Study on Routing Protocols for Vehicle Ad-Hoc Networks

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概要

この論文は，新たに提案した車両アドホックネットワークにおけるルーチングプロトコルに関する研究成果をまとめたものである．

現在，生活を支援するために偏在するコンピュータやセンサーを接続するユビキタスネットワークが，国際的に注目を集めている．ユビキタスネットワークでは，有線・無線という垣根の無いシームレスなネットワークを構築し，それを社会に役立てることを目標としている．このユビキタスネットワークを実現する主要技術の一つにアドホックネットワークがある．アドホックネットワークは，移動端末同士を無線接続して形成されるネットワークである．交換機や基地局といった通信施設を使用せずに，低コストで拡張性の高いネットワークを構築できる利点を持つ反面，ネットワークトポロジーが動的に変化することから，移動端末間のパケット伝送は容易ではない．従って，アドホックネットワークにおけるルーチングプロトコルの検討は，最も重要な研究課題の一つに挙げられる．

アドホックネットワークにおけるルーチングプロトコルの検討は，IETF の MANET (Mobile Ad hoc Network) ワーキンググループを中心に進められている．しかし，MANET ワーキンググループで提案されているルーチングプロトコルは汎用性をより重視しているため，特殊なネットワーク環境では，高い通信性能を引き出すことができない．この様な観点から，具体的なネットワーク環境として車両アドホックネットワークに焦点を絞り，車両アドホックネットワークに適したルーチング方式を提案することによる通信性能の向上を試みた．

本論文は，６章から構成されている．

第１章は序論で，本研究の背景・課題について総括し，本研究の目的について述べている．

第2章は，本研究において前提とするネットワークモデルについて述べる．

第3章では，近距離の車々間通信を実現する時のルーチングプロトコルについて論じる．車両アドホックネットワークはトポロジーの動的変化が大きいため，車々間通信を実施する際には寿命の長い安定した通信ルートを構築しなければ，通信ルート切断時に発生する制御パケットの送信がオーバヘッドの増加を招く．この問題を解決するために，本研究ではビーコンなどを使用せずに安定した通信ルートを構築する車両アドホックネットワーク向けルーチングプロトコルRSR(Relative Speed-based Routing)を提案する．RSRは隣接車両との相対速度や車間距離変化量の累積値をメトリックとするルーチングプロトコルであり，リアクティブルーチングで使用されるルート探索パケット中に相対速度，車間距離情報の要素を組み込むことにより実現する．シミュレーションによりRSRと代表的なリアクティブルーチング方式であるAODV，安定度を考慮したリアクティブルーチング方式であるFORPとを比較し，提案方式の有効性を示している．

第4章では，有線網を併用することによって，高いスループットを引き出す車々間のルーチングプロトコルについて論じている．有線網を併用する環境では，アドホックネットワークを構成する車両間の通信経路として，無線中継のみの通信経路と基地局及び既設ネットワーク経由の通信経路との2通りが存在する．本研究では，既設ネットワークを経由させる経路と無線中継のみの経路のどちらがより高いスループットを引き出すかを簡単な数式により判断するルーチング方式を提案する．無線中継のみの通信経路と，既設ネットワークを経由させる通信経路との通信性能をシミュレーションにより計測し，計測結果を元に経路選択の判断基準を導いた．提案方式をAODVに組み込み，シミュレーションにより提案方式の有効性を示している．

第5章では，車両アドホックネットワークにモバイルIPを適用する時に課題となる，フラッディングの効果的な実現方法について述べている．遠距離車両間での通信を実現させる場合，車両アドホックネットワークにモバイルIPを適用することが，現実的な解決方法である．既存研究の多くは，アドホックネットワークにモバイルIPを適用するためには，ルータ広告パケットの周期フラッディングが必要であると記している．フラッディングは，多くの無線帯域を消費することが知られており，いかに少ない無線帯域でフラッディングを実現するかは，重要な研究

課題である．本研究では，新しいフラッディング方式として，SBF (Sector-Based Flooding) と ASBF (Adaptive Sector-Based Flooding) を提案する．両者とも，位置情報を使用するフラッディング方式である．SBF は，パケット中継停止の判断基準により，SBF-1 と SBF-2 に大別される．ASBF では，各端末が自律的に周辺の端末密度を推定することにより，ピュアフラッディング，SBF-1，SBF-2 を使い分けることを特徴としている．端末密度は送信端末とセクタ代表地点間の距離をもとに推測している．シミュレーションにより，提案方式の有効性を示している．

第 6 章では，本研究によって得られた成果をまとめると共に，車両アドホックネットワークにおける残された課題やアドホックネットワークに対する今後の展望について言及している．

Abstract

This thesis summarizes research achievements of novel routing protocols suggested for vehicle ad-hoc networks. Currently, ubiquitous networks that connect distributed computers and sensors to support human life attract attention internationally. In order to realize the ubiquitous networks, following two steps are required: spreading seamless networks into every corner of our life, then making the established networks easy to use for people.

Ad-hoc networks are one of the key technologies to realize the first step. Ad-hoc networks are composed of mobile stations that communicate with each other wirelessly. Ad-hoc networks have some promising features, such as their absence of infrastructure and their high scalability. However, ad-hoc networks have their drawbacks also, such as the difficulty of packet forwarding between mobile stations, since network topology changes dynamically. Therefore, routing protocols for ad-hoc networks are one of the most important research subjects.

The standardization of routing protocols for ad-hoc networks is discussed in mobile ad-hoc networks (MANET) working group (WG) of Internet Engineering Task Force (IETF). However, these routing protocols give their weight to general versatility. Consequently, they cannot achieve high throughput in particular ad-hoc networks environments. From this point of view, this thesis focuses on vehicle ad-hoc networks as a concrete network environment and presents routing protocols that increase communication performance.

This thesis consists of six chapters. Chapter 1 is the introduction; the background, sub-

jects, and purpose of this study are organized. Chapter 2 describes network model that is the premise condition of this study.

Chapter 3 describes routing protocols for short distance inter-vehicle communications. A point to consider with respect to vehicle ad-hoc networks is that dynamic changes in topology frequently occur. Unless a stable communications route with long life is constructed in intervehicle communications, the transmission of control packets generated when the communications route is disconnected will increase the overhead. In order to solve this problem, this thesis proposes relative speed-based routing (RSR) for vehicle ad-hoc networks in which a stable communications route is constructed without using beacons or similar means. RSR is a routing protocol that uses the relative speed and the cumulative change of the distance to neighboring vehicles as the metric. The protocol is realized by including the relative speed and intervehicle distance information as elements in the route request packets used for reactive routing. RSR is compared by simulation to ad-hoc on-demand distance vector (AODV), which is a typical reactive routing protocol, and flow-oriented routing protocol (FORP), which is a reactive routing protocol emphasizing stability. It is shown that RSR is better in terms of packet arrival ratio and stability.

Chapter 4 describes routing protocols for inter-vehicle communications via established networks. In such network environments as vehicle ad-hoc networks combined with established wired networks, two types of routes exist between vehicles: routes using wireless links only and routes via access points and the established networks. This thesis presents a new routing protocol that uses simple formulas to decide which route is effective, a route using wireless links only, or a route via the established networks. The formulas are derived from the results of simulation on the communication performance of some routes that uses IEEE802.11b as wireless links and Ethernet of 100 Mbit/s as wired links. The performance of our proposed routing protocol, which is realized as an extension of AODV, is evaluated by simulation. The results show that the proposed routing protocol is effective especially under a high data rate situation compared with AODV.

Chapter 5 describes flooding methods that are needed to realize long distance inter-vehicle communications. In order to realize communication from a vehicle to another vehicle in a distance, application of mobile IP protocol is a realistic approach. There exist many reports as for applying mobile IP to ad-hoc networks. However, most of them require periodical flooding of agent advertisement packets. Periodical flooding of the packets wastes precious wireless bandwidth much. Therefore, an efficient flooding method is needed to reduce wireless bandwidth waste. This thesis presents sector-based flooding (SBF) and adaptive sector-based flooding (ASBF) that are flooding methods for vehicle ad-hoc networks using position information. SBF is divided into two methods, SBF-1 and SBF-2; the difference is the number of criteria used to decide whether to re-broadcast or to drop the packet. In ASBF, each node selects a flooding method from among SBF-1, SBF-2, and pure flooding, depending on its local node density. The node density is obtained from the distance between the sender node and the sector representative position. Simulation results show that SBF reduces the number of packet transmissions generated in flooding and ASBF has high packet reachability with few packet transmissions.

Chapter 6 concludes the achievement of this study. The future works and international trends of vehicle ad-hoc networks are described, too.

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Chapter 1

Introduction

1.1 Background of this study

Ubiquitous networks that support human life with many computers working autonomously and cooperatively attract attention internationally. In Japan, u-Japan[*1] policy that utilizes widely deployed broadband network environment was announced by Ministry of Internal Affairs and Communications (MIC) as a national project on July 2004 [1]. The purpose of u-Japan policy is to make use of network environment for resolution of social issues. This u-Japan policy is executed in following two steps. The first step is to spread seamless network environment between wired networks and wireless networks into every corner of our life. The second step is to make the network environment easy to use for elderly people or people with disabilities. Ad-hoc networks are an important key technology to realize this first step.

Ad-hoc networks are computer networks composed of some mobile stations that can communicate with each other wirelessly. Each station can communicate with distant stations via intermediate stations by wireless multi-hop manner. Additionally, each station autonomously reads the situation and judges how to work. Therefore, ad-hoc networks differ greatly from

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[*1] 'u' represents ubiquitous, universal, unique, and user-oriented.

personal handy phone system (PHS) or cellular phone networks that needs fixed communication infrastructure and centralized control mechanism. Ad-hoc networks have some promising features; for example, they have good station mobility tolerance, they have high scalability, they do not need an infrastructure, and they have autonomous and distributed control.

Ad-hoc networks have a long history. Ad-hoc networks have their origin in packet radio network (PRNET) project that was started in the 1970s for the purpose of military use [2–4]. At the time, large-scale integration (LSI) was in an early phase of development. Therefore, the packet radio equipment was very large, very heavy, and hard to carry. PRNET project revealed usefulness and limitation of ad-hoc networks through considerable research and field tests as for their media access control (MAC) protocol, their error control, their flow control, their addressing, and their routing protocol.

Research on ad-hoc networks for nonmilitary use was activated in the 1990s. Most of the research did not suppose specific target application and was based on theoretical analysis or simulation evaluation. Internet Engineering Task Force (IETF) established mobile ad-hoc network (MANET) working group (WG) for the purpose of standardization of routing protocols for ad-hoc networks [5]. MANET WG continues its session even now. In the mid 2000s, wireless local area networks (LAN) that was standardized at IEEE 802.11 committee [6] became widely used. Consequently, the research target was increasingly shifted to development and evaluation of test bed for ad-hoc networks using wireless LAN. On May 2004, IEEE 802.11s task group (TG) was established to standardize the MAC protocol for wireless mesh networks that are a form of ad-hoc networks.

Currently, the research and development is continued on ad-hoc networks for concrete application targets. Well-known applications are vehicle ad-hoc networks [7], disaster area networks [8], sensor networks [9], personal area networks [10], and home area networks. Vehicle ad-hoc networks aim at reducing casualties in traffic accidents or enhancing amenity in vehicles by establishing ad-hoc networks among vehicles. In disaster area networks, ad-hoc networks are used as temporary substitution networks for damaged communication infrastructures. The research and development to save lives in disaster area by implementing ad-hoc networks in autonomous robots is continued, also [11]. Sensor networks are networks connecting many sensors wirelessly for the purpose of home or office security, environmental measurement, healthcare, growing crops, building management, and so on. Personal area networks aim at enhancing convenience of life by connecting wearable devices, such as wrist watches, cellular phones, blood-pressure gauges, and so on, wirelessly. Home area networks also aim at enhancing convenience of life by connecting some appliances, such as personal computers, televisions, refrigerators, air conditioners, electronic ovens, and so on, wirelessly [3].

Among above ad-hoc networks applications, vehicle ad-hoc networks especially capture public attention from the viewpoint of decrease of accidents on the road, high economic effect, and improvement of natural environment. The research and development on vehicle ad-hoc networks is categorized into three: vehicle platooning, collision avoidance system, and inter-vehicle message communications. The vehicle platooning is the technology for automatic driving. Each vehicle cooperatively communicates with each other and forms platoon. Additionally, each vehicle can detect and avoid obstacles on the road automatically. This vehicle platooning can realize stable and steady driving, which leads low-fuel consumption and the decrease of distribution costs. The collision avoidance system aims at avoidance of vehicle collision at intersections. Each vehicle broadcast packets periodically to inform neighbor vehicles about its location, driving speed, driving direction, and so on. Vehicles can avoid collisions by obtaining information of neighbor vehicles proceeding into the same intersection and then announcing it to the driver. The inter-vehicle message communications is a kind of application to enhance amenity in vehicles for drivers or passengers. In this application, a vehicle that detects slips or spins of their tires can inform following vehicles about bad road condition through ad-hoc networks. Additionally, a vehicle that runs into trouble can inform neighbor vehicles about occurrence of the vehicle accident immediately through ad-hoc networks, which urges neighbor vehicles to search the detour driving route.

Vehicle ad-hoc networks are expected as a promising application of ad-hoc networks to realize ubiquitous networks. However, they have still many subjects to be solved for wide prevalence, such as routing protocols, quality of service (QoS), security, antennas, transmission power control, and low power consumption. Among these technical subjects, routing protocols are one of the most important subjects. If routing protocols are settled and combined with wireless equipment, such as wireless LAN, we could immediately develop prototypes, execute field tests, and discuss the commercial viability. From this point of view, this study focuses on routing protocols for vehicle ad-hoc networks. I hope this study becomes part of the answer to prevalence of ubiquitous networks, and serves as a foundation for the resolution of social issues.

1.2 Purpose of this study

This study focuses on routing protocols for vehicle ad-hoc networks. The routing protocols for ad-hoc networks are mainly discussed in IETF MANET WG. Although these routing protocols give their weight to general versatility, vehicle ad-hoc networks include particularity. For example, every vehicle moves on the road. Some vehicles are at a stop on the road or parking space, some vehicles move very fast. Some places, such as intersection of cities, are very high vehicle density; some places, such as rural area, are very low vehicle density. Consequently, the routing protocols discussed in MANET WG cannot achieve high communication performance in vehicle ad-hoc networks. The purpose of this study is to suggest and evaluate routing protocols that achieve high communication performance in vehicle ad-hoc networks. Specifically, routing protocols on following three vehicle ad-hoc networks environments are discussed: routing protocols for short distance inter-vehicle communications;

routing protocols for inter-vehicle communications via established wired networks; flooding protocols needed for long distance inter-vehicle communications.

The first topic is routing protocols for short distance inter-vehicle communications. The purpose of this routing protocol is to determine a route from a vehicle to another vehicle located within two or three kilometers using wireless links only. The network topology of vehicle ad-hoc networks changes dynamically, because each vehicle moves fast. Unless stable communication route between vehicles are constructed, the precious wireless bandwidth is wasted much because of frequent wireless link disconnection followed by route re-construction process. Therefore, this thesis presents optimized routing protocols that construct a stable route without periodic beacons for vehicle ad-hoc networks.

The second topic is routing protocols for inter-vehicle communications via established wired networks environment. Combining vehicle ad-hoc networks with wired communication infrastructures is an essential subject to realize ubiquitous networks. High quality communications between distant vehicles can be realized when wired communication infrastructures are used effectively. However, routing protocols discussed in MANET WG are not supposed to be used in these networks environment. Therefore, this thesis presents routing protocols that improves communication performance between vehicles by using wired communication infrastructures effectively.

The last topic is flooding methods that are needed to realize long distance inter-vehicle communications. In the future, large scale vehicle ad-hoc networks will be established if many vehicles equip wireless communication function. In this situation, application of mobile IP protocol to vehicle ad-hoc networks is a realistic approach in order to communicate from a vehicle to another vehicle in a distance. If mobile IP protocol is applied to vehicle ad-hoc networks, each vehicle can send packets to another vehicle in a distance via a local foreign agent (FA), a home agent (HA), and a FA nearest to the destination vehicle as follows.

The large scale vehicle ad-hoc networks are divided into some small ad-hoc networks; each small ad-hoc networks includes one FA. The FA, which is connected with wired communication infrastructure, transmits agent advertisement packet that includes information about its small ad-hoc networks to vehicles periodically. Every vehicle registers its location to the HA via the FA whenever it detects migration into a new small ad-hoc networks by receiving the agent advertisement packets. In this environment, the originator vehicle sends packets to its local FA, which forwards the packets to the destination FA via HA. The destination vehicle can receive packets from its local FA.

There exist many reports as for applying mobile IP to ad-hoc networks [12–20]. However, most of them require flooding of agent advertisement packet that is defined in the mobile IP protocol. Periodical flooding of packets wastes precious wireless bandwidth much. Therefore, this thesis presents effective flooding protocols that achieve high packet reachability and low overhead.

As described above, the purpose of this study is to suggest and evaluate 1) routing protocols for short distance inter-vehicle communications, 2) routing protocols for inter-vehicle communications via established networks, and 3) flooding methods that are needed to realize long distance inter-vehicle communications.

1.3 Organization of this thesis

This thesis is composed of six chapters. Chapter 2 describes a network model and its components supposed in this study. Some definitions are described in the chapter, too.

Chapter 3 describes routing protocols for short distance inter-vehicle communications. A new routing protocol named relative speed-based routing (RSR) is proposed in this chapter. RSR can construct a stable communications route between vehicles without using beacons or similar means. Performance of RSR is evaluated and compared with existing routing protocols by simulation.

Chapter 4 describes routing protocols for inter-vehicle communications via established networks. A new routing protocol is proposed in this chapter, which uses simple formulas to decide which route is effective: a route using wireless links only or a route via the established networks. Performance of this routing protocol is evaluated and compared with existing routing protocols by simulation.

Chapter 5 describes flooding methods for mobile IP protocol in vehicle ad-hoc networks. New flooding methods named sector-based flooding (SBF) and adaptive sector-based flooding (ASBF) are proposed in this chapter. Both flooding methods use position information of each station effectively. Performance of these flooding methods are evaluated and compared with existing flooding methods by simulation.

Chapter 6 concludes this study. An appendix is described after chapter 6. Theoretical explanation and supplementary information for proposed flooding methods in chapter 5 are described in the appendix.

