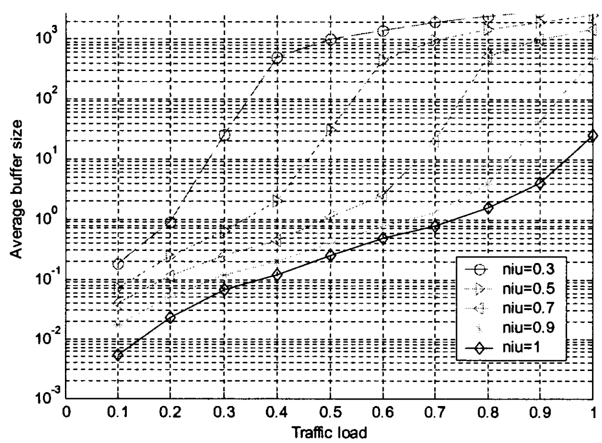

Figure 4.6 The traffic load vs. the average node buffer length with logarithm scale.

In Figure 4.6, it can be found that the higher service capture probability, the less buffer length needed. The reason is that once a vehicle node has more opportunities to contact others, less buffer it needs to store packets temporarily.

4.5.3 Throughput vs. Traffic Load

The average throughput using the same process is examined. The throughput of one node forwarding packets is defined as: the total transmitted packets divided by the total packets it can send. Figures 4.7 and 4.8 give the simulation results with different buffer length. Again, higher service capture probability leads to better throughput as expected.

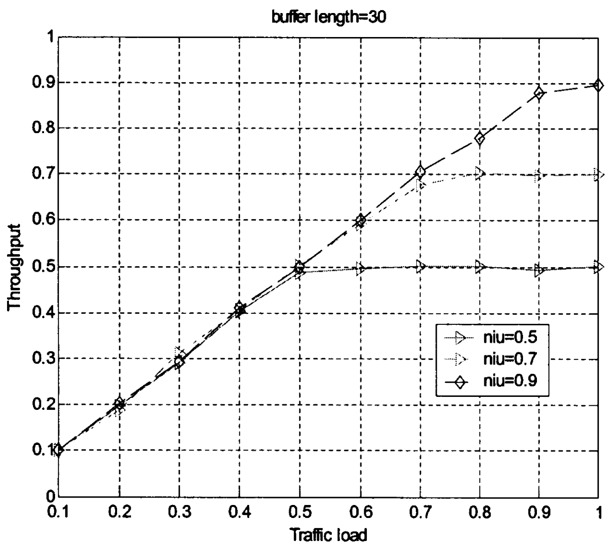

Figure 4.7 The traffic load vs. the average per node throughput with buffer=30.

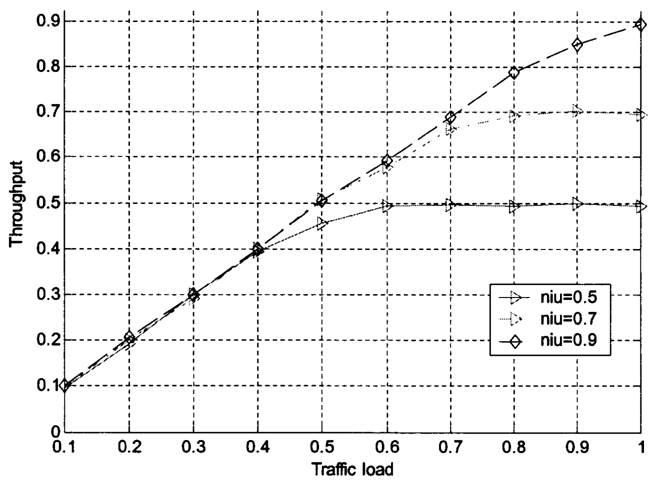

Figure 4.8 The traffic load vs. the average per node throughput with buffer=10.

4.5.4 Delay vs. Traffic Load

This work also investigates the average node forwarding delay by simulating the average delay value per node. The forwarding delay here is the time difference from the moment a packet arrives at the buffer and the moment it is served. Previously, it is simply proved that the delay (waiting time) is related to traffic load and the buffer size. In Figure 4.9, the average delay is almost less than 10s because the buffer will discard coming packets once it is full.

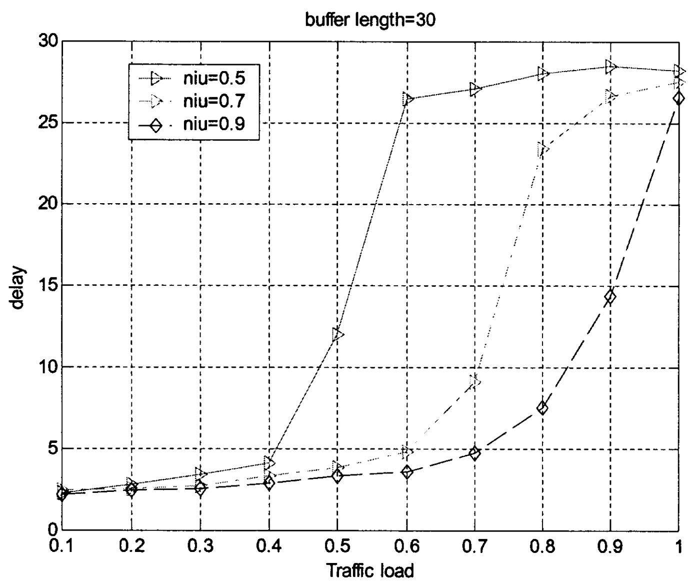

Figure 4.9 The traffic load vs. the average delay per node with buffer=30.

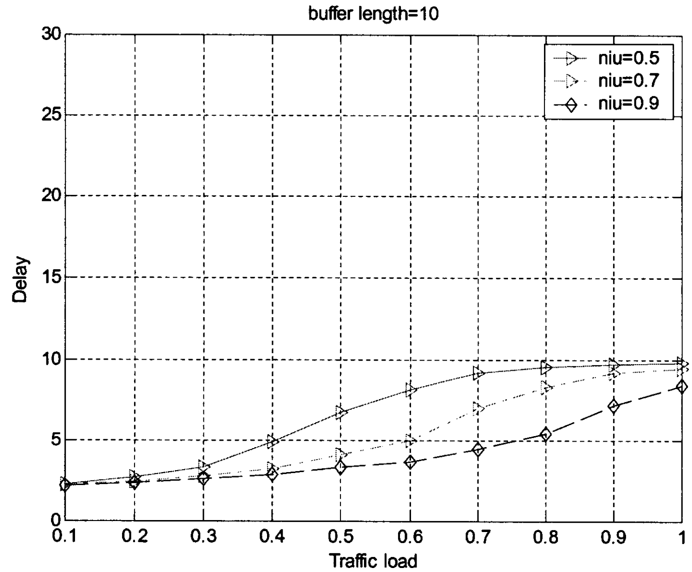

Figure 4.10 The traffic load vs. the average delay per node with buffer=10.

4.5.5 Delay vs. Throughput

The relationship between throughput and delay is also examined using simulations with different buffer length. It is observed that the delay is quite large when high throughput can be achieved. Besides that, it is obvious that higher service capture probability results in higher throughput at the same delay level. It makes sense because the higher probability, the higher traffic density.

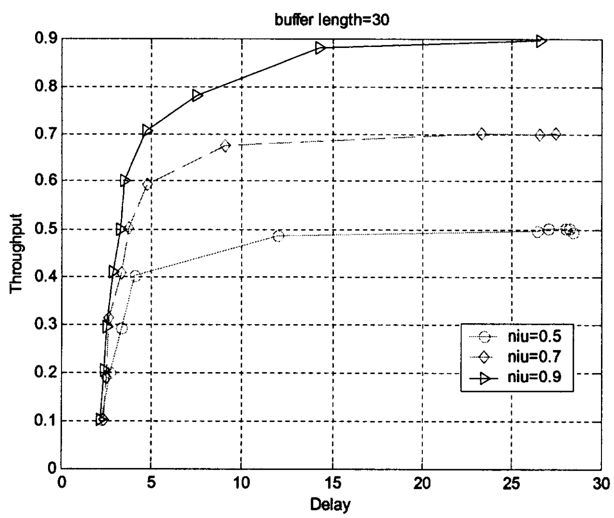

Figure 4.11 Delay vs. throughput per node with buffer=30.

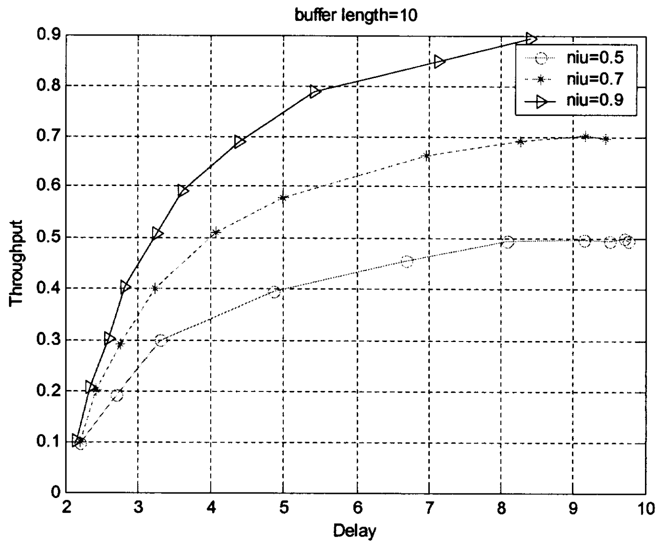

Figure 4.12 Delay vs. throughput per node with buffer=10.

4.6 Summary

This chapter addresses how the mobility of vehicles can improve the performance of ad hoc wireless networks formed among vehicles on highways. In conclusion, epidemic routing improves message delivery by exploiting the vehicle's mobility. First, it is found that high mobility of nodes on the highway improved end-to-end transmission delay if messages are relayed—that is, if they are held at intermediate nodes until favorable forwarding paths appear. The improvement leads to practical delay values at smaller traffic densities than that for conventionally forwarded messages with ideal routing information. Thus, the hypothesis is verified via simulation and well matches one's expectation. Next, the improvement is higher for traffic scenarios with more relative movement. There are two sources of relative movement: traffic in opposing directions on bidirectional highways, and muti-lane traffic within the same direction.

Finally, since the delays measured at low vehicle densities increase to the order of seconds, such conditions cannot support delay-sensitive applications, e.g., interactive multimedia. However, there are many non critical applications, such as some of the localized applications which are delay-tolerant and are therefore suitable for this environment.

This proposed method does not achieve much improvement in terms of latency and throughput for high density cases since the chance of network partitioned is tiny. In future research, taking advantage of opposing direction traffic should be included so that it makes the proposed method more practicable. Moreover, most ad hoc networks have hierarchical architectures. Then clustering techniques should be combined with the proposed method and the new topology model should be considered. At last, suitable buffer management schemes can be developed, for example, priority-based and hop count.

CHAPTER 5

A ROUTING STRATEGY FOR VEHICULAR AD-HOC NETWORKS IN CITY ENVIRONMENTS

5.1 Introduction

As stated previously, the automotive domain now is able to take advantage of vehicular ad hoc networking technologies to improve road traffic safety and efficiency. However, inter-vehicle communication in city areas is quite different from that in highway environments due to some new constraints. First, the radio transmission distance may be greatly reduced because of adverse conditions, such as the multipath effect, which is induced by high concrete buildings that block the line of sight and reflect the radio signal many times. Second, the traffic regulations in urban areas can shape the road traffic significantly. For example, the traffic lights of all intersections can partition and control traffic with certain timing sequence. Vehicles in urban areas are more likely gathered into separated groups according to the timing of traffic lights. Moreover, different traffic hours lead to different traffic patterns accordingly. Traffic congestions may occur frequently and increasingly in rush hours but in most cases they happen only in main traffic roadways. Last, but not least, the density of equipped wireless-packet-communication vehicles may vary for a given region, thus limiting the connectivity of vehicular ad hoc networks. In suburban regions or during early deployment phase, the density may even be close to zero. Thus, it is likely that there are groups of vehicles which can communicate with each other but are separated among those groups. Such groups are called scatternets [Kendy Kutzner 2003]. Apparently, there is a need to inter-connect such groups.

On the other hand, the urban traffic conditions also provide opportunities for vehicular ad hoc networks to utilize some known constraints. The layout of roadways, for instance, is usually known with the aid of GPS devices and digital geographical maps. Multiple routes can be calculated according to current traffic conditions. Moreover, public transportation services are also known to the users of vehicular ad hoc networks. A driver (or a vehicle) can easily obtain the knowledge of bus routes, the schedule of trains and subways with the help of on-board equipments. Accordingly, one (or the vehicle) can predict current traffic conditions and take further steps.

In ITS, the primary need of a driver naturally is to reach the end of trip within the least time while driving safely and efficiently. Comfort aspects have become more and more important as well recently. A driver not only needs to know where the traffic jam and/or accident are, but also requires communications with other entities. If the communication peer is in a vehicular ad hoc network, a routing strategy is needed for inter-vehicle communication. If the peer is a host of Internet, the Internet service and access are needed for such a driver. Therefore, drivers and passengers in vehicular ad hoc networks are able to surf the web, check emails, browse mobile advertisements, and even play games or share multimedia resources with friends in other vehicles.

This chapter is going to propose a routing strategy for vehicular ad hoc networks in city areas in order to implement the above applications. Previous research [Stojmenovic 2002] has shown that position-based routing strategies are more suitable for vehicle ad hoc network than traditional ad hoc routing protocols. However, current proposals still have obvious drawbacks while being applied in urban regions as stated in Subsection 5.2. The proposed routing strategy takes into account the transportation constraints and achieves better performance in terms of packet delivery rate and average delay.

5.2 The Proposed Routing Strategy

Traditional ad hoc routing protocols suffer from handling the high mobility specific to vehicular ad hoc networks. In recent works [Wang 2005][Blum 2004] researchers have shown that routing approaches using position information, e.g., obtained from on-board GPS devices, can deal with the mobility of the nodes in highway scenarios very well. A general survey on position-based routing approaches is presented in [Stojmenovic, 2002]. Schwingenschlogl [2002] introduced geocasting ability to the classical AODV protocol.

Position-based routing approaches include two parts: location service and forwarding strategy. The location service provides sending nodes the geographical information of the destination nodes. The geographical information includes the ID of a node, accurate or coarse position information, and the expiration time of these data. The forwarding strategy determines the data path based on location information. Many forwarding strategies have been proposed [Stojmenovic, 2002] but most of them are variations of three basic greedy algorithms. They are a) Most Forwarding Progress within Radius (MFR), b) Nearest with Forwarding Progress (NFP), and c) Compass routing. However, they still have problems when being applied in vehicular ad hoc networks. MFR may lead to long hops while signal strength cannot be adjusted. NFR may fail to deliver a packet if the next hop node is not available. Compass routing could generate path loop when vehicles have high mobility. A new position-based routing protocol, including location service and forwarding strategy, therefore, is proposed in the following sections.

5.2.1 Location Service

Like other location service schemes, the proposed location service requires that every vehicle have the location information of its direct neighbor. With the increasing popularity of on-board GPS navigation systems, vehicles are able to know the position information of their one hop neighbors.