Chapter 2

Network model

A network model supposed in this study is shown in Figure 2.1. The network model consists of three components: routers, access points, and mobile stations.

Routers equip some interfaces. One of them is connected to an established network, such as exclusive wired networks for vehicles. The others are connected to access points. Routers forward both unicast and broadcast packets. The unicast packets received from an interface are forwarded to one interface only. The broadcast packets are forwarded to either the interface connected to the established network or all the interfaces connected to access points. The outgoing interface is decided by the destination IP address in IP header. Routers can forward control packets of ad-hoc routing protocols only to interfaces connected to access points. In other words, the control packets are never sent to the backbone network.

Access points are connected to a router with an Ethernet or optical cable. Each access point uses IEEE 802.11 b/g as its wireless communication protocol. IEEE 802.11 b/g has two operation modes: infrastructure mode and ad-hoc mode. Usually, an access point connects mobile stations that operate in infrastructure mode to the wired network. However, mobile stations in ad-hoc networks operate in ad-hoc mode. Therefore, some devices or ideas must be applied to connect an access point with mobile stations in ad-hoc networks. There are

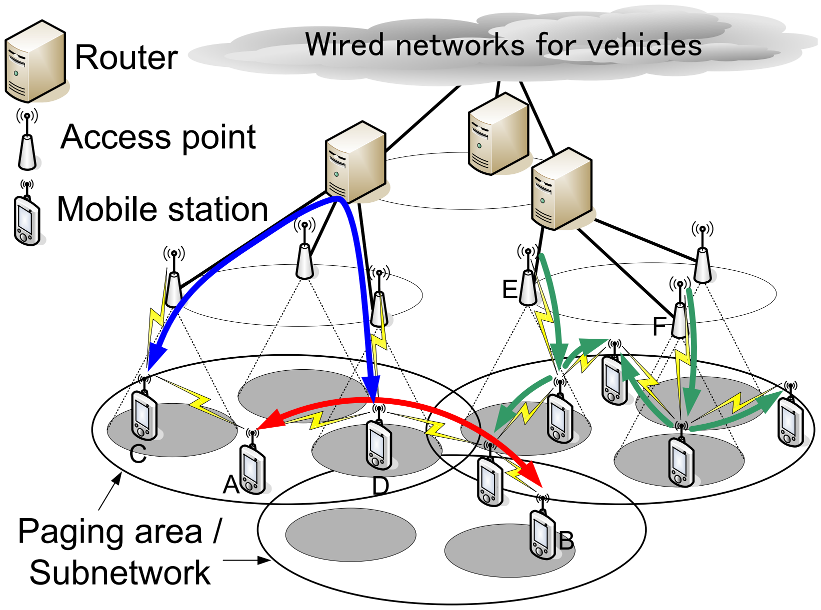


Figure 2.1: Network model.

generally two ways to solve this problem. One is to develop mobile stations that can operate in both infrastructure mode and ad-hoc mode simultaneously using two antennas and wireless channels. The other is to develop access points that can connect mobile stations operating in ad-hoc mode. This study supposes the latter case. Such an access point is easily developed by following four steps. First, prepare for Linux machine. Second, equip it with an Ethernet interface and an IEEE 802.11 b/g interface. Third, configure the IEEE 802.11 b/g interface as ad-hoc mode. And last, turn on routing or bridge function between the interfaces. Access points are connected to ad-hoc networks by installing an ad-hoc routing protocol to them. Access points use an omni-directional antenna. Communications between access points are executed via the router through the wired network.

Mobile station is a general term of vehicle, personal digital assistant (PDA), laptop computer, and so on. Mobile stations establish ad-hoc networks with IEEE 802.11 b/g. The maximum direct communication distance is defined as 80 m or 100 m in this study. Mobile stations use an omni-directional antenna and single wireless channel. Mobile stations located outside a wireless coverage of an access point can access to the established wired networks via a mobile station located in the wireless coverage of an access point.

As for IP address assignments to this network environment, two ways can be considered roughly. The routing protocols suggested in this thesis can be applied to both of them; methods to assign IP address to each mobile station are out of scope in this study. One is that considering overall ad-hoc networks as a subnetwork. In this network, wireless coverage under one router forms a paging area. When a mobile station moves to another paging area, the mobile station sends message to the established wired networks and registers its location with a database. When a mobile station communicates with another mobile station located inside the pre-defined wireless hop coverage, the route is constructed by wireless links only. Otherwise, a mobile station sends packets to the nearest access point, which forwards the packets to its router. The router again forwards the packet to the paging area in which the destination station is located after searching the database.

The other is that the wireless coverage of all access points under one router establishes one subnetwork. The wireless coverage of an access point is not necessarily overlapped with the wireless coverage of other access points. This architecture makes it effective to send packets from a mobile station to another mobile station, because mobile stations in a subnetwork have common network address. Routers can identify the outgoing interface to the target mobile stations based on their network address. In this environment, it is needed to change a mobile station's IP address and register its new IP address with the address management server whenever the mobile station moves outside its subnetwork border. Methods to realize this address management is out of scope in this study, too.

As described in Chapter 1, this study focuses on routing protocols: routing protocols for short distance inter-vehicle communications; routing protocols for inter-vehicle communications via established networks; and flooding methods that are needed to realize long distance inter-vehicle communications. The routing protocols for short distance inter-vehicle communications are presumed to use wireless links only (see station A and station B in Figure 2.1). Every vehicle can communicate with other vehicles located in different paging area or subnetworks. The difficulties of this situation caused by difference of the network IP address between originator and destination are out of scope in this study. Application of IPv6 is the one of the solution for this addressing problem. In IPv6, three kinds of IP addresses exist: link local address, site local address, and global address. Use of link local address enables mobile stations in ad-hoc networks to communicate with each other without concern for subnetwork borders. In IPv4, multi-home technique, overlay networks, implementation of ad-hoc routing in layer two (media access control layer) might solve this addressing problem.

The routing protocols for inter-vehicle communications via established networks are presumed to be used in intra-paging area or intra-subnetwork (see station C and station D in Figure 2.1). Usually, mobile IP protocol is applied to communication between different paging areas or subnetworks via established network.

The flooding methods for vehicle ad-hoc networks are presumed to be used for propagation of router advertisement packets in mobile IP protocol (see access point E and F in Figure 2.1). Each mobile station decides a paging area or subnetwork to which it belongs based on hop count or other elements in router advertisement packets. Each mobile station that migrates into a new paging area or subnetwork sends a registration request packet, which is forwarded to home agent (HA) via foreign agent (FA). This mechanism enables all packets to reach the destination via established wired networks accurately.

In this study, network simulator 2 (NS-2) is used for evaluation. NS-2 is a reliable and widely used network simulator [21].

Chapter 3

Routing Protocols for Short Distance Inter-Vehicle Communications

3.1 Introduction

There is active research on intervehicle communications systems in which moving vehicles are connected by wireless links and information is exchanged between vehicles for the safety and comfort of the driver and the passengers [22–24]. In this system, no special communications infrastructure is required, and communications to vehicles moving outside the communications range can be achieved because each vehicle performs autonomous routing. Therefore, applications such as intervehicle voice and picture transmission can be realized at low cost.

However, a point to consider in connection with ad-hoc networks that connect vehicles moving at high speed is that there are frequent dynamic changes in the topology. Therefore, the control packet which is generated in order to maintain or change the route may consume a large fraction of the wireless communications bandwidth. Consequently, there must be a thorough investigation of the routing protocols used in intervehicle communications over ad-hoc networks.

The MANET WG of IETF [5] and other organizations are continuing investigations of ad-hoc networks, and various routing protocols have been proposed. The routing procedures can be broadly divided into position-based routing and protocol-based routing [25]. In position-based routing, the positional coordinates of the communications partner are included in the packet. Then, by comparing the positional coordinates of the neighboring stations and the positional coordinate of the communications partner, the packet is sent to the optimal neighboring station. Application to intervehicle communications is also being considered [26, 27].

In position-based routing, it is assumed that the positional coordinates of the communications partner are already known. It is possible to acquire positional information on the communications partner by using the cellular network. However, it may lose the advantages of the ad-hoc network, because the method cannot be used in an environment in which the infrastructure is not yet completed, or when new costs are incurred by the use of the infrastructure facilities. A method of realizing location service on an ad-hoc network has also been proposed [28–30]. However, this requires periodic flooding of positional information at each station, which may produce the "broadcast storm" problem in an environment with a high vehicle density [31].

Protocol-based routing can be further divided into proactive routing and reactive routing. Proactive routing is a protocol in which a station's routing table is updated by exchanging messages regularly with neighboring stations [32, 33]. In contrast, reactive routing works as follows. When communications is required, the originating station performs flooding of route-request packets toward the destination station. On receiving the packet, the destination station unicasts a reply packet to the originating station by the reverse route in order to establish an information transfer route [34, 35].

It is reported that the packet arrival ratio is higher in reactive routing than in proactive routing when the stations are moving at highspeed [36]. In that sense, reactive routing is better as a routing protocol in ad-hoc networks connecting moving vehicles.

As regards reactive routing, the following problem has been pointed out. When the speed of the stations is increased, control packets followed on changes of routes are generated more frequently. When the station density increases, the overhead due to flooding of control packets is increased [36]. Therefore, in applications to intervehicle communications, it is important to consider stability in setting the route and to reduce overhead by reducing the frequency of route changes.

Protocols proposed for the construction of stable routes in reactive routing include associativity-based routing (ABR) [37], signal stability-based adaptive routing (SSA) [38], and the flow-oriented routing protocol (FORP) [39].

ABR and SSA are protocols in which each station periodically transmits a beacon. The stability is estimated on the basis of consecutive receptions of the beacon and the received signal intensity, and the most stable route is selected. The accuracy of stability estimation is improved when the beacon transmission interval is reduced. However, the overhead, the CPU load, and the probability of collision with data packets are increased due to the beacon in environments with a high vehicle density, such as urban centers, parking lots, and traffic jams. Therefore, it is desirable to realize a protocol of assuring a stable route without using beacons or similar means.

FORP is a routing protocol in which the length of stay in the communications area is used as the metric. A route can be constructed without using beacons. On the other hand, it has been pointed out that the number of hops and the delay tend to increase, and the probability of packet collision is markedly increased when the traffic increases [40].

This chapter proposes the relative speed-based routing (RSR) protocol for vehicle ad-hoc networks, in which a stable route is selected without using beacons or similar means. RSR is a routing protocol in which the relative speeds of the neighboring vehicles are calculated and the route with the lowest cumulative value is selected. This chapter proposes a protocol in which only the relative speed is considered (RSR-1) and a protocol in which the change in the intervehicle distance is also considered, in addition to the relative speed (RSR-2). In both protocols, the frequency of route changes is reduced to a low value.

The proposed protocols are compared to AODV and FORP by simulation, and it is shown that the proposed protocols are better in terms of both packet arrival ratio and route stability. The proposed protocol is useful not only in ad-hoc networks for vehicles that are in similar motion for long periods, as on a highway, but also in vehicle ad-hoc networks in environments with high vehicle density, such as urban centers.

3.2 Related Works

Reports on routing protocols using the inter station distance and the speed as metrics include Reference [41], location-aided routing (LAR) [42], and Reference [43]. The protocol described in Reference [41] has the following features. In intervehicle broadcast communications, the overhead is reduced by restricting the number of vehicle hops, based on positional information and the direction of movement. The protocol proposed in this paper differs from the protocol described in Reference [41] by the fact that the unicast route is constructed with an emphasis on stability.

LAR is a reactive routing protocol based on positional information and speed. It has the ability to reduce overhead as follows. Only stations in an area determined from the position of the originating station and from the position and speed of the destination station relay route request packets. However, the same problem as in position-based routing is produced in LAR, namely, that a location service must be utilized in order to acquire positional information on the destination station. Furthermore, the proposed protocol differs from the purpose of LAR in that positional information and speed information are utilized as indices in constructing a stable route.

Reference [43] proposes a routing protocol based on LAR in which route stability is further improved by using the speed of the station as the metric. When a station receives route request packet, it includes position and speed information in the packet. The destination station selects a route with a highly stable speed vector from the route request packets received over multiple routes. The problem of increased overhead may arise if the position and speed information of the originator and all hopping stations are included the packet. Another problem is that each station relays route request packets in the order of the arrival, which may prevent information on routes with high stability from arriving at the destination.

The RSR-1 routing protocol proposed in this paper differs in the following respects from the protocols hitherto proposed. Each station stores a relative speed metric which indicates stability. Then the route request packets whose relative speed metrics indicate higher stability are relayed. RSR-2 differs from the conventionalprotocols in that routes with higher stability are constructed by including the change in the intervehicle distance in addition to the relative speed.

3.3 Proposed Protocol

3.3.1 RSR-1

In reactive routing, the procedure shown in Figure 3.1 is performed when a packet is sent from the originating station. Each station maintains a routing table. When data are to be transmitted, if the route to the destination is not contained in the routing table, or if the route exists but has already timed out, a route request packet (called a route request, RREQ) is broadcast.

In RSR-1, the cumulative value of the relative speed is determined by using the RREQ. Figure 3.2 shows the information elements for route construction contained in RREQ. The

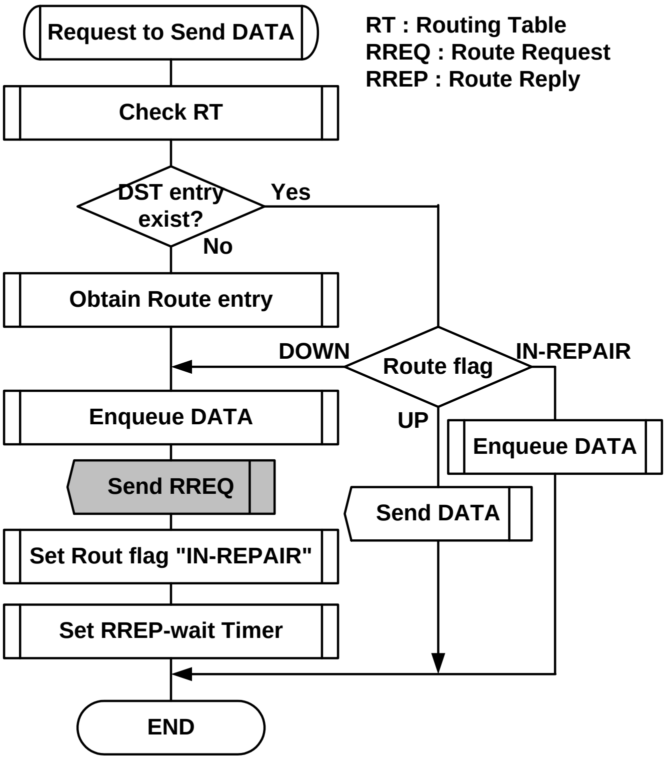
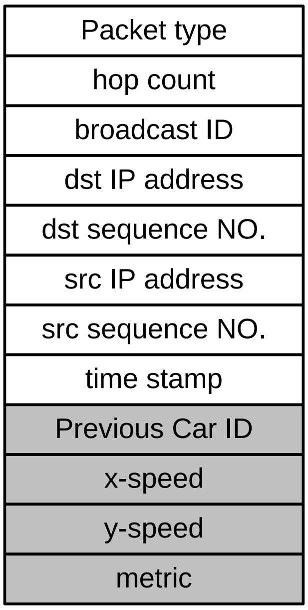


Figure 3.1: Data transmission process.



Packet type
hop count
broadcast ID
dst IP address
dst sequence NO.
src IP address
src sequence NO.
time stamp
Previous Car ID
x-speed
y-speed
metric

Figure 3.2: RREQ elements of RSR-1.

shaded part is information inherent to RSR-1. The other parts are general information elements used in AODV and other reactive routing protocols. In this study, RSR is included as a functional extension in AODV and the resulting performance is evaluated.

"Previous Car ID" is the ID of the vehicle that sent the packet. "x-speed" is the speed of the packet sending vehicle in the east-west direction and "y-speed" is its speed in the north-south direction. "metric" is the cumulative value of the relative speed. x-speed is positive when the vehicle is moving to the east and negative when it is moving to the west. y-speed is positive when the vehicle is moving to the north and negative when it is moving to the south. The vehicle starting the route request sets its own information in Previous Car ID, x-speed, and y-speed. Zero is set in the metric. Then the RREQ is sent. The data on x-speed and y-speed can be acquired via GPS or various sensors.

Figure 3.3 shows the processing flow in RREQ reception. Each station maintains a broadcast table (BC table), which is used to check whether an RREQ has already been received. The RREQ information is made unique by using "src IP address" and "broadcast ID" in Figure 3.2. In RREQ relay stations, if the information does not exist in the BC table, or if it is registered in the BC table but the metric of the received RREQ is less than the metric for the effective period in the routing table, the received RREQ information is placed in the BC table and the packet is relayed. Otherwise the received RREQ is discarded.

In the relaying process, the metric in the RREQ packet is updated by adding the relative speed of the vehicle indicated by Previous Car ID and the updating vehicle. Previous Car ID, x-speed, and y-speed are overwritten with the information for the updating vehicle. The updated metric, the number of hops to the RREQ originator, and the next hopping station ID are retained in the routing table. Each station receives RREQs from multiple routes, but only one route for a given destination is retained in the routing table.