This work makes use of reactive location service (RLS) in order to learn the current position of a desired communication partner. RLS is a direct translation of the route discovery procedure used in reactive non-position-based ad hoc routing protocols to the position discovery of position-based routing. Essentially, the querying node floods the network with a position request for some specific node id. When the node that corresponds to the requested id receives the position request, it sends a position reply back to the querying node. When a node wants to communicate with another node using position-based routing, it needs to add the geographical position of the destination node to the headers of all packets sent to this destination. The routing scheme then forwards these packets to the given position, which – in an ideal case – would be the present location of the destination node at the time of the packets arrival. In a real world situation the geographical position can never be 100% accurate and it is the task of a location service to provide the current location as precisely as possible. To do this the location service may use any algorithm that is able to provide an (id, location)-pair to an inquiring node.

In RLS the algorithm works as follows: A node querying the geographical position of a certain node issues a location query packet. The query packet contains the source node's location and id as well as the id of the destination node. It is flooded throughout the network until it reaches said destination node or its time-to-live (TTL) expires. If the destination is not reached, RLS assumes unreachability, which represents one of the following cases:

> *Network Partitioning* If the network is partitioned, with source and destination in different partitions, the destination can never be reached by the query and it will eventually expire.
>
> *Inactive Node* The destination node does not exist or has (temporarily) been deactivated. Thus it can never be reached by the query.
>
> *Large Distance* Source and destination may be farther apart (in hops) than the maximum time-to-live would account for.

The above cases are indistinguishable for RLS since error detection is based on a timeout mechanism at the sending node. Note that network congestion can have the same impact on RLS as network partitioning.

To avoid infinite packet looping and duplication during flooding, nodes must be kept from forwarding queries they have already processed. Therefore the source node marks all location query packets it sends with a sequence number that increases with each attempt of the source node to acquire the destination node's location. Each forwarding node then uses a sequence number cache to check if it is permitted to forward this packet by comparing the sequence number stored in the query packet to the one in its cache. If no cache entry exists or the stored sequence number is smaller, the node has not sent out this query before and updates its cache before rebroadcasting it. A cached sequence number bigger than the one contained in the packet indicates a duplicate or looped packet and the query is discarded.

When a destination node receives a query packet that carries its id, it creates a location reply packet that is marked with the querying node's id and location as destination information and carries the responding node's id and location as payload. This reply is sent back to the source by means of the underlying routing protocol. The reception of a reply packet at the querying source completes the location discovery cycle. The destination's location is inserted into all packets buffered for this destination, and the packets are sent out.

Flooding defines a simple distribution method for packets: Each node re-broadcasts all packets it receives. If assume that the network is not partitioned, and if the TTL of the packet is at least as high as the diameter of the network and no link layer failures occur, all packets will reach every node in the network.

For RLS this proposal considers Binary Flooding. In many real-world scenarios communication is often local, for example at conferences or during courses on campus. It therefore makes sense to use a flooding scheme that distinguishes two types of communication: near and far communication. It is called, which was inspired by the route requests of Dynamic Source Routing, binary flooding. The source node first floods a close range neighborhood (e.g. one or two hops) to see if near traffic is intended. If no reply is received, the traffic is classified as far and *dmax* is set to the allowed limit – instead of increasing it gradually.

5.2.2 Forwarding Strategy

Since the control signals of different traffic lights are correlated to some extent if not time-varying, and then they can be used by vehicles passing through intersections to calculate the next hop based on the forwarding strategy. This proposal requires that sensors installed on traffic lights are able to locally broadcast the current status of traffic lights in all directions. The status of a traffic light has the following meanings: a) is it red, green or yellow? b) how long will it change to another status? c) which direction is it in charge of? d) the timing difference *d* with the next traffic light in the direction that it controls. Figure 5.1 shows an illustration.

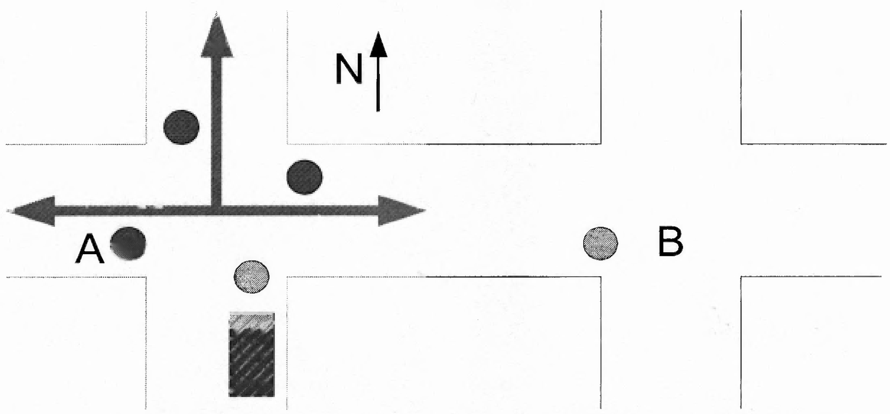

Figure 5.1 An illustration of sensors of traffic lights.

The shaded vehicle in Figure 5.1 will go straight or make turns at this intersection. Wherever it goes, the corresponding sensor will inform the vehicle its current status. If the vehicle makes a right turn, for example, it knows whether the traffic light B is red or green and when it will change to green or red. Figure 5.2 illustrates the timing relationship of A and B.

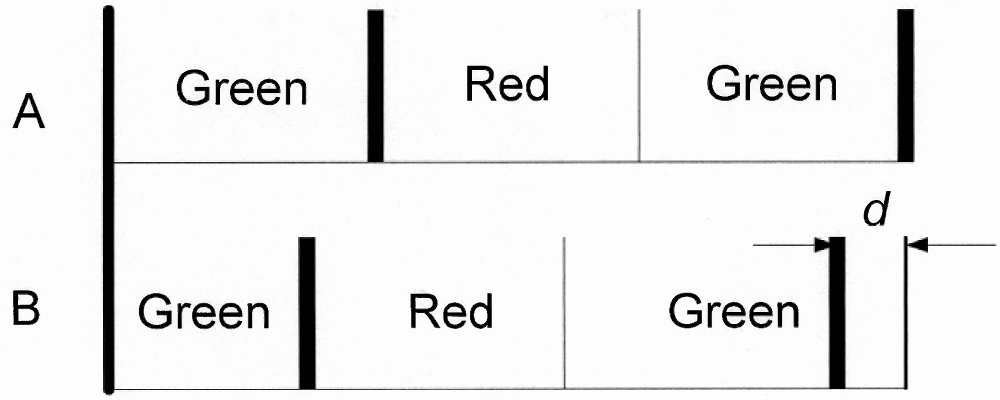

Figure 5.2 An illustration of timing relationship of adjacent traffic lights.

It is noted that d can be time varying during different traffic hours. Upon receiving the status of A, the vehicle then can predict that the traffic light B will be green or red by the time it reaches to B based on the street map and the on-board GPS receiver.

Once the location information of the destination is available, a sending vehicle then has two moving vectors as shown in Figure 5.3.

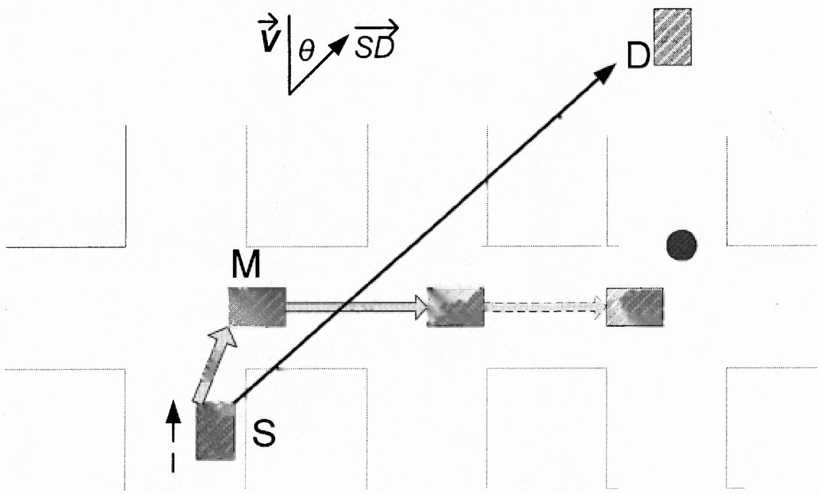

Figure 5.3 The next hop decision based on the moving vectors.

The closest distance between a source node S and destination D is denoted as r and is determined as follows:

1) Let $\vec{V}$ be the motion-vector of a node, pointing in the direction that the node is moving.

2) A second vector is drawn from the node to the destination, and is denoted by $\vec{SD}$.

3) The angle between these two vectors is given by:

$$\theta = \cos^{-1}\left(\frac{\vec{SD} \cdot \vec{V}}{\left|\vec{SD}\right|\left|\vec{V}\right|}\right)$$

4) The predicted closest distance of the node to the destination is

$$r = \sin\theta * \vec{SD}$$

Furthermore, if $\theta > 90$, the node is heading away. If $\theta < 90$, the node is moving towards the destination. The node may also be standing still. A current node will only forward messages to the next node towards the destination while the next node will not be stopped by the following traffic lights. In Figure 5.3, vehicle S senses that it will be stopped by a red traffic light ahead, and then the next relaying vehicle is its direct neighbor M moving vertically and towards the destination. Because M is allowed to move towards the destination by the green traffic lights and has a big chance to find another vehicle closer to D. While M selects its next hop using the same rule, it must make the decision according to the status of current traffic lights. With N as the neighbor node, Table 5.1 summarizes the rules for forwarding messages to the neighbor.

Table 5.1 The Forwarding Rules

Current	Neighbor	Forward
Still	Still	No
Still	Away	No
Still	Towards	Yes
Away	Still	Yes
Away	Towards	Yes
Towards	Still	No
Towards	Away	No

5.3 A Multicast Protocol For Real Time Traffic Visualization

Nowadays vehicles equipped with on-board GPS and geographical navigation systems have a great deal of freedom in terms of route planning and local service query. However, one of the most important functions, which will greatly benefit drivers to make quick but reasonable route planning, has not attracted enough attention and is still missing in shipped vehicles. It is the ability of acquiring real time traffic information for drivers. Traditionally, a driver can know the real time traffic only via radio broadcasting or by observing the road traffic surrounded his vehicle with eyes. Such information is either too imprecise or may be stale to make an optimal judgment. When traffic piles up, a driver cannot know how far an accident away from his vehicle or how long the traffic congestion extends during the rush hour, not along any available routes to avoid traffic jams. Previous works have not proposed any solutions to acquiring local real time traffic information. The only method is to broadcast a querying packet and wait for the replied packets. Apparently it will lead to the broadcast storm problem, and furthermore the available bandwidth is highly wasted. Besides that, it is difficult to control the broadcasting region when drivers need to know only the traffic related to their planned trajectory.

In this section, a multicast protocol is proposed in order to help drivers obtain real-time traffic conditions in any designated areas. Users can also customize the scale of traffic information being delivered to them. First drivers must designate the end of their trip, and then the on-board navigation system will calculate a valid route based on certain criteria. The vehicular node broadcasts a querying packet to its direct neighbors. The querying packet contains the id and location of the vehicle, the desired travel end, the location of a designated point to limit the broadcasting boundary and a scale factor F. F is initially 0 and the distance of the source the designated point is assumed as R. When its direct neighbors receive the querying packet, they reply with their current location information and take the next steps:

1) F is increased by 1 and forward the querying packet to their direct neighbors who are qualified for the rules defined next:

   a) Neighbors must be closer to the end than the source vehicle.

   b) If not, vehicles moving toward the destination should also replay the packet .

   c) For those neighbors violating the above conditions, they are selected with a probability of $\frac{1}{2^F}$.

2) Upon receiving the forwarded packets, vehicles should reply their location information and repeat the procedure depicted in 1).

Therefore, the querying packet is mainly disseminated among vehicles who are ahead of the source vehicle or possible to cause any delay of the source vehicle. The number of those less correlated vehicles replying the querying packet will be decreased drastically when F becomes larger. This multicasting method is a kind of directed flooding technique and can effectively reduce the broadcasting problem. Figure 5.4 depicts how the method works.

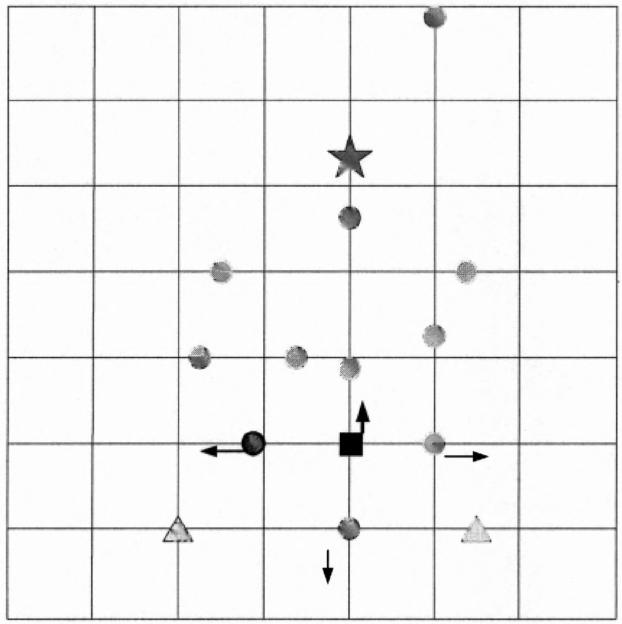

Figure 5.4 An illustration of the proposed multicasting protocol.

The square node is a source vehicle and the top node is the destination. The star represents the designated boundary that limits the propagation of a querying packet. The round nodes stand for vehicles that join the multicasting tree and the triangle nodes are vehicles not in interest of the source. The three green nodes with moving direction arrows must be selected because they are the direct neighbors of the source node.

Upon receiving the replied querying packet, the source vehicle is able to display the position information of related vehicles within the designated boundary onto the on-board screen. Thus the driver will have a roughly visualized traffic distribution image that is helpful.

5.4 Performance Evaluation

5.4.1 Simulation Setup

To measure the performance of the proposed routing strategy and the multicast protocol, a simulation framework is set up with a terrain size of 4000m × 4000m with one source and one destination located at the opposite corner, as shown in Figure 5.5. Nodes move using the Manhattan Grid model between 5~10 m/s, following city street structures. Each cell represents a building block and there is a street between two blocks. Spaces between streets are buildings and therefore, radio waves cannot propagate through them. Thus, two nodes can only communicate directly with each other when they are in their respective transmission ranges and also obey the 'line-of-sight' rule.

Two classical ad hoc routing protocols, Dynamic Source Routing (DSR) and Ad Hoc On-Demand Distance Vector Routing (AODV), are used to compare with the proposed method. Simulations were finished with NS2 CMU extensions. The transmission rate is 2 Mbps and the transmission distance has two values, 250m and 500m, because small range may lead to no connectivity in city areas. A packet of 512 bytes is sent every 10 seconds, for 1000 seconds. The simulation runs for 5000 seconds, to allow packets to propagate through the system after the data sending phase is complete.