Let the speed of the vehicle receiving the RREQ of the k-th hop be (Sk_{own-x}, Sk_{own-y}) and the speed of the vehicle indicated by Previous Car ID be $(Sk_{prev-x}, Sk_{prev-y}) = (x -$

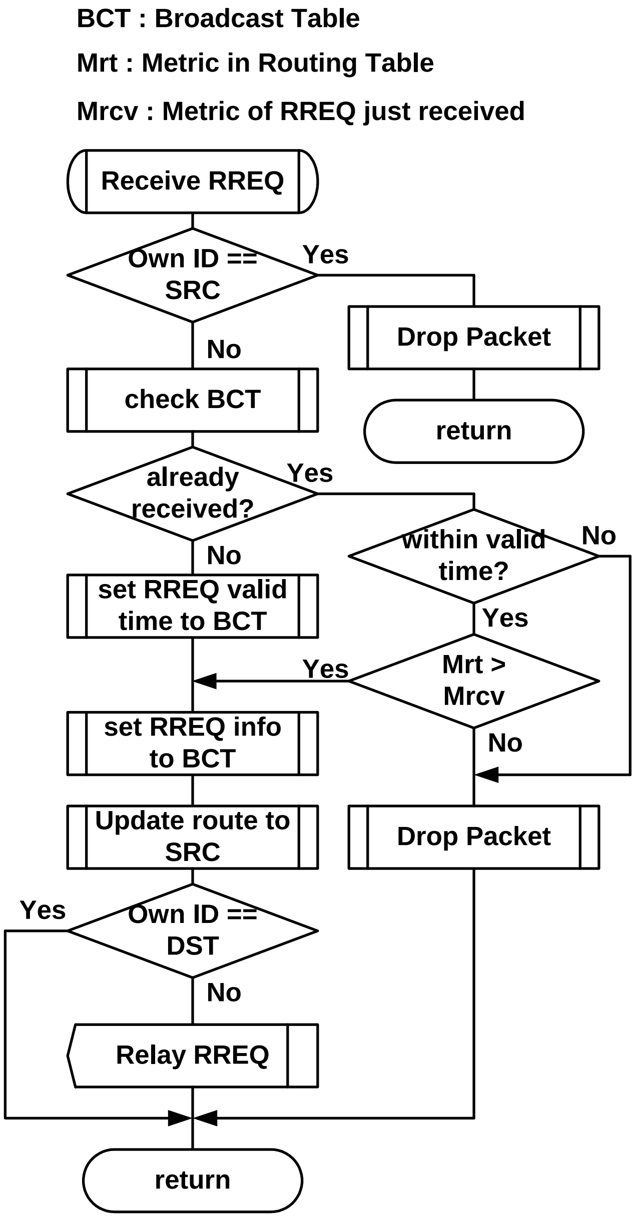


Figure 3.3: RREQ reception process.

$speed, y - speed)$. Then the cumulative metric M at the n-th hop is

$$M = \sum_{k=1}^{n} \sqrt{Sxk^2 + Syk^2} \tag{3.1}$$

where

$$Sxk = Sk_{own-x} - Sk_{prev-x}$$

$$Syk = Sk_{own-y} - Sk_{prev-y}$$

When the destination station receives RREQs, the RREQ received from multiple routes are retained in the queue for a certain period, and the RREQ with the smallest metric is selected from these. If there are multiple RREQs with the lowest metric, the RREQ received first is selected. The information in the BC table is retained for several tens of seconds, but the destination station waits for RREQs from multiple routes only for several tens of milliseconds. The destination station unicasts the route replay packet (RREP) to the originating station over the route with the lowest metric. The route is established when the originating station receives the RREP, and the communications can be started.

3.3.2 RSR-2

When a vehicle moving on a straight road tries to find a route to another vehicle moving on the same road, the probability that a vehicle moving in the opposite lane is selected as the relay vehicle is greatly reduced if RSR-1 is used. Therefore, it is likely that route stability will be greatly improved. However, when only the relative speed is used as the metric, it is sometimes uncertain whether a stable route has been formed. Consider, for example, the situation as shown in Figure 3.4.

Vehicles A to D are moving at the same speed, and vehicle A tries to establish a route to vehicle D. A stable route can be formed if vehicle B is selected as the relay vehicle because vehicle B is in the same lane as vehicles A and D. The relative speed of vehicle A as seen from vehicle B is the same as that seen from vehicle C, although the directions are different.

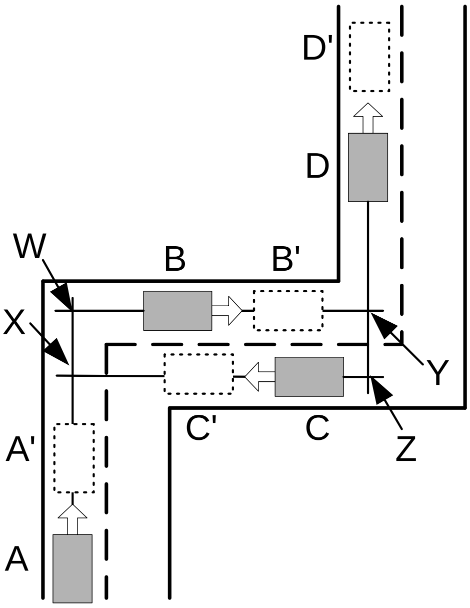


Figure 3.4: A meandering road model.

Similarly, the relative speed of vehicle B is the same as that of vehicle C seen from vehicle D. Therefore, RSR-1 selects vehicle B or vehicle C in order of arrival.

In order to alleviate this problem, the change in the intervehicle distance is included in the metric in RSR-2, in addition to the relative speed. The routing algorithm of RSR-2 is the same as that in RSR-1. The difference is that position information is added to the information elements of RREQ, and the change in the intervehicle distance is included in the calculation of the metric. The information elements of the RREQ used in RSR-2 are shown in Figure 3.5, where "x-position" is the position of the vehicle in the east-west direction and "y-position" is its position in the north-south direction. The other elements are the same as in the previous section.

In RSR-2, each vehicle that received an RREQ derives a linear function expressing the course of the vehicle indicated by Previous Car ID. This linear function can be derived using the position information (x-position, y-position) and the direction of movement information

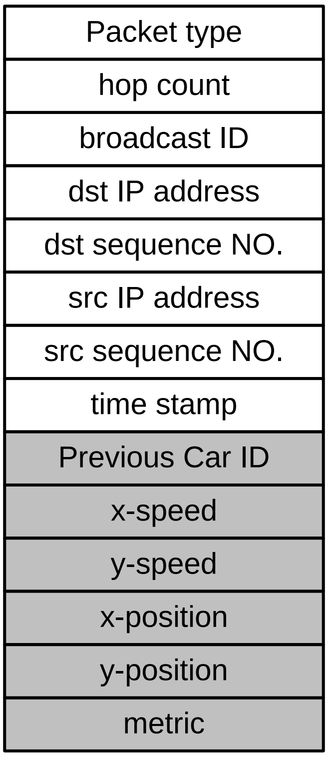


Figure 3.5: RREQ elements of RSR-2.

(x-speed, y-speed) in the RREQ. The course of this vehicle itself that received the RREQ is similarly represented by a linear function, and the intersection of the two expressions is determined. In Figure 3.4, when RREQ sent by vehicle A is received by vehicle B, the point labeled W is the intersection.

Let the position of vehicle A be (Ax, Ay) = (x-position, y-position), the position of vehicle B be (Bx, By), the position of the intersection in the direction of movement be (Wx, Wy), the predicted position of vehicle A after a unit time be $(A'x, A'y)$ = (x-position+x-speed, y-position+y-speed), and the predicted position of vehicle B after a unit time be $(B'x, B'y)$. Then the intervehicle distance Dis between vehicles A and B when vehicle B receives an RREQ from vehicle A, and also the intervehicle distance Dis' between vehicles A and B after a unit time, can be calculated by Equations 3.2 and 3.3, respectively. For smaller differences between Dis and Dis', the route can be considered stable, because the change in relative position is smaller.

In RSR-2, the cumulative metric M at the n-th hop is calculated by Equation 3.4, based on Equations 3.1 to 3.3:

$$\begin{aligned} Dis &= \sqrt{(Ax - Wx)^2 + (Ay - Wy)^2} \\ &\quad + \sqrt{(Bx - Wx)^2 + (By - Wy)^2} \end{aligned} \tag{3.2}$$

$$\begin{aligned} Dis' &= \sqrt{(A'x - Wx)^2 + (A'y - Wy)^2} \\ &\quad + \sqrt{(B'x - Wx)^2 + (B'y - Wy)^2} \end{aligned} \tag{3.3}$$

$$M = \sum_{k=1}^{n} \left(\sqrt{Sxk^2 + Syk^2} + \left| Disk - Dis'k \right| \right) \tag{3.4}$$

Here, $Disk$ and $Dis'k$ are the intervehicle distance between the vehicle receiving RREQ at the k-th hop and the vehicle indicated by Previous Car ID, and their intervehicle distance after a unit time. When there is no intersection between the linear function representing the direction of movement of the vehicle in question and the linear function representing the direction of movement of the vehicle indicated by Previous Car ID, the following simple intervehicle distance expression is used:

$$Dis = \sqrt{(Ax - Bx)^2 + (Ay - By)^2}$$

$$Dis' = \sqrt{(A'x - B'x)^2 + (A'y - B'y)^2}$$

3.4 Evaluation by Simulation

3.4.1 Simulation model

The effectiveness of the proposed routing protocol was evaluated by simulation. Figure 3.6 shows the moving vehicle model used in the simulation. In order to produce a model in which

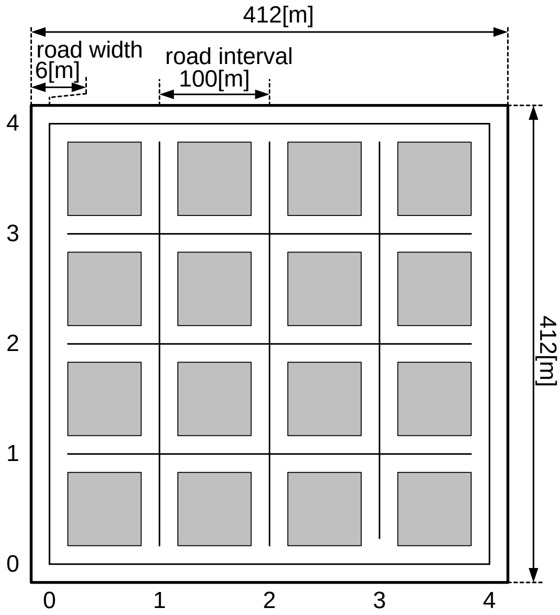


Figure 3.6: Simulation model.

vehicles turn to the right or left at crossings, as in urban centers, we assumed the Manhattan model, in which two-lane roads with a lane width of 6 m were extended in the east-west and north-south directions at 100-m intervals in an area 412 m square. Vehicles (100, 200, or 300) were placed at random on the roads, and the simulation was performed.

The speed of the vehicles was set in two ways in the simulation. One way consisted of setting the speed at random in the range of 27 to 40 km/h, and the other consisted of setting the speed at random in the range of 70 to 100 km/h. A vehicle arriving at a crossing or T-branch determines at random whether to go straight, turn to the right, or turn to the left, based on the probabilities reported in Reference [44].

The wireless communications protocol was based on IEEE802.11b with a wireless bandwidth of 11 Mbit/s. In order to achieve stable communications, we assumed an environment in which packets with a low received power were intentionally discarded in the MAC layer. The communications area was set as 80 m.

An arbitrary vehicle pair was assumed in this simulation model. Assuming that UDP data units of 512 bytes are sent by 10,000 packets at 50-ms intervals, we investigated the number of route changes, the packet arrival ratio, and the overhead in order to evaluate the protocol performance. Table 3.1 shows the simulation parameters. For comparison, AODV, which is a typical reactive routing protocol, and FORP, which is the reactive routing protocol emphasizing stability, have also been investigated.

3.4.2 Distance-number of hops relationship

Generally, in an environment in which the stable communications can be realized, communications with low delays and high throughputs can be expected when the number of hops to the destination is smaller. From this viewpoint, the relation between the intervehicle distance and the number of hops in each routing protocol was investigated. Two hundred vehicles were assumed to move at a maximum speed of 40 km/s, and data were sent and received between arbitrary pairs of vehicles. By modifying the connections, 100 routings are performed, and the resulting data were approximated by a linear function. Figure 3.7 shows the results.

It is evident from the figure that a larger number of hops is required in FORP than in AODV, RSR-1, and RSR-2. The number of hops is somewhat larger in RSR-1 than in AODV. The reason is as follows. In AODV, the destination station selects the relay station for the minimum number of hops on the basis of the first received RREQ. In RSR-1, in contrast, relay processing is performed when an RREQ with a smaller metric is received. Therefore, a vehicle moving nearby at a smaller relative speed is selected as the relay station, rather than a vehicle far away with a larger relative speed. The number of hops in RSR-2 is somewhat larger than in AODV and RSR-1. This is due to the selection of stable routes by also considering the intervehicle distance in addition to the relative speed. RSR-1 and RSR-2 with consideration of stability can construct a route with shorter hops than FORP, which similarly emphasizes stability.

Table 3.1: Simulation parameters.

Field	412 × 412 [m]
Number of lanes[*2]	2
Number of vehicles	100, 200, 300
Vehicle speed[*3]	28-40, 70-100 [km/h]
Madia Access Control	IEEE802.11b with RTS/CTS
Frequency	2.4 [GHz]
Preamble	Short preamble (72 [bit], 2 [Mbit/s])
Transmission data rate	11 [Mbit/s]
Transmitted Power (P_t)	10 [mW]
Received Power (P_r)[*4]	$P_r = P_t k d^{-3}$
Reception threshold[*5]	-87 [dBm]
Carrier sense threshold[*6]	-100 [dBm]
Communication range	80 [m]
Length of queue in routing layer	64 [packets]
Length of queue in link layer	250 [packets]
Data packet length	512 [byte]
Data packet generation interval	0.05 [s]
Number of data packet generations	10,000
RREQ waiting time at destination station	20 [ms]
Simulation time	500 [s]

[*2] Basically, every road has two lanes. One is for vehicles moving toward north or east. The other is for vehicles moving toward south or west. However, each vehicle can pass other vehicles on the same lane freely because each vehicle moves with constant speed decided by random number.

[*3] The speed of the vehicles is changed by random number whenever the vehicles arrive at intersections or T-branches.

[*4] The Friis transmission equation was used to calculate reception power: $P_r = P_t \left(\frac{\lambda}{4\pi d}\right)^2$ where λ is the wavelength, and d is the distance between sender and receiver. This equation can be generalized to calculate approximate reception power in various environments: $P_r = P_t k d^{-n}$ where k is the constant value, and n is the attenuation constant (n=2 for free space, n=2.7-3.5 for suburban area, and n=4 for indoor). The value of n was three in this simulation.

[*5] The reception threshold was decided according to the definition that commmunication rage is 80 m.

[*6] The carrier sense threshold was decided according to the definition that it should be lower than reception threshold by 13 dBm.

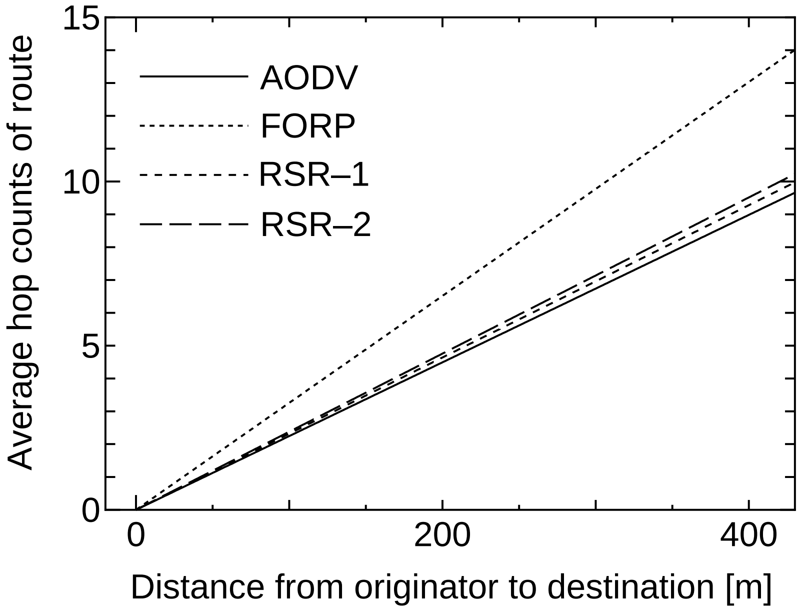


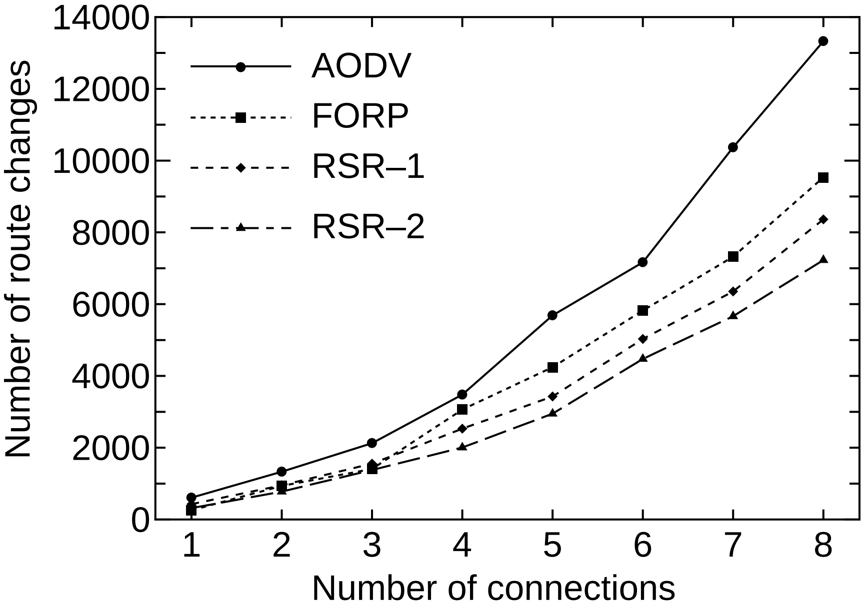
Figure 3.7: Relationship between distance and hop counts.

3.4.3 Change of number of connections

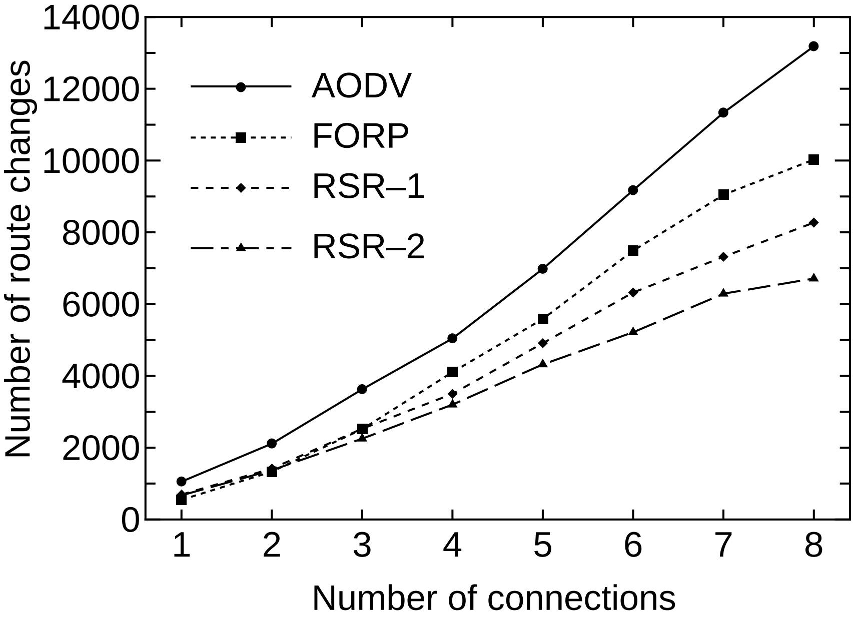
In order to ascertain the stability of the route when the proposed protocol is applied, 200 vehicles were assumed, and the number of route changes, the packet arrival ratio, and the overhead are examined while sending/receiving data between two arbitrary vehicles. Figure 3.8(a) and 3.8(b) show the measured number of route changes for maximum speeds of 40 and 100 km/h, respectively, when the number of connections is varied.