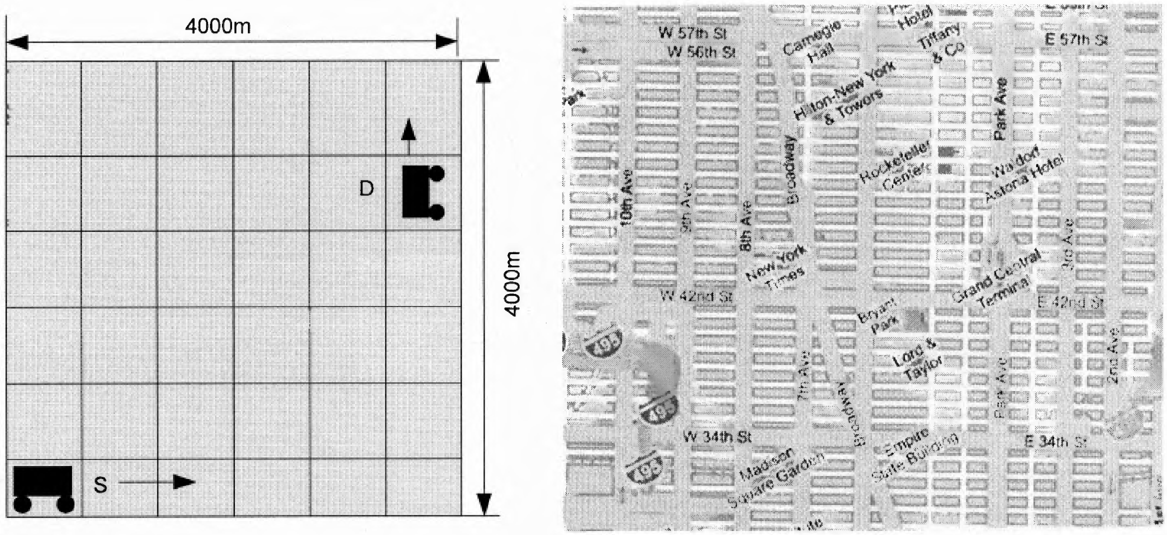

Figure 5.5 The simulation setup using Manhattan grid model.

Several pairs of vehicles are randomly selected as communication peers. The CORSIM simulator is used again to generate near real urban traffic with different traffic density. The average number of vehicles in each street segment is in the range of 5-50. The metrics measured in the simulations are packet delivery rate (Figure 5.6), latency for the first packet (Figure 5.7), the number of hops (Figure 5.8), and the comparison of bandwidth consumption (Figure 5.9). Each point in the above mentioned graphs is based on at least 10000 packets exchanged.

The simulations on achievable packet delivery rate (Figure 5.6) shows good results for the position-based approach compared with DSR that shows some performance problems. Compared with AODV the proposed method still gains some advantage. The observed latency in Figure 5.7 for the first packet of a connection is similar to that of DSR and the proposed methods with a small advantage for DSR. This is to be expected

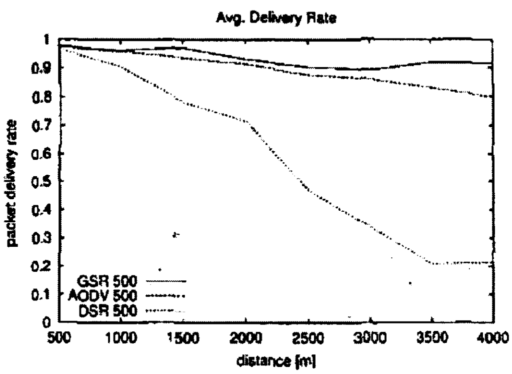

Figure 5.6 Packet delivery ratio vs. communication distance.

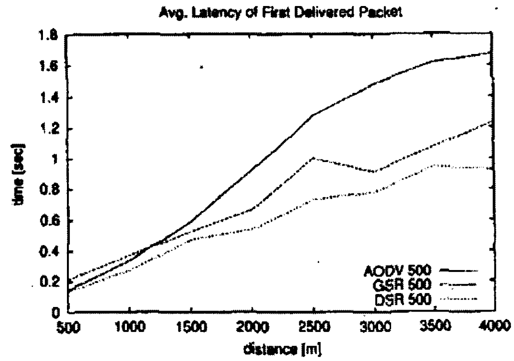

Figure 5.7 Latency of the first packet.

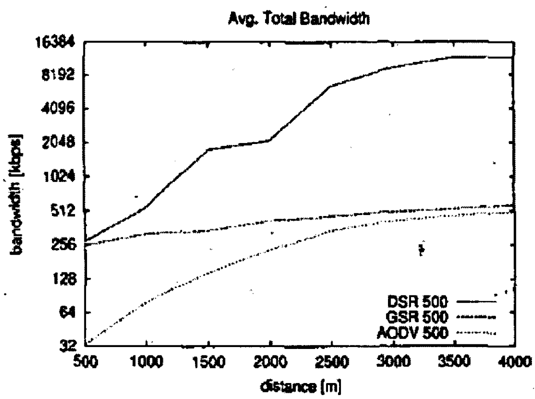

Figure 5.8 Average bandwidth consumption.

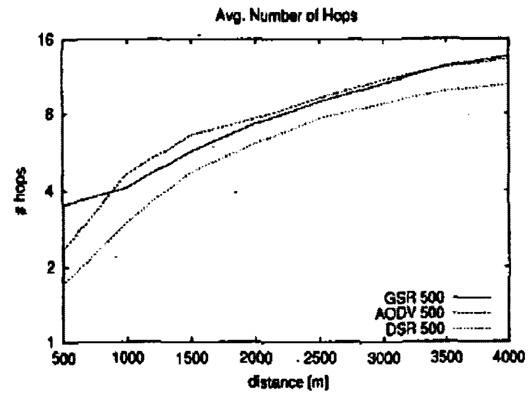

Figure 5.9 Average number of hops.

Since the route establishment in DSR and the location discovery in position-based routing are very similar, the usage of expanding ring search technique of AODV is responsible for the higher latency since it is a trade-off between bandwidth consumption and latency. Figure 5.8 shows that both AODV and the proposed method have a slightly longer route to the destination node. The explanation is that DSR is more aggressive to choose any node with the most progress, which also leads to frequent route breaks. The main problem of DSR is the noticeable bandwidth consumption for routing overheads (Figure 5.9). DSR creates large packets because of the source route in the headers, especially during the route discovery phase, which leads to a significant bandwidth overload. Mobility is another reason that causes DSR failure. However, DSR is maybe preferable when a given street does not have enough connectivity since it can find other routes.

5.5 Summary

This chapter discussed the constraints of routing protocols for vehicular ad hoc networks in city environments. It is observed that traffic lights can shape the road traffic and split them into scattered groups. Therefore, a new proposal is introduced to utilize this property in order to forward packets while reducing the probability of link failure cause by vehicle mobility. The study shows that this method can significantly reduce the hops for reaching a destination and is robust to topology changes of vehicular ad hoc networks. A new multicast protocol is also proposed to help drivers acquire local real time traffic information. Based on a binary selective flooding algorithm, a vehicle is able to collect enough road traffic status and then display them using the on-board screen. This method does not cause broadcast storm and is flexible to control the boundary of multicasting.

CHAPTER 6

AD-HOC ROBOT WIRELESS COMMUNICATION

6.1 Introduction

As VLSI technology advances and computing power grew in the past twenty years, robots became more and more intelligent, robust and consumed less and less power. Moreover, they are required to handle more and more so-called teamwork. It means that they must be developed to possess the capability of constructing a network and performing cooperative works. A key driving force in the development of cooperative mobile robotic systems is their potential for reducing the need for human presence in dangerous applications [Parker, 1998]. Such applications as the disposal of toxic waste, nuclear power processing, fire fighting, military or civilian search and rescue missions, planetary exploration, security, surveillance, and reconnaissance tasks have elements of danger. In these cases, wireless communication provides the low cost solutions for mobile robot networks to cooperate efficiently.

In the early robot wireless communications, infrared technology was applied in a large scale [Kahn 1997][Hsu 2000] because of its low cost. But infrared wave cannot pass through obstacles (e.g. wall) and infrared systems have poor communication rate and quality (rain effect). Radio frequency (RF) technology is preferred in the design of mobile robot communication. Robots can communicate with others by RF point-to-point link or broadcasting mechanism [Chlamtac 1985]. The frequency hop spread spectrum (FHSS) and direct sequence spread spectrum (DSSS) modulation technologies are extensively applied at the Industrial Scientific Medical (ISM) band (2.4 GHz), which is license-free in many countries [Wong 1995][Arai 1993]. The proliferation of Internet-like networks has motivated research to address wireless LAN (IEEE 802.11), Bluetooth standards, and ad hoc networking fashion in mobile robot systems [Basagni 1999][Genovese 1992]. Figure 7.1 shows the evolution of robot wireless communication.

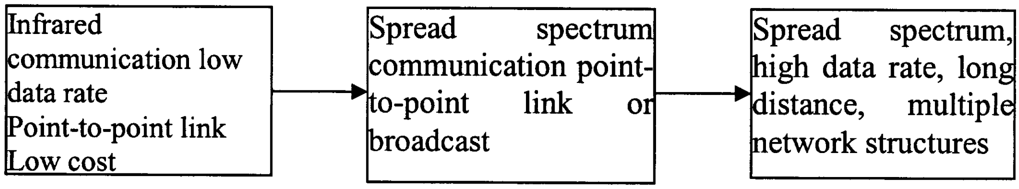

Figure 6.1 The evolution of robot wireless.

Table 6.1 compares wireless communication technologies that are available for mobile robot communication.

Table 6.1 Wireless Communication Technologies for Mobile Robots

	Infrared	IEEE 802.11b	Bluetooth
RF band (GHz)		2.4/5	2.4/5
Modulation		DSSS	FHSS
Data rate (Mbps)	0.1- 4	11 (shared)	0.72 future 10/20
Range (m)	4	30-100	10-100
Network structure	PPP	Infrastructure and ad hoc	Ad hoc
Power	5 mw	1w	0.3mw-30mw

The wireless communication link is characterized by long bandwidth-delay, dynamic connectivity, and error-prone links. The robots are often equipped with low-power short-range wireless network interfaces, which only allow direct communication with near neighbors. Hence, it is virtually impossible for each node to know the entire network topology at any given time. Under these circumstances the only practical approach to distributed command, control and sensing is to employ an ad hoc wireless networking scheme [Winfield 2000].

In contrast to a WLAN network that needs some base towers, an ad hoc network is an infrastructureless network where the nodes themselves are responsible for routing the packets. Mobile nodes communicate with each other using multihop wireless links. There is no stationary infrastructure e.g., no base stations. Each node in the network also acts as a router, forwarding data packets for other nodes. Furthermore, because the topology in such a network can be highly dynamic, traditional routing protocols can no longer be used [Perkins 1999].

The design of ad hoc networks has focused on the development of dynamic routing protocols that can efficiently find routes between two communicating nodes. The routing protocol must be able to keep up with the mobility of nodes that often changes the network topology drastically and unpredictably. Recently there has been a renewed interest in this field due to the common availability of low cost laptops and palmtops with radio interfaces. A mobile ad hoc networking (MANET) working group has also been formed within the Internet Engineering task force (IETF) to develop a routing framework for IP-based protocols in ad hoc networks.

This chapter proceeds as follows. First it reviews MANET and its routing protocols in Section 6.2. Section 6.3 discusses the protocol stacks and explains why ad hoc is practicable for mobile robot wireless communications. Section 6.4 illustrates some applications. Finally Section 6.5 concludes the chapter.

6.2 Robotic MANET

MANET is a collection of mobile nodes which form a temporary network. The network has dynamic and unpredictable topology. In such networks there is no centralized administration or standard support services. Moreover, each host is modeled as an independent router. Hosts use wireless RF transceivers as network interface. They have limited bandwidth, power supply, and limited transmitter range. The network allows multiple radio hops but it lacks of symmetrical links. Ad hoc routing protocols can be broadly categorized into proactive and reactive protocols [Royer 1999].

Proactive routing protocols have the characteristic of attempting to maintain consistent up-to-date routing information from each node to every other node in the network [Shah 2002]. Every node maintains one or more routing tables that store the routing information, and topology changes are propagated throughout the network as updates so that the network view remains consistent. The protocols vary in the number of routing tables maintained and the method by which the routing updates are propagated. Two common proactive protocols among many are.

Destination-Sequenced Distance-Vector Routing protocol (DSDV) [Perkins 1997] is based on the Bellman-Ford algorithm for shortest paths and ensures that there is no loop in the routing tables. Every node in the network maintains the next hop and distance information to every other node in the network. Routing table updates are periodically transmitted throughout the network to maintain table consistency; and

Link-State Routing (LSR) [Jacquet 2002] is a proactive protocol in which each node floods the cost of all the links to which it is connected. Every node calculates the cost of reaching every other node using shortest path algorithms. Moreover, the protocol can work correctly even if one-way links are present while DSDV assumes two-way links.

In contrast to proactive ones, reactive protocols create routes only when desired. This means that an explicit route discovery process creates routes and this is initiated only on an as-needed basis [Shah 2002]. It can be either source initiated or destination-initiated. Once a route has been established, the route discovery process ends, and a maintenance procedure preserves it until the route breaks down or is no longer desired. Ad-Hoc On-Demand Distance Vector Routing (AODV) is a reactive routing protocol although it is based on the distance vector algorithm like DSDV. It is a source-initiated protocol, with the source node broadcasting a Route Request (RREQ) when it determines that it needs a route to a destination and does not have one available. This request is broadcast till the destination or an intermediate node with a "fresh enough" route to the destination is located. Intermediate nodes record the address of the neighbor from which the first copy of the broadcast packet is received in their route tables, thus establishing a reverse path.

In conclusion, proactive routing protocols can be deployed in a small size and slow topology-changed network. The routing packets needed by protocols would not add too much load of the network under this situation. However a reactive protocol may be more suitable for a large scale and fast topology-changed network because the routing tables that are maintained at each node should be small compared to the size of the network to avoid requiring large caches. A large network can often be divided into some small subnets. Then proactive protocols and reactive protocols may co-exist. For example, proactive protocols can be used in subnets while reactive protocols are used among subnets.

6.3 Mobile Robot Communication Networks

6.3.1 Mobile Robot Networking Layered Model

Mobile robot wireless networks provide the networking infrastructure to support the quality of service (QoS) needs (bandwidth, latency and reliability) of robot communications. They must support: quick reconfiguration (802.11, token ring [Sugiyama2000]), mobility management (mobile IP, AODV), service level agreement (SLA) management, and QoS (mobile Internet Protocol). Figure 7.2 gives the layered model of mobile robot networking.

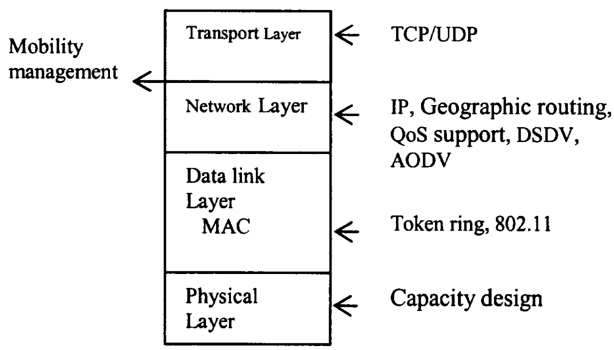

Figure 6.2 Mobile robot networking layered model.

In the system of cooperative multiple mobile robots, communications among them are critically important. Each robot should exchange the information collected through its sensors and negotiate its task scheduling with the other robots. These robotic communications are executed through the random access telecommunication among mobile robots. Experiments of robotic communication among several robots are reported using wireless LAN or infrared sensory systems [Alami 1998][Sugar 1999]. Wireless

LAN devices that make use of spread-spectrum modulation and a UHF carrier (typically 2.4 GHz) offer the potential for high message data rates over a reliable physical layer implementation. Specially, the model called Murdoch [Gerkey 2001] used a publish/subscribe messaging model to coordinate autonomous robots.