It is evident from part (a) of the figure that the number of route changes is reduced to lower values by both RSR-1 and RSR-2 than by AODV and FORP, and that stable routes are formed. In particular, the number of route changes is smaller in RSR-2, and is about half that of AODV. As a whole, the number of route changes increases with the number of connections, because the probability of collision of data packets is increased.

It is evident from part (b) of the figure that the tendency of the stability is maintained even if the vehicle speed is increased. In both AODV and FORP, a vehicle moving in the



(a) Max vehicle speed = 40km/h



(b) Max vehicle speed = 100km/h

Figure 3.8: Relationship between number of connections and number of route changes.

opposite lane may be selected as the relay station. When a vehicle moving in the opposite lane is selected, the route is disconnected in a shorter time as the vehicle speed is increased. In RSR-1 and RSR-2, there is a high probability that a vehicle moving in the same lane will be selected as the relay station, and more stable routes can be constructed than in AODV and FORP.

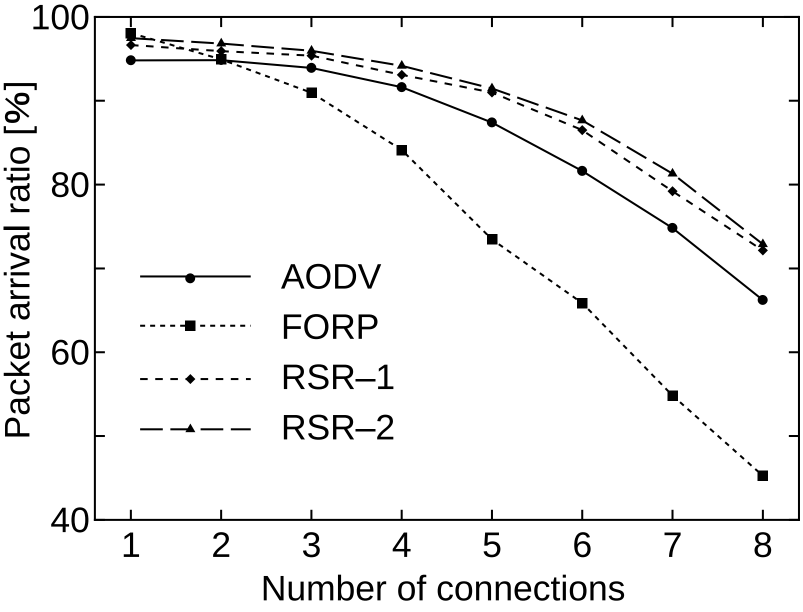
Figure 3.9(a) and 3.9(b) show the measured packet arrival ratios for maximum speeds of 40 and 100 km/h, respectively.

It can be seen from part (a) that both RSR-1 and RSR-2 achieve high packet arrival ratios, especially RSR-2. In AODV, even though the number of route changes is nearly twice that in RSR-2, the packet arrival ratios do not differ much. This is due to the packet retransmission control in the routing protocol. In AODV, the route is changed very frequently and many packets cannot arrive at the destination even if retransmission control is applied.

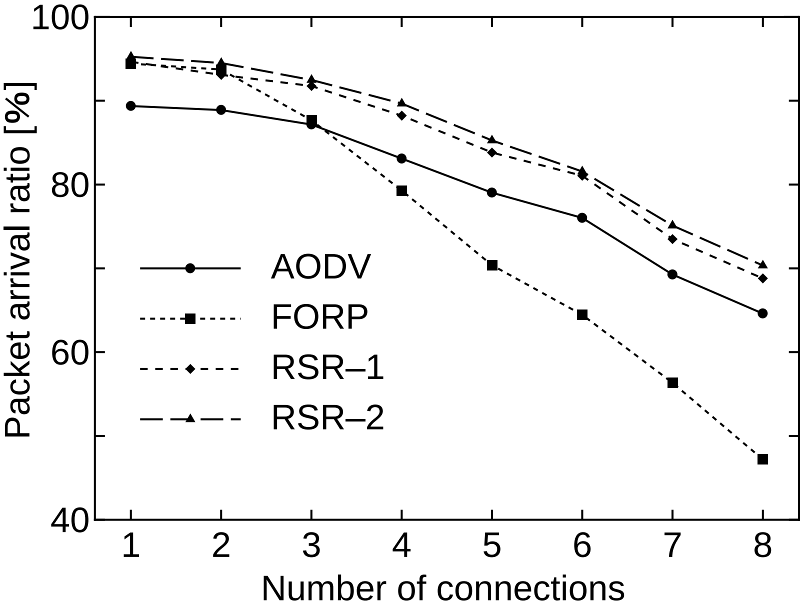
In FORP, the packet arrival ratio is highest when the number of connections is one, but it deteriorates rapidly with an increasing number of connections. It is reported that the throughput in ad-hoc networks decreases by a factor of 1/Hop [4]. Consequently, the throughput reaches its limit earlier in FORP than in the other routing protocols, even if the distance to the destination is the same, because a larger number of hops are required. Furthermore, the data packet collision probability increases with the number of hops, which implies that the packet arrival ratio is greatly degraded by an increase in the number of connections.

It can be seen from part (b) of the figure that the superiority of RSR-1 and RSR-2 is maintained even if the vehicle speed is increased. In AODV, the route is constructed without considering stability, and the arrival ratio is affected much more by the vehicle speed than in the other protocols. FORP has a high packet arrival ratio in a 1-connection environment, but the packet arrival ratio is greatly degraded when the number of connections is increased.

Figure 3.10(a) and 3.10(b) show the measured overhead for maximum speeds of 40 and



(a) Max vehicle speed = 40km/h



(b) Max vehicle speed = 100km/h

Figure 3.9: Relationship between number of connections and packet arrival ratio.

100 km/h, respectively. Part (a) reveals that RSR-1 and RSR-2 achieve low overhead. In AODV, the overhead is larger than in RSR-1 and RSR-2 due to frequent changes of route. In FORP, the overhead is larger than in AODV even though changes of the route occur less often than in AODV. This is because a large number of RREQs are generated in constructing a connection. It is evident that the overhead increases rapidly with an increasing number of route changes due to an increased number of connections.

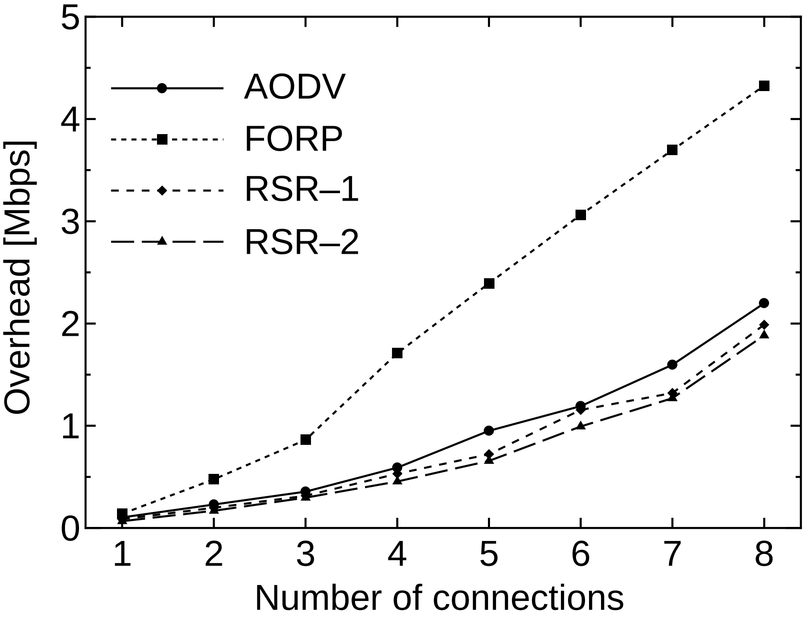
It is evident from (b) in the figure that the tendency of the overhead is maintained when the vehicle speed is increased. The overhead is smallest in RSR-2. In the sense that greater wireless bandwidth can be used for data packet communications, RSR-2 is judged more effective than the other routing protocols.

3.4.4 Effect of number of vehicles

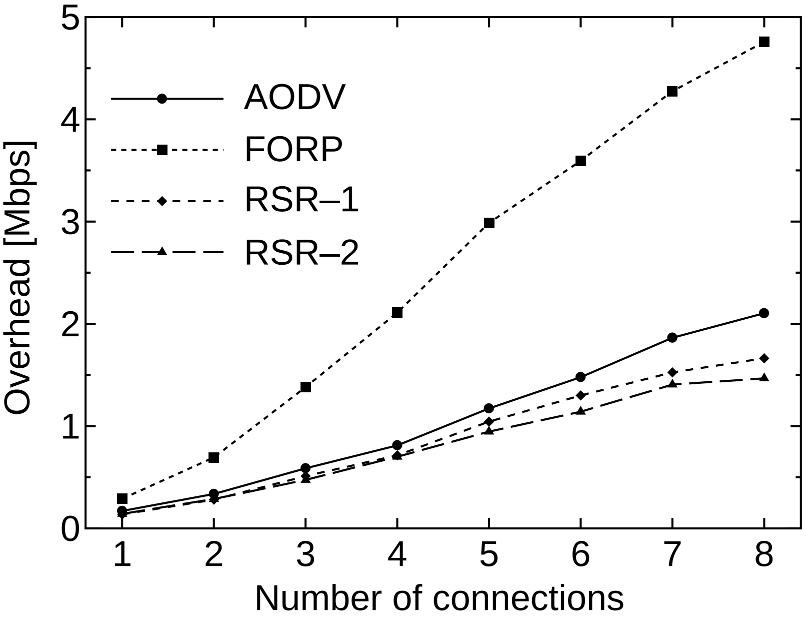
We wish to determine the effect when there is a change in the vehicle density. The number of connections is fixed at 3 and the number of route changes, the overhead, and the packet arrival ratio are examined while varying the number of vehicles as 100, 200, and 300. Figure 3.11 shows the measured numbers of route changes. It is evident from the figure that the number of route changes decreases in RSR-1 and RSR-2 as the number of vehicles increases. The reason is as follows. When the vehicle density is increased, the probability that a vehicle exists within the communications area with nearly the same relative speed as the vehicle in question is increased, which helps to construct a more stable route.

In FORP too, the number of route changes decreases with increasing vehicle density, because more stable routes can be constructed. In AODV, on the other hand, the number of route changes remains almost constant regardless of changes in the vehicle density, because route stability is not considered.

Figure 3.12 shows the measured overhead values. It is seen that the overhead increases in any protocol with increasing vehicle density. The reason is that the number of vehicles



(a) Max vehicle speed = 40km/h



(b) Max vehicle speed = 100km/h

Figure 3.10: Relationship between number of connections and overhead.

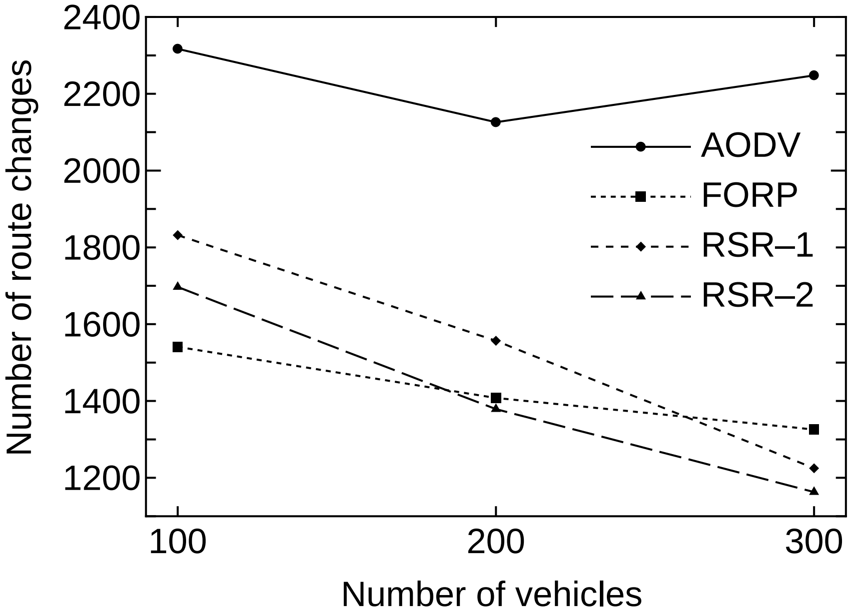


Figure 3.11: Relationship between number of vehicles and number of route changes.

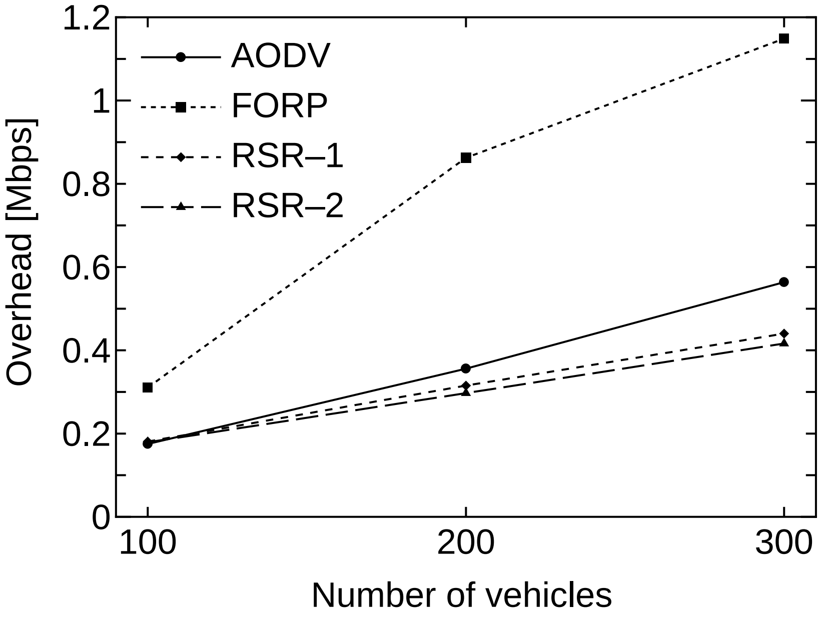


Figure 3.12: Relationship between number of vehicles and overhead.

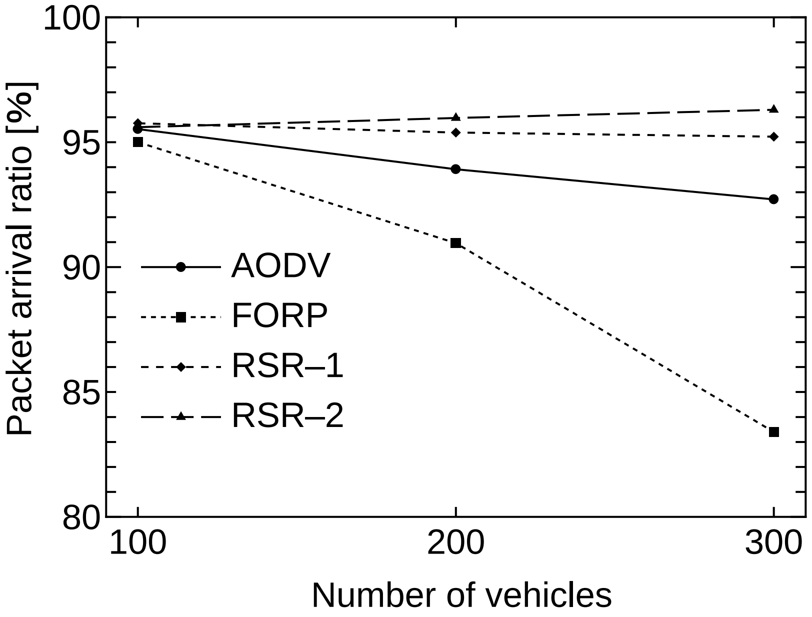


Figure 3.13: Relationship between number of vehicles and packet arrival ratio.

sending RREQs increases with the vehicle density. The effect of changes of vehicle density is more remarkable in FORP, because RREQs are sent more frequently for each connection. RSR-1 and RSR-2 are seen to be effective in the sense that changes in the number of vehicles have a smaller effect, because the number of route changes is reduced by constructing stable routes.

Figure 3.13 shows the measured packet arrival ratios. It can be seen that the packet arrival ratio is the highest in RSR-2 as the number of vehicles is changed. In FORP, the packet arrival ratio is degraded when the number of vehicles is increased. The reason is as follows. When the number of vehicles is increased, more wireless bandwidth is consumed due to RREQ flooding. Therefore, FORP, with the largest number of hops, is affected most seriously by changes in the number of vehicles. The packet arrival ratio is also degraded in AODV and RSR-1. The reason is likewise the consumption of wireless bandwidth due to an increasing number of control packets.

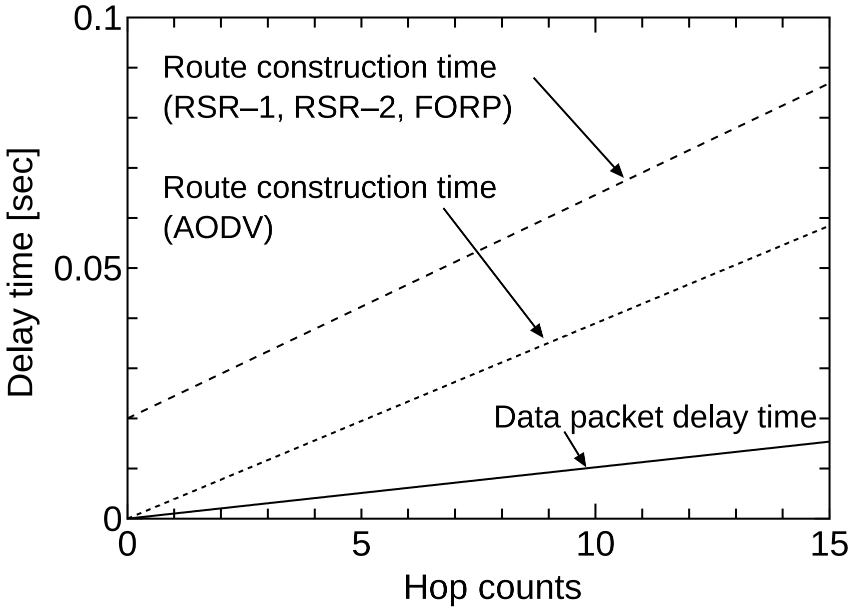


Figure 3.14: Relationship between hop counts and delay time.

3.4.5 Delay time

The time delay between stations is an important factor to be considered in the voice and picture transmission. Consequently, the relation between the number of hops and the delay time in each routing protocol was investigated. Two hundred vehicles were run at a maximum speed of 40 km/h, and data are sent and received between arbitrary pairs of vehicles. The measurement was performed 100 times while varying the connection pairs. Figure 3.14 shows the result of approximation of the obtained data by a linear function. The delay time plotted is the time required for communications below the MAC layer. The packet processing time in the upper layers is not included, because it depends greatly on the processing performance of the CPU in the station.

It can be seen from the figure that the data packet delay time is about 1 ms for each hop. Considering that the relation between the intervehicle distance and the number of hops is almost the same for AODV, RSR-1, and RSR-2, it is inferred that the relation of the delay time to the intervehicle distance is almost the same for all of these protocols. On the other hand, the delay time is larger in FORP than in the other protocols, even if the intervehicle distance is the same, because the number of hops is larger for the same intervehicle distance.

The time required to construct a route is the sum of the RREQ arrival time from the originator to the destination, the RREQ waiting time for multiple routes at the destination station, and the RREP arrival time from the destination to the originator. In AODV, a route construction time more than twice the data sending/receiving time is required. This is due to the random delay applied in RREQ relaying in order to avoid packet collision. In RSR-1, RSR-2, and FORP, the destination station waits for a certain period for RREQs from multiple routes when receiving RREQs. In this study, this waiting time was set as 20 ms. Consequently, the delay time is 20 ms longer as a whole than the route construction time in AODV.

The delay time required for sending and receiving data immediately after detecting the disconnection of a route is the sum of the route construction time and the data packet delay time. Although the route construction time in RSR-1 and RSR-2 is longer than that in AODV, the effect of the delay in picture transmission is reduced by constructing routes emphasizing stability and reducing the number of route reconstructions.

3.5 Conclusions

This chapter proposed the RSR protocol for the vehicle ad-hoc network. RSR has the features that stable routes can be constructed without using beacons, and that the relative speed and the distance to neighboring vehicles are used as metrics. RSR was evaluated by simulation, and was seen to be better than AODV and FORP in terms of packet arrival ratio and route stability. In particular, it was shown that the number of route changes was low regardless of the speed of the vehicle.

RSR can be used effectively not only in intervehicle communications on the highway, but also in intervehicle communicationsin environments with high vehicle density, such as urban centers and parking lots, because beacons are not used. A problem left for further study is to connect vehicle ad-hoc networks to cable networks.

Chapter 4

Routing Protocols for Inter-Vehicle Communications via Established Networks

4.1 Introduction

Ad-hoc networks enable any stations in the network to communicate with each other with wireless connections. The communication between stations that are located beyond the direct communication range is realized autonomously by relaying packets via intermediate stations in the ad-hoc networks. Ad-hoc networks have been developed as networks that need no infrastructure such as access points and exchangers.

However, research and development on systems that realize high flexibility and expansibility by combining ad-hoc networks with established networks have been reported recently [45, 46]. In hot spot services, the expansion of the communication area can be expected by this system. In offices or factories, everyone can work in a wide sphere irrespective of the location of access point by connecting ad-hoc networks to the existing LAN. In intervehicle communications, high-quality communications between distant vehicles can be realized.

Under the environments in which ad-hoc networks are combined with established networks, placement of some access points is desirable in order to raise interconnectivity between ad-hoc networks and the established networks and avoid load concentration on an access point. In this network environment, two types of routes between mobile stations that compose ad-hoc networks exist: routes using wireless links only and routes via access point and the established networks.

The routes via established networks can increase throughput compared with the routes using wireless links only when the established networks, which have high transmission rate and line quality compared with ad-hoc networks, are used effectively. However, in communication between neighbor stations, the routes using only wireless links are desirable in terms of throughput, communication delay, and loads on the access points. Therefore, the decision of a route is an important subject in environments in which ad-hoc networks are combined with established networks.

The major routing protocols for ad-hoc networks are discussed in the MANET working group of IETF [32–35,47]. It is assumed that these protocols are basically used in a situation that every station is equipped with the same wireless communication devices and decides routes by the minimum hop counts between stations. Therefore, the most suitable routes that realize high throughput cannot be selected by simply applying these protocols to the environment in which stations have different communication devices, such as ad-hoc networks combined with established networks.

Some routing protocols improve communication performance in an environment such that each station has certain wireless communication devices and uses some wireless channels simultaneously [48,49]. These protocols require the following two steps to avoid the interference of wireless channels. First, each station periodically ascertains the numbers of wireless channels being used by neighbor stations and the amount of traffic on those wireless channels.

Then, each station controls wireless channels for itself so that they do not overlap with the other wireless channels in use. However, the implementation of this wireless channel assignment to each wireless communication device, and routing protocols for this mechanism are somewhat complex since the location and density of stations in a radio interference range and the amount of traffic vary momentarily in ad-hoc networks.

To improve performance by a simple method is desirable, since the simplicity of protocols is an important evaluation factor with implementation, operation, and cost. Moreover, Reference [48] deals not with ad-hoc networks combined with wired networks, but with wireless networks only. Reference [49] deals not with communications between mobile stations, but only with communications from mobile stations to stations in backbone networks.

References [50–53] discuss routing protocols for ad-hoc networks combined with established networks. References [50–52] focus on Internet access from mobile stations in ad-hoc networks. Communications between mobile stations in ad-hoc networks is not described in these papers. Reference [53] describes a method to communicate between mobile stations via wired networks using dynamic source routing (DSR) as the ad-hoc routing protocol. However, applications of DSR to wired networks are simply discussed; routing protocols that improve throughput between mobile stations in ad-hoc networks combined with estab-lished networks are not described.

This chapter presents a routing protocol between mobile stations in ad-hoc networks combined with established networks. The feature of our proposed method is to decide a route not simply by using the minimum hop counts between stations, but using several formulas. The formulas consist of hop counts from the originator to the upper access point, hop counts from the lower access point to the destination, and hop counts of a route using only wireless links between the originator and the destination. The proposed routing protocol is realized as an expansion of AODV. Simulation results show that the proposed routing protocol raises packet reachability compared with AODV.

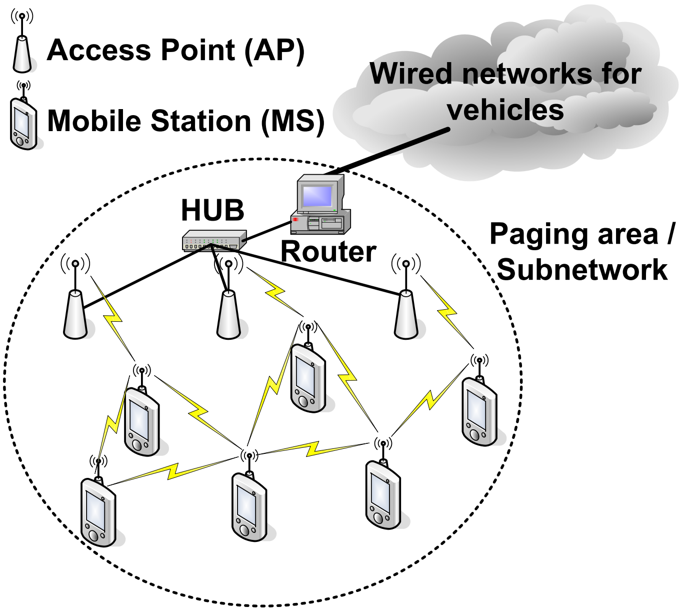


Figure 4.1: Network model.

4.2 Network model

The object of this chapter is a routing protocol between mobile stations in a subnetwork which consists of established networks, ad-hoc networks, some access points, and a router as illustrated in Figure 4.1. The established networks are defined as wired networks, which have higher transmission rates than wireless links. Ad-hoc networks include many mobile stations. The access points, at which ad hoc routing protocol is installed, have both a wired network interface and an ad-hoc network interface. All access points and stations which use a common wireless channel are deployed uniformly in the subnetwork. The distance between access points is greater than the radio communications radius. The router is responsible for forwarding data packets between subnetworks and terminating route control packets transmitted by AP. The IEEE 802.11b with RTS/CTS is used for the wireless MAC protocol.

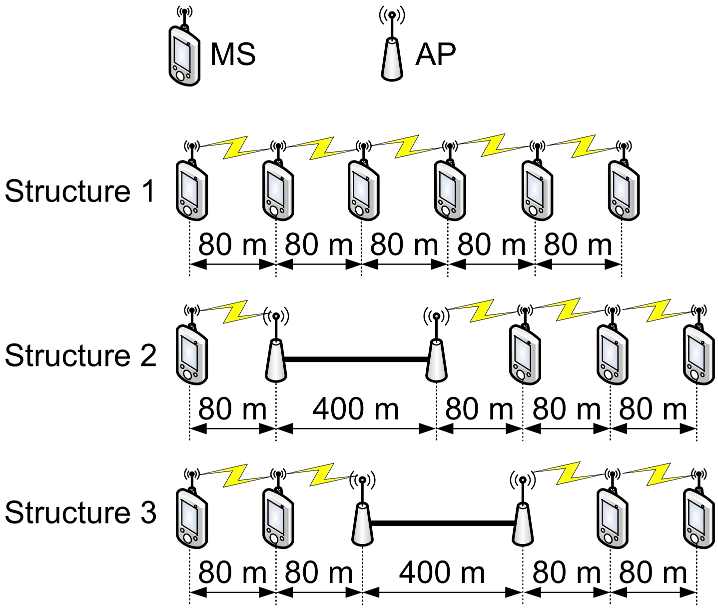


Figure 4.2: Throughput measurements test environment.

4.3 Derivation of route decision criteria

Criteria used for deciding which route is better, a route using wireless links only or a route via an established network, are derived in this section. The criteria were derived from the measurement of TCP throughput in three forms of station arrangements using stations and access points as shown in Figure 4.2. In these formations, each station or access point can communicate directly with its neighbor station or access point only. Structure #1 consists of six stations. Structure #2 consists of two access points and four stations, in which packets are absolutely forwarded via a wired link between access points when station #0 transmits packets to station #1. Structure #3 is almost the same as structure #2 except for the location of access points. The wireless com-munication method is IEEE 802.11b, whose transmission rate is 11 Mbit/s. The transmission rate of a wired link between access points is 100 Mbit/s. The radio communi-cation radius was defined as 100 m. Table 4.1 shows the simulation parameters.

Table 4.1: Simulation parameters.

Media Access Control	IEEE 802.11b with RTS/CTS
Frequency	2.4 [GHz]
Preamble	Short preamble (72 [bit], 2 [Mbit/s])
Wireless data rate	11 [Mbit/s]
Wired data rate	100 [Mbit/s]
Transmitted Power (P_t)	8 [mW]
Received Power (P_r)[*7]	$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^2$
Reception threshold[*8]	-71 [dBm]
Carrier sense threshold[*9]	-71 [dBm]
Radio communications range	100 [m]
Length of queue in routing layer	64 [packets]
Length of queue in link layer	250 [packets]
Session type	TCP
Data packet size	1460 [Byte]
Simulation period	250 [s]

[*7] The Friis transmission equation was used to calculate reception power. λ is the wavelength, and d is the distance between sender and receiver.

[*8] The reception threshold was decided according to the definition that commmunication rage is 100 m.

[*9] The carrier sense threshold was decided besed on the specification of JRC's wireless LAN.

Figure 4.3 shows the measurement of TCP throughput with variation of hop counts from station #0 to other stations or access points in each formation. In this thesis, one hop is defined as communication with a neighbor station or access point. It can be seen from this figure that the TCP throughput of the two hops in structure #1 is lower than that of three hops in structure #2 even though both include two wireless links. The same results are shown for four hops in structure #2 and three hops in structure #1, and between five hops in structure #2 and four hops in structure #1.

The causes are RTS/CTS and carrier sense of IEEE 802.11 DCF. In structure #1, stations

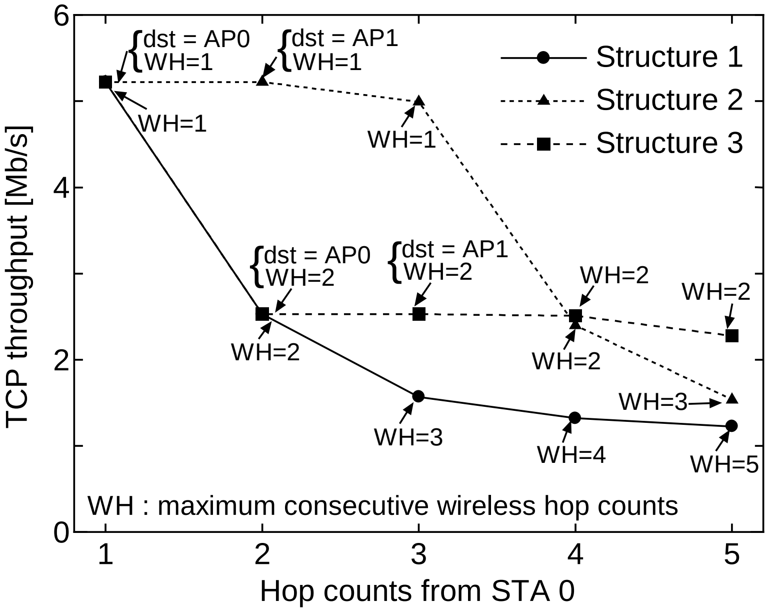


Figure 4.3: Measurement results of TCP throughput.

#1 and #2 cannot transmit packets while station #0 transmits packets to station #1 because of the RTS packets transmitted by station #0 and the CTS packets transmitted by station #1. On the other hand, in structure #2, transmissions can be executed simultaneously from access point #0 to access point #1 via wired link and from access point #1 to station #1, while station #0 transmits packets to access point #0 since access point #1 is located outside the carrier sense range of both station #0 and access point #0. Therefore, structure #2 increases the TCP throughput compared with structure #1.

The influence of RTS/CTS or carrier sense becomes much greater on routes that have more consecutive wireless links. In the results for five hops, the TCP throughput decreases in order of structures #3, #2, and #1, since the maximum number of consecutive wireless links of each structure is two, three, and five hops.

These measurements prove that high throughput can be obtained not by deciding a route using the minimum hop counts between stations, but by decreasing the number of consecutive wireless links by means of wired links in communications between mobile stations in ad-hoc networks combined with established networks. However, in a route via wired links there remains a concern that the hop counts between the originator and the destination might increase, which raises the possibility of link breakage, since ad-hoc networks consist of mobile stations. Moreover, Figure 4.3 shows that the throughput has little difference among routes that have more than three consecutive wireless links. Therefore, a route via wired links should be used when the following condition is satisfied:

$$(Map < Hw) \cap (Map \leq 3) \tag{4.1}$$

where Hw is the minimum hop count from the originator to the destination on routes using wireless links only, and Map denotes the greater of either the shortest hop count from the originator to its nearest access point or the shortest hop count from the destination to its nearest access point.

Equation 4.1 shows that a route via established networks is more effective than a route using only wireless links when Map is smaller than Hw and Map is less than or equal to three, even if the total number of hop counts of the route via established networks is greater than that of the route using only wireless links. Routes that satisfy Equation 4.1 can decrease the influence of RTS/CTS and carrier sense in IEEE 802.11 DCF, which raise the throughput compared with routes selected by the minimum hop count. Although Map is configured as three in this thesis, it is desirable to adjust Map to each target system of the wireless ad-hoc network environment.

4.4 Proposed routing protocol

The proposed routing protocol that uses Equation 4.1 to decide a route is described in this section. The proposed method is realized as an extension of AODV, one of the major routing protocols for ad-hoc networks, as an example. In AODV, the following two steps decide

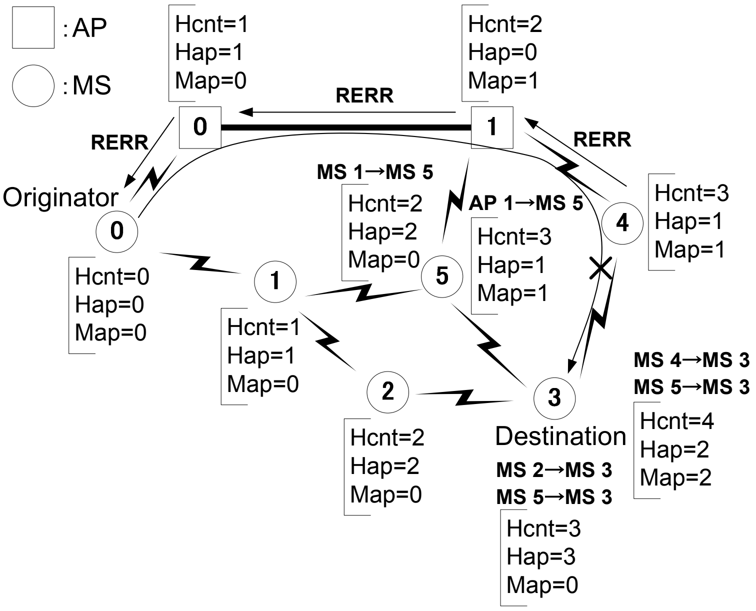


Figure 4.4: Explanation model for proposed routing protocol.

routes. First, the originator broadcasts route request packets (RREQ) to the destination. Then, the destination unicasts a route reply packet to the originator using a reverse route after receiving the RREQ. Each station that receives an RREQ or RREP keeps information on the route to the originator or destination in its routing table.