However, the applicability of these systems to a large number of robots remains to be demonstrated. A modified cellular system for wide range robotic communication is proposed [Adachi 1998]. However, the communication service area is restricted by the positions of base stations.

6.3.2 Why ad hoc?

Consider a group of mobile robots that are required to autonomously disperse throughout a region, perform distributed sensing, monitoring or surveillance, and pass the sense data to a single collection point. The robots are most likely equipped with only low power wireless transceivers whose range is too short to allow direct communication with the data collection point, but sufficient to allow robots to communicate with close neighbors. Under these circumstances an ad hoc wireless networking scheme becomes a unique choice.

The disadvantages of centralized control for robot teams were apparent as one may have observed in “Star Wars Episode I: The Phantom Menace”. The bad robots had a single centralized point of failure; A whole army was rendered useless when their controlling computer was destroyed [Vaughan 2004]. This example apparently suggests that centralized control and communication could more easily lead to a fatal system breakdown. In other words, robustness may be low. Secondly, designers may not prefer a centralized system due to the design and cost consideration. To guarantee certain level of

QoS, expensive base stations are required to cover the service area. Therefore complex system management will obviously increase the total cost of a system. On the other hand, decentralized and distributed systems based on local interactions among autonomous nodes support ad-hoc changes in population, connectivity and local constraints. They show robustness to local failures and scale very well and are sufficient for most applications. The real-world ARPAnet was conceived as protection against the Star Wars scenario. The success of its subsequent development into the Internet is evidence of the power of the decentralized control and communication concept.

In unpredictable or unplanned environments mobile robots need to create a wireless network to cooperate and schedule tasks. Multihop ad hoc networks capable of self-creating and self-organizing become a natural method used to meet such need.

6.3.3 Energy-optimized Protocols

Because mobile robots are mainly dependent on battery power, it is important to minimize their energy consumption. This chapter only discusses the communication subsystem of mobile robots. The two main layers are the media access control (MAC) and network layers.

6.3.3.1 Media Access Control (MAC) Layer. The MAC layer's primary functions are to provide access control, channel assignment, and neighbor list management. It also performs power control to ensure power savings. The main principles guiding low-power distributed MAC design include collisions avoidance, reduced protocol overhead, and power-off during idle time. First, collisions should be avoided since retransmission leads to unnecessary energy consumption and possibly unbounded delays. Secondly, protocol overhead should be reduced as much as possible, including packets dedicated for network control and header bits for data packets. Thirdly, since receivers have to be powered on at all times resulting in significant energy consumption, the more time the radio can be powered off, the greater the power savings. Researchers have developed some energy-aware MAC protocols: Power-Aware Routing in Mobile Ad hoc networks (PAMAS) schemes, time-division media access (TDMA) and the 802.11specification.

A major source of extraneous energy consumption is from overhearing [Singh 1998]. In PAMAS, radio of a node is powered off when not actively transmitting or receiving packets. In Figure 6.3, node A's transmission to B is overheard by C because C is a neighbor of A. PAMAS avoids the overhearing problem by powering off C. Thus C will not spend energy in receiving a packet that is not sent to it. But PAMAS does not address the problem of energy consumption when nodes are idle. The work [Stemm 1997][Xu 2001] shows that idle energy dissipation cannot be ignored in comparing to sending and receiving energy dissipation.

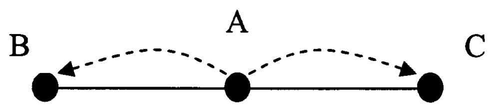

Figure 6.3 Overhearing problem.

TDMA [Pottie 2001] protocols have been proposed to reduce energy consumption in sensor networks. By reducing the duty cycle these protocols can trade idle-time energy consumption for latency. However the conclusion holds only when radio also runs at a lower data rate.

IEEE 802.11 supports power saving mode in both infrastructure and ad hoc networks: mobile nodes are brought together to form a network on the fly. 802.11 also provides power management controls to allow disabling a transceiver to conserve energy. Although they specify how to turn off the radio, they do not discuss specific policies.

6.3.3.2 Network Layer. Addressing, routing and support for different classes of service are the primary functions of the network layer. This paper only concentrates on a routing issue. Some routing protocols of ad hoc network were discussed in the previous section. They are traditionally evaluated in terms of packet loss rates, routing message overhead, and bandwidth utilization. They have not paid much attention to robot-oriented ad hoc routing protocols. A number of energy-conserving protocols for ad hoc routing have been proposed [Intanagonwiswat 2000][Ko 1998][Xu 2001][Shah 2002]. This chapter examines some recent studies: Directed Diffusion, Location-Aided Routing (LAR), Geographical adaptive fidelity (GAF), and energy aware routing.

Directed Diffusion [Intanagonwiswat 2000] is a destination-initiated reactive protocol. A destination node (controller) broadcasts its interest in certain data, and the source node reply back, setting up multiple paths to the destination in the process. Due to the multiple paths created, the scheme assures data flow in the event of node failure. However, diffusion requires the use of large caches at every intermediate hop.

LAR utilizes location information to improve performance of routing protocols in ad-hoc networks [Ko 1998]. They use location information to decrease overhead of routing discovery by limiting the search space for a desired route. But sometimes positioning information is not easily accessible, and then LAR may be affected by moderate location error or even by large, correlated error.

GAF is compatible with LAR as it is with other ad hoc routing protocols [Xu 2001]. GAF's approaches to energy savings are implemented by state transitions of nodes. An active node can enter sleep state if its energy decreased to a pre-defined level. It can also enter discovery state to update topology changes by setting an appropriate timer. GAF can balance load (energy usage) and adapt to high mobility. However, determining node equivalence by means of virtual grids is complex and difficult. Additionally, if a node is actively routing packets when it is powered off, GAF depends on the ad hoc routing protocol that allow quickly re-routing traffic. This may cause some packet loss.

The basic idea of energy aware routing is to increase the survivability of networks. Multiple paths are found between source and destinations, and each path is assigned a probability of being chosen, depending on the energy metric. Every time data is to be sent from the source to destination, one of the paths is randomly chosen depending on the probabilities. This means that none of the paths is used all the time, preventing energy depletion. Energy aware routing is also a reactive routing protocol and similar to diffusion. However, diffusion sends data along all the paths at regular interval, while energy aware routing uses only one path at all times. But due to the probabilistic choice of routes, it can continuously evaluate different routes and choose the probabilities accordingly.

The potential problem in current protocols is to find the lowest energy route and use that for every communication. Yet this is not the best thing to do for network lifetime. Using a low energy path frequently leads to energy depletion of the nodes along that path and in the worst case may lead to network partition [Shah 2002]. Energy aware routing is a promising protocol but more experiments and actual traffic scenarios are still needed. Since an ad hoc network works in a multihop way, the protocol overhead should be adequately small and then would not waste too much power. A trade-off exists between routing robustness and energy conservation. In some non-real-time applications, data packets could be buffered in caches and burst them in a combined packet, increasing the latency, but reducing the total energy consumed. Apparently, energy conservation should be considered not only in MAC and network layers, but also in application-level. Integration of energy conserving consideration in multi-layers requires the future work.

A tight integration between network, mission and motion control can compose a unified Energy-Conserving Protocol Stack for future developed Small-Scale Robots. This allows a substantial energy savings while keeping delay and throughput requirements within application constraints. Next subsection will discuss such integration.

6.3.4 Robot Control and Communication Strategies

Successful control and coordination of a group of wireless-networked robots relies on effective inter-robot communication [Ye 2001]. Robot controllers should be robust with respect to unpredictable and highly dynamic environment; due to the naturally hostile characteristic, controllers must also contend with imperfect wireless communication. Apparently the network is also part of the robots' environment and can contribute to the system's success or failure. At the simplest level, communication may succeed or fail between two nodes.