The proposed routing protocol inserts three elements into the RREQ, RREP, and routing table. One is the hop count from the originator to the destination ($Hcnt$). The second is the hop count from the originator to its nearest access point or from the destination to its nearest access point (Hap). The last is the greater of the hop count from the originator to its nearest access point and that from the destination to its nearest access point (Map).

The route decision method using the above three elements can be explained by using the simple ad-hoc network illustrated in 4.4. This figure shows the transitions of $Hcnt$, Hap, and Map when an RREQ is broadcast from station #0 to station #3 in an ad-hoc network combined with an established network environment including two access points and

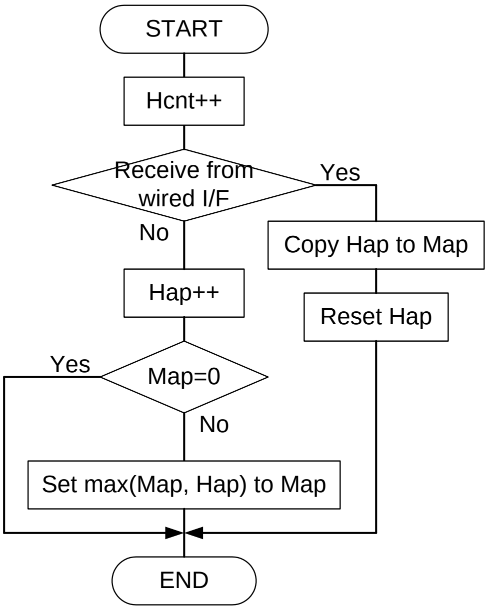
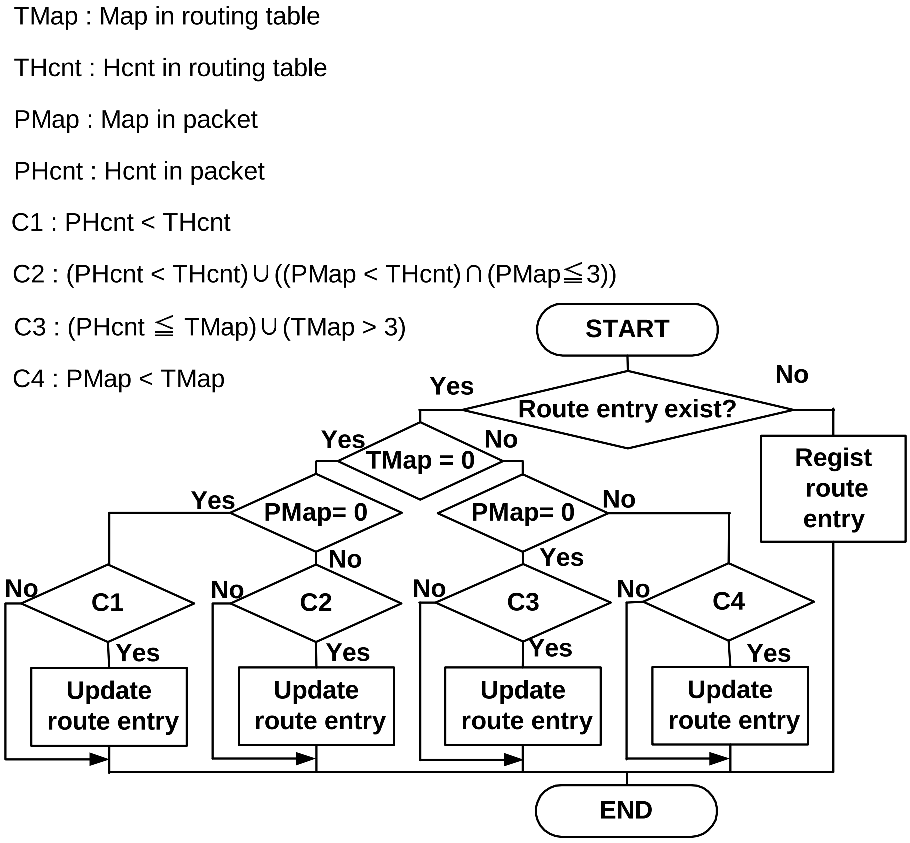


Figure 4.5: Update flow of Hcnt, Hap, and Map.

six stations. Station #0, the originator of communication, broadcasts an RREQ with $Hcnt$, Hap, and Map of zero.

Every station and access point updates $Hcnt$, Hap, and Map specified in the received RREQ according to the processes shown in Figure 4.5. First, each station or access point that receives the RREQ increments $Hcnt$ in the RREQ. Then the process branches according to the interface type from which the RREQ is received. When the RREQ is received from the wired interface, Hap is copied to Map and then cleared. This flow is processed only by access points because stations have no wired interfaces. Meanwhile, when the RREQ is received from a wireless interface, Hap is incremented and then it is ascertained whether the value of Map is zero or not. If Map is not equal to zero and Hap is greater than Map, then Hap is copied to Map. The latter case can be processed by both access points and stations. The value of Map remains zero when the RREQ is transmitted only through wireless links.

After the update of $Hcnt$, Hap, and Map, each station and access point decides a route


TMap : Map in routing table

THcnt : Hcnt in routing table

PMap : Map in packet

PHcnt : Hcnt in packet

C1 : PHcnt < THcnt

C2 : (PHcnt < THcnt) ∪ ((PMap < THcnt) ∩ (PMap ≦ 3))

C3 : (PHcnt ≦ TMap) ∪ (TMap > 3)

C4 : PMap < TMap

Figure 4.6: Flow of route decision.

to the originator and registers it with its routing table along the flow shown in Figure 4.6. If the routing table has no entry to the originator, the routing information specified in the RREQ is registered with the routing table. Meanwhile, the route to the originator has already existed in the routing table, and the process branches according to whether the value of Map in RREQ ($PMap$) or routing entry ($TMap$) is ether zero or not. The route to the originator in the routing table is updated with the route information in the RREQ when a condition under each branch ($C1$ to $C4$) is satisfied. The received packet is discarded without updating the routing table when the condition is not satisfied.

Condition $C1$ in Figure 4.6 means that the route in both the routing table and the RREQ includes only wireless links. In this case the route is decided by the minimum hop count from the originator to the destination. Condition $C2$ means that the route in the RREQ also includes wired links, while the route in the routing table includes only wireless links. The content of $C2$ is the same as Equation 4.1. Condition $C3$ means that the route in the routing table includes wired links while the route in the RREQ includes only wireless links. Although $C3$ is slightly different from $C2$, its content is also the same as Equation 4.1. Condition $C4$ means that the route in both the routing table and the RREQ includes wired links. In this case the route that has a smaller value of Map is selected.

Station #5 in Figure 4.4 is a good example to explain the route decision process described above. First, the case in which station #5 receives the first RREQ from station #1 is assumed. In this case, station #5 has no route entry to the originator in its routing table. Therefore, the route to the originator is registered using the information included in the RREQ, and the RREQ is rebroadcast later. After that, station #5 receives the RREQ from access point #1. The route to the originator in the table is updated using the route information in the RREQ, and then RREQ is rebroadcast, since condition #2 is true. On the other hand, if station #5 receives the first RREQ from access point #1, the sequence is the same as for the RREQ, namely, that the route to the originator is updated and the RREQ is rebroadcast. However, the next received RREQ from station #1 is discarded without updating the routing table, since condition #1 is false.

The destination, station #3, transmits an RREP packet to the originator after a certain fixed period since the reception of the first RREQ. The destination applies the route decision flow shown in Figure 4.6 to every RREQ received during the fixed period. Therefore, the RREP is transmitted to the originator by the most effective route. $Hcnt$, Hap, and Map in the RREP are cleared by the destination and processed similarly to the RREQ in each relay station. The originator that receives the RREP updates the route entry to the destination by applying the route decision process shown in Figure 4.6.

When a wireless link is disconnected, the station or access point that detects the link disconnection transmits a route error packet (RERR) to the upper station or access point. The RERR is relayed to the originator and then the RREQ is broadcast again to the destination to create a new route. For example, a route from station #0 to station #3 via access points #0, #1, and station #4 is assumed. Station #4, which detects the wireless link disconnection with station #3, transmits the RERR to access point #1. The RERR is forwarded via access point #0 to station #0, which broadcasts an RREQ to station #3. Then a new route between stations #0 and #3 is created again.

4.5 Evaluation on simulation

4.5.1 simulation model

The effectiveness of the proposed routing protocol was evaluated by simulation. The proposed routing protocol was realized as an extension of AODV and compared with the original AODV. Figure 4.7 shows the simulation model used in the evaluation and Table 4.2 shows the simulation parameters.

Two access points connected by a 100 Mbit/s cable were sited on the edges of a square with a side of 400 meters. In this field, 150 stations were deployed at random. Each station moved by a random waypoint model at a random speed in the range of 0.6 to 1.7 m/s or 2.8 to 5.6 m/s. A pair of stations, communicating UDP packets of 512 bytes, were chosen at random. The effectiveness of the proposed routing protocol was evaluated by investigating the packet arrival rate, overhead, and delay time in this simulation environment. In this chapter, the overhead is the amount of information in control packets such as the RREQ, RREP, and RERR generated in the simulation.

Table 4.2: Simulation parameters.

Simulation area	400×400 [m]
Number of STAs	150
Number of APs	2
Distance between APs	400 [m]
STA speed	0.6-1.7, 2.8-5.6 [m/s]
Media Access Control	IEEE 802.11b with RTS/CTS
Frequency	2.4 [GHz]
Preamble	Short preamble (72 [bit], 2 [Mbit/s])
Wireless data rate	11 [Mbit/s]
Wired data rate	100 [Mbit/s]
Transmitted Power (P_t)	8 [mW]
Received Power (P_r)[*10]	$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^2$
Reception threshold[*11]	-71 [dBm]
Carrier sense threshold[*12]	-71 [dBm]
Radio communications range	100 [m]
Length of queue in routing layer	64 [packets]
Length of queue in link layer	250 [packets]
Session type	UDP
Data packet size	512 [Byte]
Data packet Tx pattern	Constant bit rate
Data packet Tx rate	0.4-2 [Mbit/s]
Simulation period	250 [s]

[*10] The Friis transmission equation was used to calculate reception power. λ is the wavelength, and d is the distance between sender and receiver.

[*11] The reception threshold was decided according to the definition that commmunication rage is 100 m.

[*12] The carrier sense threshold was decided besed on the specification of JRC's wireless LAN.

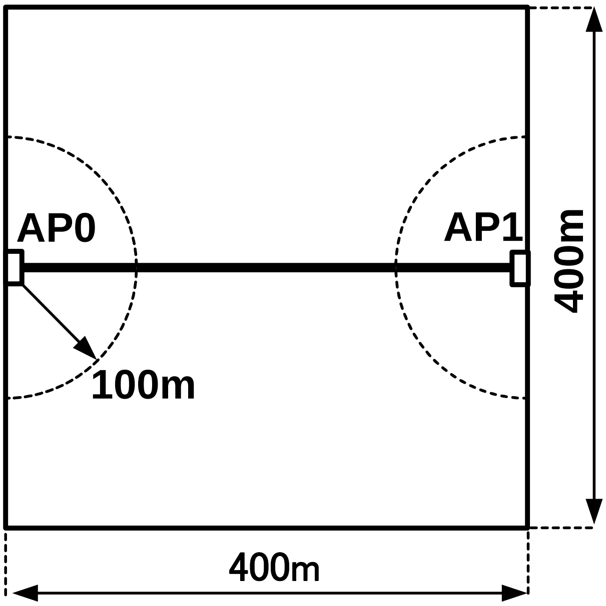


Figure 4.7: Simulation model.

4.5.2 The variation of data transmission rate

The communications performance for various data transmission rates between a pair of stations selected at random was evaluated. The aim of this investigation is to prove that the proposed routing protocol, which decreases the number of consecutive wireless relays and increases the number of communication links that can transmit data simultaneously, improves throughput in a simple connection. The measurements were repeated 20 times and the average was evaluated.

Figure 4.8 shows the result of packet arrival ratio for each protocol at various transmitted data rates. It can be seen from this figure that the proposed routing protocol has a better packet arrival rate than AODV at a high data rate. At low data rates, the packet arrival rates of both protocols are almost the same because of the large wireless bandwidth. However, the influence of RTS/CTS or carrier sense on data transmission increases along with the data rate. In the proposed routing protocol, data can be transmitted simultaneously on three parts of a

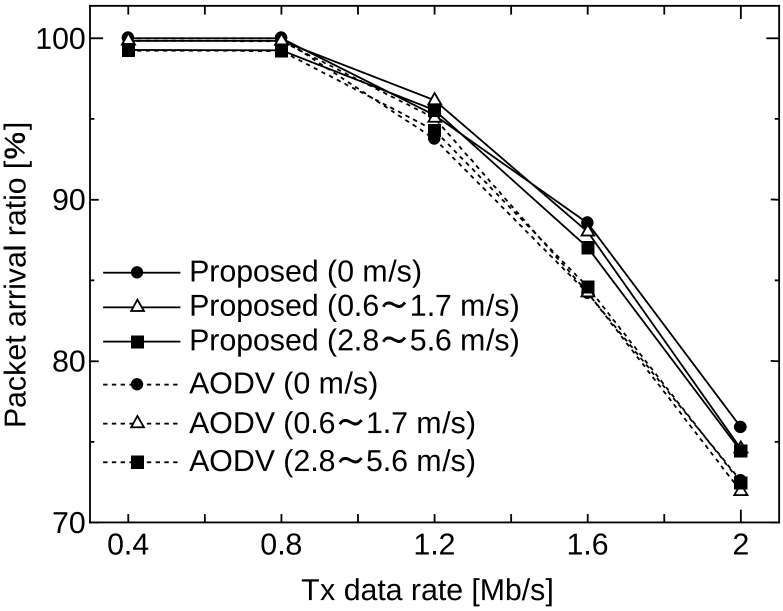


Figure 4.8: Relationship between packet arrival ratio and data transmission rate.

route: from the originator to the access point, between access points, and from access point to the destination. Therefore, the packet arrival rate is higher than on a route that includes only wireless links for routes with a high hop count. This tendency is independent of station mobility.

Figure 4.9 shows the overhead for each protocol at various transmitted data rates. It can be seen from this figure that the overhead of AODV is higher than that of the proposed routing protocol at high data rates. The main reason for the overhead is the control packets generated during route re-creation after packet collisions. At high data rates, the packet collision ratio of DATA or RTS/CTS becomes high. The proposed routing protocol, which transmits data via access points, reduces overhead compared with AODV, which decide routes by the minimum hop counts, since the proposed routing protocol has a low packet collision ratio. Wireless links are easily broken in situations of high station mobility, which leads to high overhead.

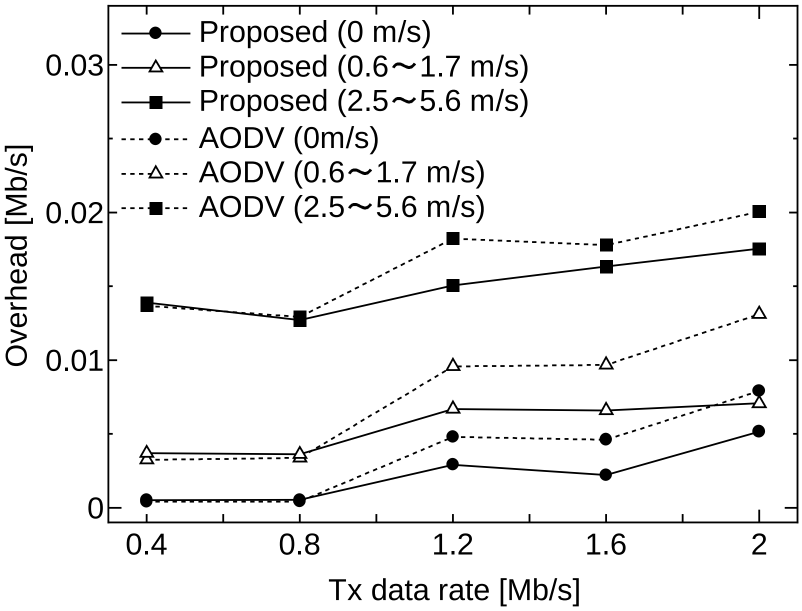


Figure 4.9: Relationship between overhead and data transmission rate.

Figure 4.10 shows the hop counts from the originator to the destination for each protocol at various transmitted data rates. It can be seen from this figure that a route selected by the proposed routing protocol has a greater hop count than that of AODV regardless of the transmitted data rate. In the proposed routing protocol, the hop count of a route tends to increase rather than decrease the wireless hop count. The increase in the hop count of a route increases the delay time. Therefore, the delay time from the originator to the destination was also investigated.

Figure 4.11 shows the delay time in the application layer for each protocol at various transmitted data rates. It can be seen from the figure that although the delay times of the proposed routing protocol and AODV are almost the same at low data rates, the delay time of AODV is longer than that of the proposed routing protocol at high data rates. The throughput between mobile stations in ad-hoc networks combined with established networks is decided by “1/(the maximum consecutive wireless hop counts)” as shown in Figure 4.3. The

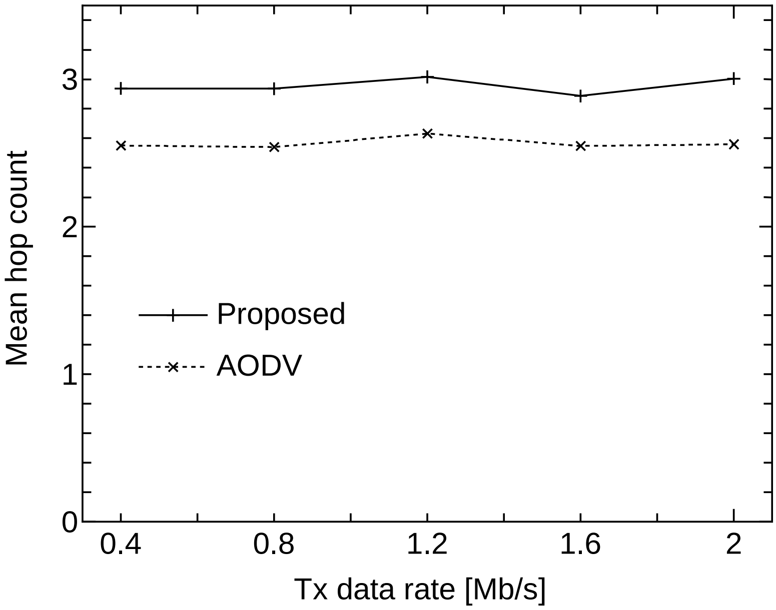


Figure 4.10: Mean hop counts.

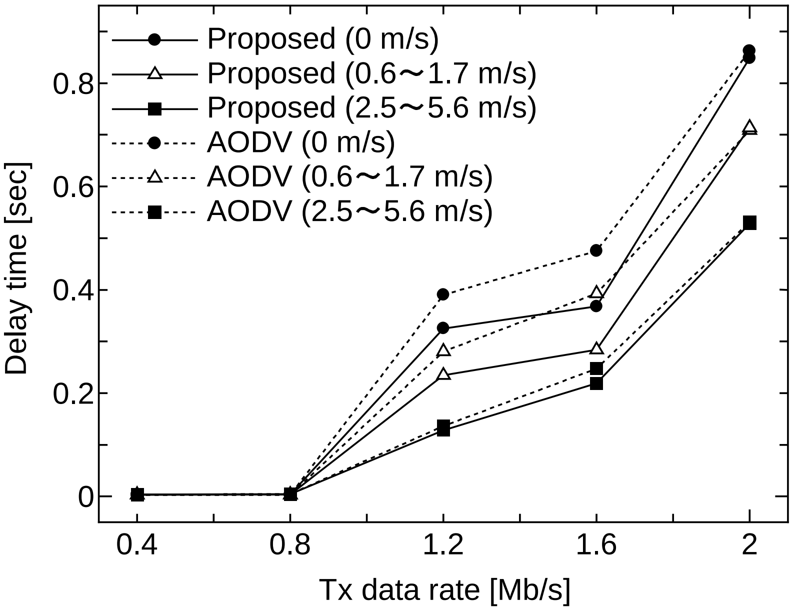


Figure 4.11: Relationship between delay time and data transmission rate.

proposed routing protocol, which selects the route that has the lowest consecutive wireless hop counts, achieves higher throughput than AODV. This means that the duration of each packet's stay in a queue at each station decreases in our proposed routing protocol, which shortens the delay time from the originator to the destination. However, at a data rate of 2 Mbit/s, the proposed routing protocol has the same delay time as AODV, since the data rate exceeds the throughput capacity of many routes, which prolongs each packet's stay in the queue. The delay time tends to be short in fast mobility situations, since packets stacked in the queue are discarded as a result of route changes.

4.5.3 The variation of the number of connections

In the proposed routing protocol, degradation of communication performance is of concern along with an increase in the number of connections, since the load on access points also increases. Therefore, the relationship between the communications performance and the number of connections at a data rate of 0.4 Mbit/s was evaluated.

Figure 4.12 shows the packet arrival ratio for each protocol for various numbers of connections. It can be seen from this figure that the proposed routing protocol has better packet arrival rate than AODV in connections #3 to #7. The reason is that the number of wireless communications around the center of the simulation area is decreased by the proposed routing protocol, which selects detour routes via access points. However, the proposed routing protocol has almost the same packet arrival rate as AODV in connection #10, since the loads on the access points increase and the proposed routing protocol tends to select the same route as AODV.

Figure 4.13 shows the number of packets through AP for each protocol at various numbers of connections. The number of packets passing through access points is saturated in connection #5 in the proposed routing protocol. Therefore, in connection #7 or #10, a route via access points is hard to select, which means that a route tends to be selected by the

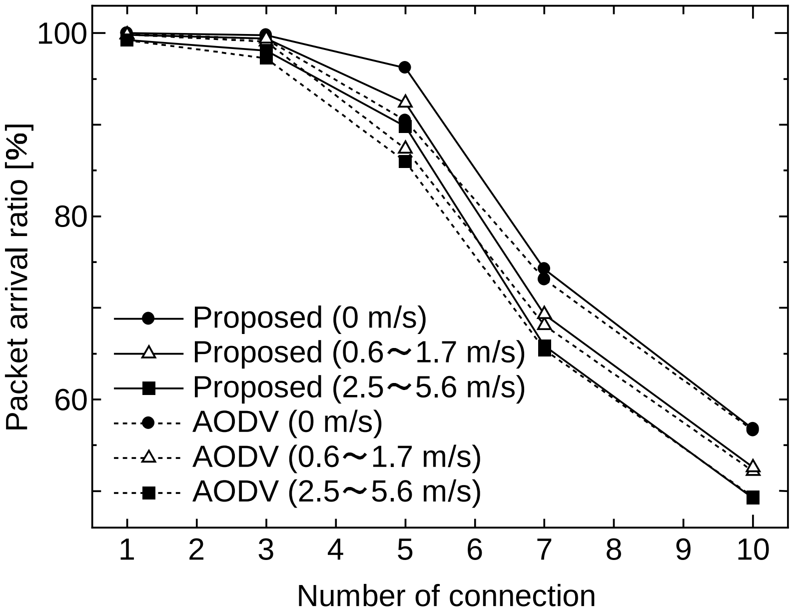


Figure 4.12: Relationship between packet arrival ratio and number of connections.

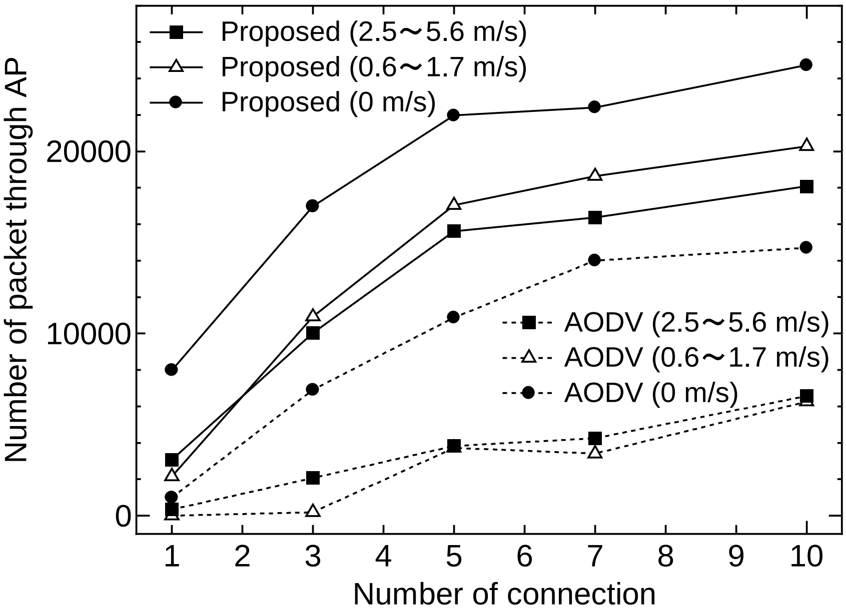


Figure 4.13: Relationship between number of packet through wired links and number of connections.

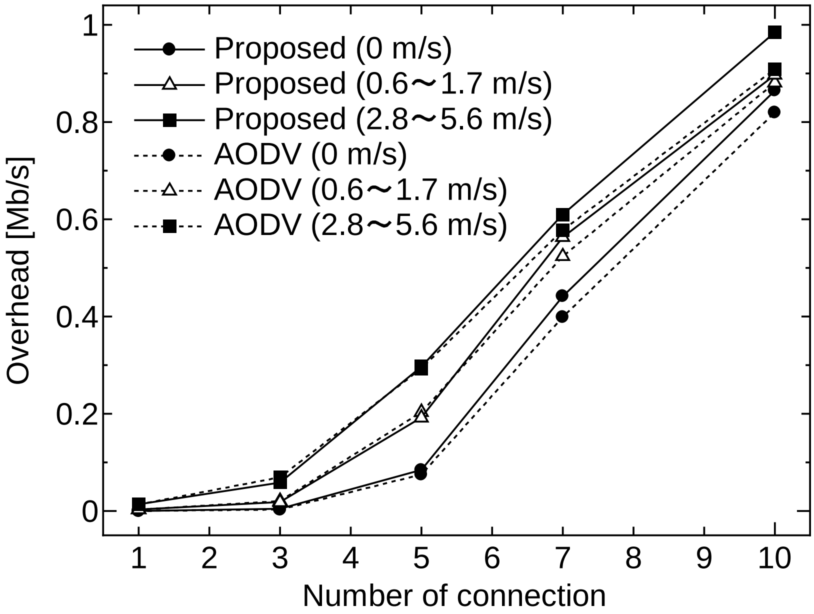


Figure 4.14: Relationship between overhead and number of connections.

minimum hop counts of wireless links, as in AODV. The number of packets passing through access points decreases with increasing station mobility, since many packets are discarded as a result of route changes. In AODV, whether a route via access points is selected strongly depends on the position of relation of the originator, destination, and access points. Therefore, the number of packets passing through access points in AODV decreases compared to the proposed routing protocol.

Figure 4.14 shows the overhead for each protocol for various numbers of connections. The overhead of the proposed routing protocol is greater than that of AODV in many connections, since the amount of information in the RREQ in the proposed routing protocol is greater than that in AODV. When the numbers of RREQs generated in both protocols are the same, the overhead of the proposed routing protocol is greater than that of AODV.

Figure 4.15 shows the delay time for each protocol for various numbers of connections. In a few connection situations, the delay time of the proposed routing protocol is shorter

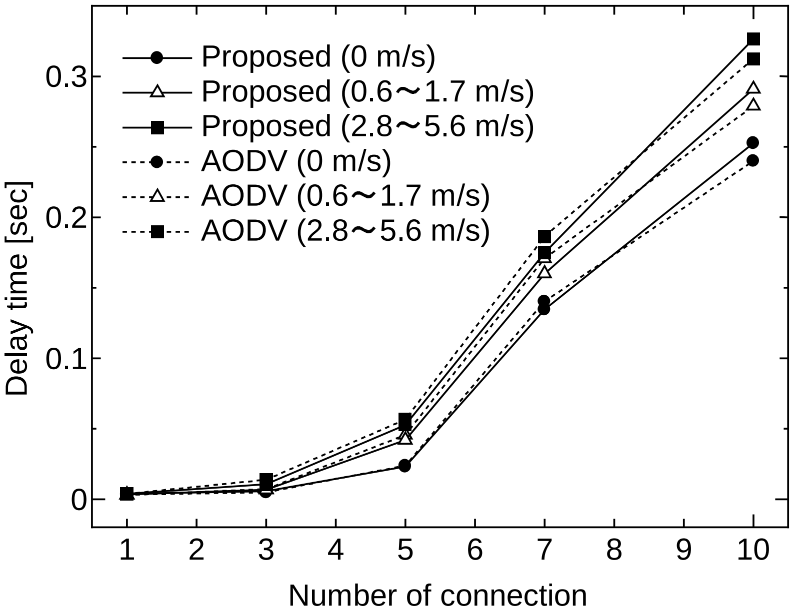


Figure 4.15: Relationship between delay time and number of connections.

than that of AODV. However, the delay time of the proposed routing protocol is longer than that of AODV in 10 connections. The proposed routing protocol has the advantage that the transmission rate and packet reachability between stations are improved when using established networks that have high transmission rates and line quality. However, it also has the drawback that the delay time tends to increase in many connections, since the load on access points increases. Communication between stations and access points then becomes a bottleneck.

4.5.4 Number and arrangement of stations or access points

To investigate the influence of the number of stations on the proposed routing protocol, the relationship between the number of stations and the packet arrival rate was simulated for a data rate of 1.6 Mbit/s, one connection, and station mobilities of 0.6 to 1.7 m/s. The results are shown in Figure 4.16. It can be seen from this figure that the packet arrival rate of the proposed routing protocol is higher than that of AODV irrespective of the number of stations.

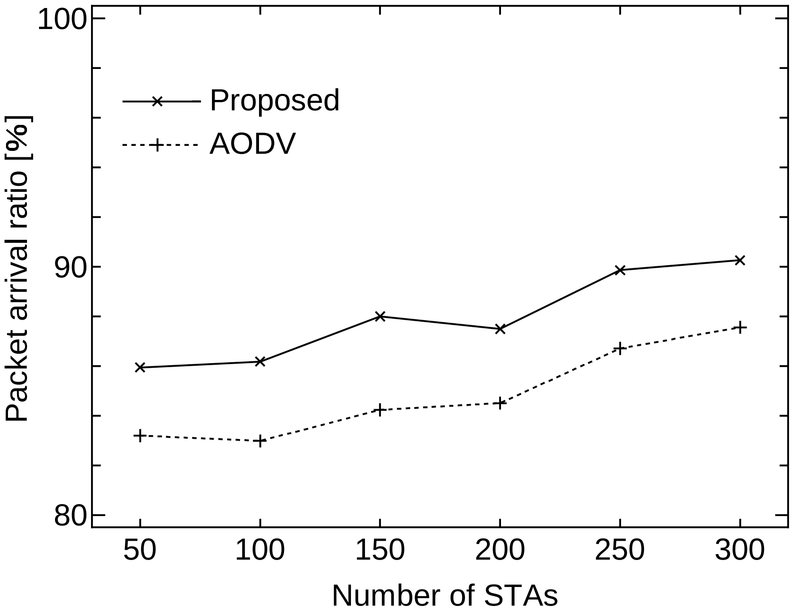


Figure 4.16: Relationship between packet arrival ratio and number of STAs.

An increase in the number of stations raises the packet arrival rate, since it is easy to create a route with a smaller hop count at high station density. The small number of consecu-tive wireless hops raises the limit of throughput and packet reachability. Meanwhile, the decrease in the number of stations lowers packet reachability, since a route tends to be created with more consecutive wireless hops, or no route may be created.

As defined in Section 2, access points are deployed uniformly in this chapter. Consequently, the proposed routing protocol selects the same route as AODV when the number of access points is very large or very small. Similarly, the proposed routing protocol selects the same route as AODV when the number of stations is very small or when the stations are concentrated in a certain area. The proposed routing protocol is suitable for improving communications performance by adding access points to an established network with a small facility investment. Examples of application of the proposed routing protocol include vehicle-to-vehicle communications system with access points arranged at major intersections, and peer-to-peer commu-nications with access points arranged in a factory or an entertainment park.

4.6 Conclusions

In this chapter, a new routing protocol for ad-hoc networks with established networks was proposed. The proposed routing protocol uses formula to judge whether a route using only wireless links or a route via wired networks is better. The performance of the proposed routing protocol, realized as an extension of AODV, was evaluated by simulation, which showed that the proposed routing protocol increases the packet arrival rate in a high data rate situation. In the future, routing protocols for ad-hoc networks on mobile IP will be investigated.

Chapter 5

Flooding Methods for Mobile IP Protocol in Vehicle Ad-Hoc Networks

5.1 Introduction

Mobile ad-hoc networks enable a station to communicate with a distant station by multi hopping via intermediate stations wirelessly. Ad-hoc networks have several promising features, such as their absence of infrastructure, their autonomous and distributed control, and their good station mobility tolerance. Therefore, there is active research on ad-hoc networks in various fields, such as battlefield networks, disaster area networks, intervehicle communications, and sensor networks.

In ad-hoc networks, a broadcasting technique called flooding, in which a source station disseminates a packet to all the other stations in the network, is frequently used. Examples of applications in which flooding is used are route discovery mechanisms in reactive routing protocols [34,35], duplicate address detection mechanisms in address auto assignment [54], and subnetwork detection mechanisms in mobile IP [16]. However, flooding causes unnecessary collisions and bandwidth waste, which decreases packet reachability to the destination of all communications in the network. Research on effective flooding methods in ad-hoc networks is thus an important subject.

Flooding methods have been categorized into four families [55, 56]: simple flooding (pure flooding), probability-based methods, neighbor knowledge methods, and area-based methods. In simple flooding [57, 58], a source station broadcasts a packet to all of its neighbors. Each neighbor station then rebroadcasts the received packet once. This process continues until all stations have the packet. This flooding scheme is referred as pure flooding.

Probability-based methods can reduce the number of packet transmissions compared with pure flooding [59]. In the methods of this category, every station uses a predetermined probability or threshold to decide whether to rebroadcast the received packet. The threshold is the number of packet transmissions received during a random assessment delay (RAD). Though the methods of this category are easy to implement, one drawback is that the best probability or threshold value varies according to the station density.

Neighbor knowledge methods, which use 1-hop or 2-hop neighbor information, can substantially reduce the number of packet transmissions compared with pure flooding or probability-based methods. Many methods have been reported in this category, which can be further divided into clustering-based methods, selecting forwarding neighbors, and internal station-based methods [60–65]. However, it has been reported that the packet reachability drops in high station-mobility situations [55]. Moreover, the periodical hello packets used in most of these methods increase overheads, especially in high station-density situations.

Area-based methods that require a positioning device, such as a GPS receiver, or signal strength information of the received packet are better than the above three categories in that they use fewer packet transmissions. The methods of this category have many advantages, such as high packet reachability regardless of station mobility, the small number of packet transmissions, and the absence of periodical hello packets. Therefore, this is the most attractive category among the four, so long as each station is capable of precisely determining its own position.

Each category has its strengths and limitations, as described above. Therefore, it is desired to choose a category for the target system based on its simplicity of implementation; application requirements, such as balancing reachability and bandwidth consumption; and features of the assumed network environment, such as station density, station mobility, and the availability of positioning devices.

Focusing on the area-based methods, a distance-based scheme [59], a location-based scheme [59], a packet relay control scheme based on priority regions (PRCSPR) [66], waiting-time driven diffusion (WDD) [67], and GeoFlood have been reported [68]. In the distance-based scheme, each station compares a predetermined threshold with the distance between itself and neighbor stations. The distance can be calculated using the signal strength of the received packets, or the location of the sender station specified in flooding packets. If any station is closer than the threshold distance, the station cancels rebroadcast. Although this method can reduce the number of packet transmissions, it suffers from the same problem as probability-based methods: the best threshold value varies according to the station density.

The location-based scheme differs from the distance-based scheme in that it uses not distance but additional coverage area as a metric. Although this scheme is more robust than the distance-based scheme, it also uses a threshold to decide whether to rebroadcast or to drop the packet.

PRCSPR and WDD substantially reduce bandwidth consumption. However, the packet reachability drops in low station-density environments. In PRCSPR, the communication area of a sender station is divided into concentric ring-shaped zones, the center of which is the sender station itself. Each receiver station calculates the zone to which it belongs using its own position and the sender station's position specified in flooding packets. The stations in the farthest zone from a sender station set a short RAD, whereas the stations in the nearest zone set a long RAD. The stations that receive no same packets during its RAD rebroadcast the packet. WDD is very similar to PRCSPR.