Robots typically operate under strict real time constraints [Gerkey 2001][Ye 2001]; fast navigation and dynamic environments require that control inputs are acquired in a timely manner. Heavy load on a wireless network increases the average data transmission time, and reduces the frequency response of controllers. Thus it may reduce the capability of the controller. Reducing load by more efficient communication can decrease latency and allow robots to be more responsive to dynamic environments.

Bandwidth is a precious resource if a robot's task involves transmitting huge data to a user (e.g. live video). Controller data is unwelcome overhead on the shared communications channel [Gage 1993]. Efficiency becomes increasingly important when scaling to a large numbers of nodes. Efficient communications are essential to save power and reduce latencies. It can be achieved by considering the interaction between controller and communication channel; controllers should be designed to take into account protocol characteristics and propagation conditions, and specialized protocols can be designed for mobile robot applications [Gerkey 2001][Ye 2001]. An example application in which a team of mobile robots explores an initially unknown environment to locate a supply of resource [Ye 2001] is used to illustrate such needs.

6.4 Applications of mobile robot communications

Robot communication applications choose ad hoc networks when central bases are not available in many cases and/or a strong need arises to avoid the vulnerability of centralized infrastructure. In the following applications they can be used to improve the robustness and scalability performance of a multi-robot system.

6.4.1 Robot Soccer Game

In [31][32], different types of robot soccer players take part in some official robot soccer games, for example, FIRA Cup. CENDORI and SOCCERBOT deploy the wireless LAN devices which are based on 802.11 standard. [Murata 2002] use the Bluetooth ad hoc network to coordinate the team performance.

6.4.2 Explosive Ordnance or Hazardous Materials Disposal

In the Mobile Detection Assessment and Response System (MDARS) project [Gage 1997], mobile robots were organized in a centralized way in a large warehouse near San Diego to detect intruders and anomalous conditions such as flooding or fires. It was proved that an ad hoc network could provide more flexibility and robustness in a highly mobility environment than WLAN.

6.4.3 Rescue and Recovery Operations

Robot teams can play an important role in disaster recovery such as earthquake rescue operations or nuclear plant accidents. By means of ad hoc network, robots can coordinate their activities with reliable communication regardless the conditions of all fixed infrastructures.

6.4.4 Unmanned Vehicles

Unmanned Aerial Vehicles (UAVs) and Unmanned Marine Vehicles (UMV) are emerging as a viable and cost effective alternative to space and ocean surveillance. These teams must operate in remote regions with little/no infrastructure, hence the autonomous teams of UAVs and UMVs are organized into a MANET. Such configurations result in relatively stable topologies and thus robust communications.

6.4.5 Planetary and Volcano Exploration

NASA developed many robots such as Pathfinder, Robonaut for Mars exploration or other space journey; Dante is a volcano explorer robot. More studies are needed to investigate if ad hoc networking is feasible [Weisbin, 2000].

6.5 Summary

Ad hoc mobile robot communications are a promising networking technology. Yet they represent a relatively underdeveloped application field. The chapter discusses ad hoc protocols and analyzes energy conservation routing protocols whose system performance metric is energy saving. Other metrics such as connectivity, throughput, accuracy, security, robustness and bandwidth efficiency, should also be considered in measuring the performance. In the design of wireless robot networks, one needs to evaluate overall performances with respect to practical requirements. In an energy-constrained environment, protocols should pay more attention to energy consumption, but for a real time image-sensing task, system throughput and bandwidth utilization are more important. Therefore, Different protocols need to be developed to optimize different metrics. Moreover, future research is required to develop prioritized protocols so that a system can deploy protocols according to the priority of performance metrics in real time.

CHAPTER 7

CONCLUSIONS AND FUTURE RESEARCH

7.1 Conclusions

This doctoral dissertation presents the investigations of some important issues in on mobile ad hoc networks applying intelligent transportation systems, multiuser detection technique based on IEEE 802.11 MAC layer and robot mobile networking technology.

7.1.1 Summary of Contributions

The contributions of this dissertation are summarized into three aspects:

1) Space and network diversity combining for packet collision separation

   A novel signal separation algorithm is proposed. Essentially it is a kind of multiuser detection technologies and can nicely solve the masked node problem induced by IEEE 802.11 RTS/CTS handshaking protocol. It outperforms the traditional NDMA multiple access method in that it combines both spatial and network diversities. Colliding packets can be more easily separated given certain conditions. To do so, this research introduces orthogonal packet ID sequences for signal processing and two types of epoch for analyzing its performance. Both analytical and simulation results prove that this approach has significant improvement in terms of throughput and delay.

2) Position-based clustering approach for vehicular ad hoc network

   Constantly changing topology of vehicular ad hoc network is quite different from the topology of regular mobile ad hoc networks. It is impossible to obtain global network information for nodes and organize vehicles according to their traditional routing metrics. The proposed clustering approach is based on vehicle's location which is used to elect cluster head according to certain priorities and control cluster size. This work is different from the previous research in that it is not a position-based routing mechanism. Although pure position-based routing has no need for routing table, location information services, whichever are local or global, are required. In highly dynamic vehicular environment, it is extremely hard to provide real time services if not impossible. This work integrates the geographic information into the network topology management while maintaining compatibility of conventional routing schemes. This work shows that position-based topology management is better than ID-based and connectivity-based methods in terms of cluster stability and communication overheads.

3) Epidemic routing for vehicular ad hoc network

Based on the conventional best effort packet delivery service, this research improves it to accommodate store and forward characteristics. Not only rapid topology change but short-lived data paths impose great difficulty on delivering messages for neighboring vehicular nodes. Neither proactive nor reactive routing algorithms are suited for vehicular communication. Combined with position-based routing, this store and forward routing method can improve the successful delivery rate to some extent. Considering the inherent features of vehicular ad hoc networks, this research also investigates the impact of multiple lanes in roadway on the probability of successful message delivery with respect to the spatial redundancy.

7.1.2 Limitations

This research has the following limitations:

1) In order to utilize the multiple diversities, each node whose packets collided with each other must retransmit L more times. Meanwhile, no other nodes are allowed to transmit any signal or data during next time slots. This requirement may not be apparently satisfied even when traffic load is even moderate.

2) Although position information can be obtained through some GPS-like devices, location errors may cause loops during cluster establishment.

3) Once traffic density is low or network partitioning rate is quite high, messages have to stay in buffers for longer time and then low connectivity rate is expected.

7.2 Future Research

There are several ways in which this work could be extended in the future. Some important and promising directions are listed as follows:

1) While applying ad hoc networking technologies in inter-vehicle communication, safety and efficiency are not the only objectives of VANETs. Comfort aspects are also important to drivers as well and have attracted more attention recently. Drivers may want to communicate with their friends in other vehicles using some sophisticated applications by the aid of the underlying infrastructures. Such as video conferencing, voice chatting, game playing, medical monitoring and more are potential applications that are desired for certain groups users. These cooperative tasks require a new multicasting protocol to support such services without sacrificing network resources. Under vehicular environment, multicasting is quite different from that of regular MANET.

2) Security is becoming the top issues either for ad hoc network research or commercial industries. It is certainly critical for vehicular ad hoc network too. The mobility pattern and vehicular traffic models apparently affect the implementation of security in VANET. For example, heavy computational load for authentication and encryption may reduce the available bandwidth considering the short-live data path. Good tradeoff between them needs to be made. Moreover, tracing a hostile user becomes more difficult since its speed and position keep changing.

3) For intelligent transportation system, vehicle types can significantly affect the performance of VANET. Vehicles have different sizes, speed and mobility patterns. For example, buses with larger volume can decrease available road capacity but on the other hand, they have deterministic routes to provide services. Then VANETs could take advantages of such traffic patterns by taking into account the diversity of vehicles. However, previous researchers have not yet paid adequate attention to it in their related works. The future research may contribute some helpful solutions to this issue.

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