GeoFlood achieves high packet reachability regardless of the station density. However, the number of packet transmissions is much more than that of the other methods. In this method, every station defines quadrants, the center of which is the station itself. Each station rebroadcasts a packet unless it receives the same packet from all of the quadrants during a predefined period of time.

The important factors in flooding are reachability, meaning that all stations in the network can have the packet; efficiency, meaning that the packet is propagated with less wireless bandwidth; and speed, meaning that the packet is propagated in a short delay period. Of these three factors, reachability is the most important because the purpose of flooding is to disseminate packets to all of the stations in the network. However, PRCSPR lacks reachability in low station-density situations. Although GeoFlood satisfies the reachability requirement, it lacks efficiency in high station-density situations. A reliable flooding method must have high reachability, efficiency, and speed, regardless of the station density. Therefore, a new flooding method that overcomes the drawbacks of PRCSPR and GeoFlood is needed.

This chapter presents sector-based flooding (SBF) and adaptive sector-based flooding (ASBF) for mobile ad-hoc networks. Both SBF and ASBF are categorized as area-based methods. The goal of SBF is to reduce the number of packet transmissions. SBF is divided into SBF-1 and SBF-2 according to the criteria used for their rebroadcast cancellation. The goal of ASBF is to accomplish high packet reachability, regardless of station density variation, with fewer transmissions. The basic idea of ASBF is that each station selects a flooding method from among SBF-1, SBF-2, and pure flooding depending on its local station density.

The remainder of this chapter is organized as follows. In the next section, conditions and definitions used in this chapter are described. In section 3, the concepts and drawbacks of SBF are described. The basic idea of ASBF is described in section 4. Our simulation environment and the results of SBF and ASBF compared with pure flooding, GeoFlood, and PRCSPR are presented in section 5. Finally, section 6 summarizes our work.

5.2 Conditions and definitions

In SBF or ASBF, it is assumed that each station is equipped with a GPS receiver to enable it to determine its own position precisely. Moreover, ideal radio wave propagation is considered, which means that the communication area is a circle centered on the station. The terminology used in this chapter is as follows.

- “Communication radius” means the maximum distance over which direct communication is possible.
- “Communication area” means the area where a station can directly communicate with other stations. The communication area of a station is defined as the area within the communication radius from the station.
- “Sender station” means a station that sends a packet.
- “Originator station” means a station that originates flooding. An originator station is also one of the sender stations.
- “Receiver station” means a station that receives a packet. Some receiver stations become sender stations.
- “Delay time” means the period from the reception of a packet to the rebroadcast of the packet.
- “Maximum delay time” means the maximum value of the delay time.

- "Propagation delay" means the period from the initiation of flooding to completion of flooding.
- "Reachability" means the ratio of stations that could receive a message from the originator. When all stations received the packet, the reachability is 1, or 100%.
- "ID" means identification data.

5.3 Sector-Based Flooding (SBF)

5.3.1 Protocol

The idea of SBF is to divide the sender station's communication area into some virtual areas called sectors and to allow only one station in each sector to rebroadcast the packet. The purpose of using sectors is to reduce the number of packet transmissions generated in a flooding. The sectors are formed by dividing the sender station's communication area into sectors of equal angle at the center. The number and the direction of sectors are fixed; they are predefined in each station. Each sector includes a sector representative position that is set at the center of the arc on the sector. If stations exist at every sector representative position of every station's communication area, flooding is executed with the smallest number of relays. Figure 5.1 shows the relationship of sender station position (x0, y0), receiver station position (x1, y1), the sectors, and the sector representative position in a three-sector formation as an example.

In the three sector example, sectors are formed differently according to the hop count. This raises packet propagation efficiency because only one of the three sector representative positions exists in the area where the packet has already been disseminated. For odd hop count, a communication area is divided into north (sector 1), south-east (sector 2), and south-west (sector 3). For even hop count, it is divided into north-east (sector 4), south (sector 5),

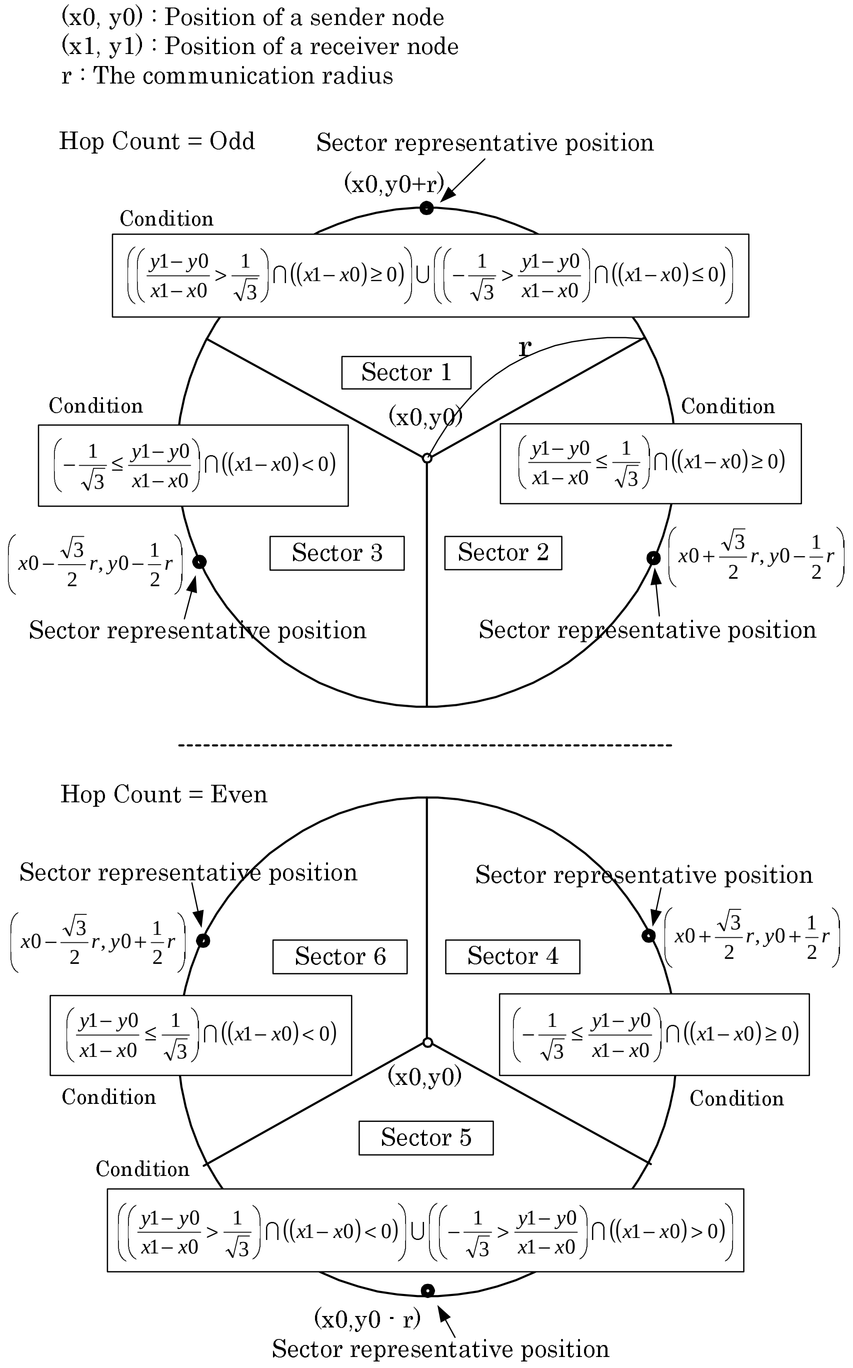


Figure 5.1: Concept of SBF.

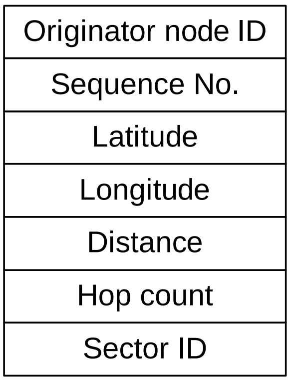
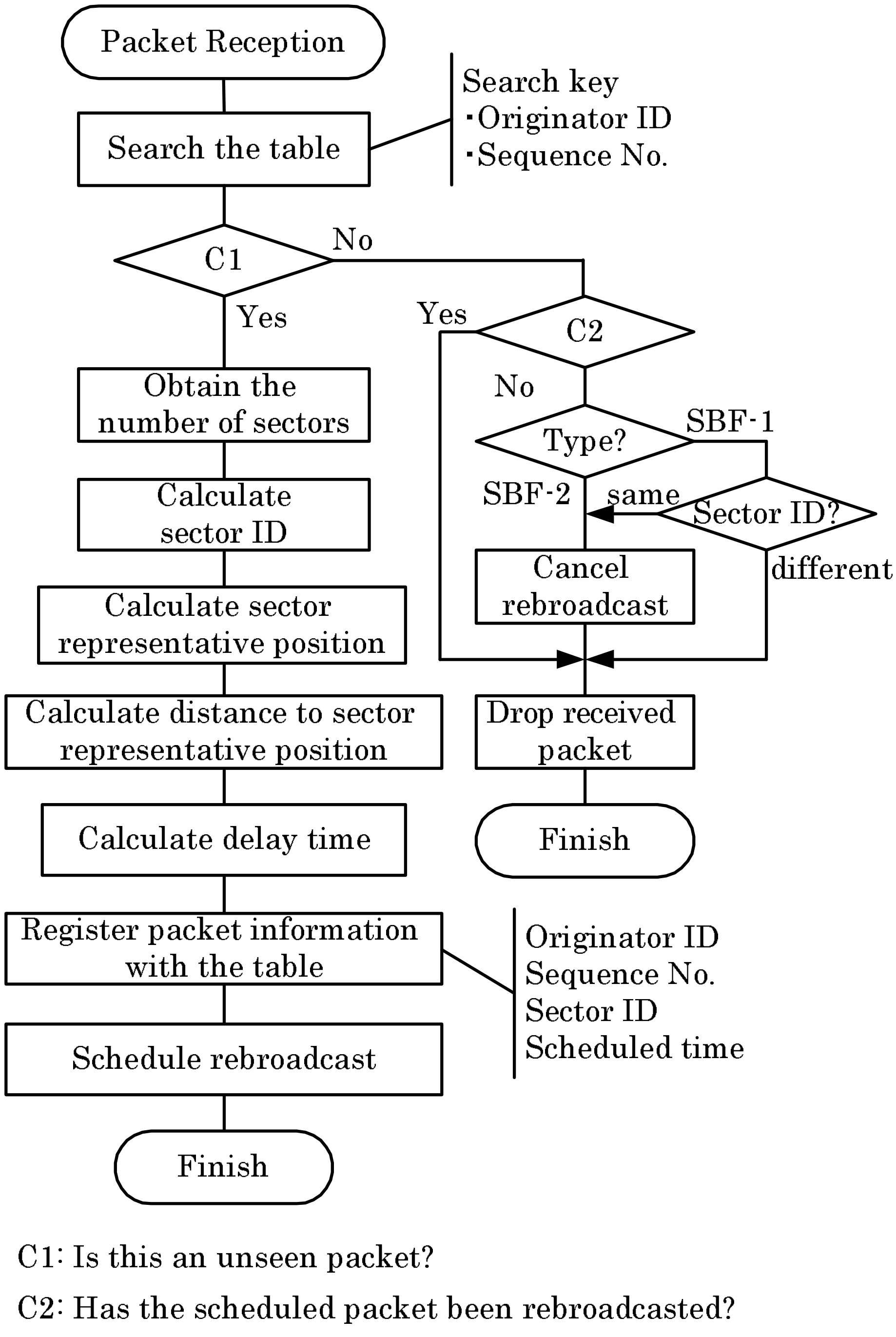


Figure 5.2: SBF elements in a flooding packet.

and north-west (sector 6). Constant sector formation regardless of the hop count is used in sector division by even numbers to put many sector representative positions outside of the area where the packet has already been disseminated. Variable sector formation depending on the hop count, as described above, is desired in sector division by odd numbers for the same reason.

In SBF, flooding packets need to include the information shown in Figure 5.2. The originator station ID and sequence No. are used to identify the packet. The latitude and longitude show the position of the sender station. The distance shows the distance from a receiver station to the sector representative position. The hop count shows the number of hops from the originator station. The sector ID shows the ID of the sector. The originator station starts flooding after setting its own station ID, sequence No., latitude and longitude in the packet. The latitude and longitude are obtained from the GPS receiver. The distance, hop count, and sector ID in the packets are all set to zero.

Each station processes received packets according to the flowchart shown in Figure 5.3. When a station receives an unseen packet, first a predefined number of sectors configured in its table is obtained. Second, the station calculates the located sector ID using its own position obtained from the GPS receiver and the sender station's position specified in the received



C1: Is this an unseen packet?

C2: Has the scheduled packet been rebroadcasted?

Figure 5.3: Flooding packet reception process in SBF.

packet. The relationship among the sender station's position, receiver station's position, and sector ID in the three-sector formation is illustrated in Figure 5.1. Third, the station calculates the sector representative position of its located sector. The method of calculating the sector representative position for the three-sector formation is also illustrated in Figure 5.1. Fourth, the station calculates the distance from the station to the sector representative position. Fifth, the delay time until rebroadcast of the received packet is calculated. The delay time, $Delay$, is calculated as follows:

$$Delay = Dis/Com\_radius \times D_{max} \tag{5.1}$$

where Dis means the distance from the station to the sector representative position, Com_radius means the communication radius, and D_{max} means the maximum delay time. The originator ID and sequence No. that are specified in the received packet, and the calculated sector ID and scheduled time are registered in the station's own table. Finally, the rebroadcast of the received packet is scheduled after overwriting the latitude, longitude, distance, and sector ID in the received packet with its own information.

The scheduled rebroadcast is canceled when the station receives a packet that includes the same identifiers as those registered in the table by the scheduled time. This means that only the receiver station nearest to the sector representative position in each sector can be the next sender station. SBF is divided into two methods, SBF-1 and SBF-2; the difference is the number of elements used to decide whether to rebroadcast or to drop the packet. SBF-1 uses the originator station ID, sequence No., and sector ID as identifiers, whereas SBF-2 uses the originator station ID and sequence No.

SBF has no mechanism for packet collision. This means that sender stations never retransmit a collided packet, and receiver stations behave as if they had never received the collided packet.

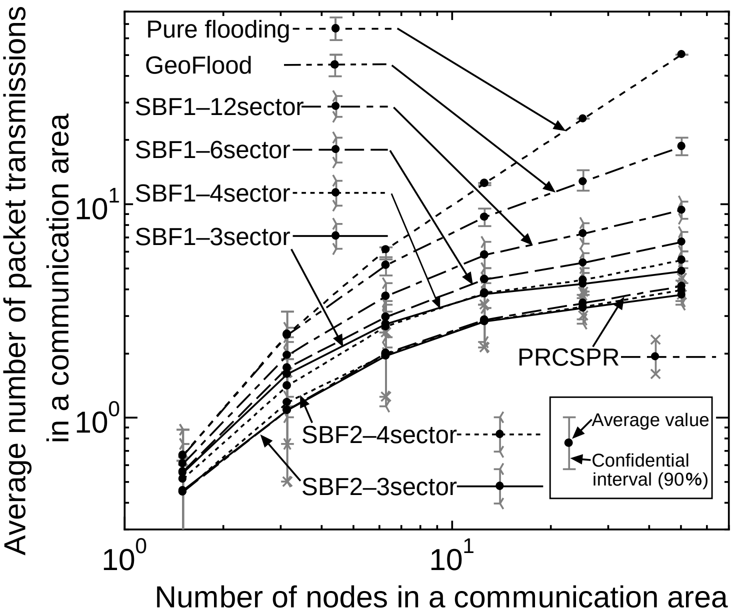


Figure 5.4: Relationship between the number of stations in a communication area and the number of packet transmissions.

5.3.2 Performance

The effectiveness of the SBF was evaluated by simulation on ns-2 [21]. Table 5.1 shows parameters used in this simulation. All stations were deployed at random in a 500-square-meter field. Each station moved at random, with a maximum speed of 2.2 m/s. A station selected at random sent flooding packets periodically. For comparison, pure flooding, GeoFlood, and PRCSPR were investigated too.

Figure 5.4 shows the results of each protocol in terms of the number of packet transmissions while varying the number of stations in a communication area. The number of stations in a communication area was calculated as $N \times CA/SA$, where N is the number of stations, CA (=31400) is the communication area, and SA (=250000) is the simulation area. Similarly, the number of packet transmissions in a communication area was calculated as $P \times CA/SA$, where P is the total number of packet transmissions generated during a flooding. It can

Table 5.1: Simulation parameters.

Simulation field	500 × 500 [m]
Number of stations	12, 25, 50, 100, 200, 400
station mobility	0 - 2.2 [m/s]
Media Access Control	IEEE802.11b
Data rate (broadcast)	2 [Mbit/s]
Frequency	2.4 [GHz]
Preamble	Short preamble (72 [bit], 2 [Mbit/s])
Transmitted Power (P_t)	8 [mW]
Received Power (P_r)[*13]	$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^2$
Reception threshold[*14]	-71 [dBm]
Carrier sense threshold[*15]	-71 [dBm]
Communication radius	100 [m]
Length of queue in link layer	250 [packets]
Packet length	64 [bytes]
Flooding interval	1 [s]
Maximum delay time	350 [ms]
Simulation period	500 [s]

[*13] The Friis transmission equation was used to calculate reception power. λ is the wavelength, and d is the distance between sender and receiver.

[*14] The reception threshold was decided according to the definition that commmunication rage is 100 m.

[*15] The carrier sense threshold was decided besed on the specification of JRC's wireless LAN.

be seen from this figure that three-sector SBF-2 is the best flooding method in terms of the smallest number of packet transmissions. Regarding the influence of the number of sectors, the fewer the number of sectors becomes, the fewer the number of packet transmissions becomes, because at least one station in each sector rebroadcasts the packet. When the number of stations N is 12, many stations cannot receive and rebroadcast packets. Therefore, the average number of packet transmissions in a communication area is lower than one.

SBF-2 transmits fewer packets than SBF-1 because the number of conditions to cancel the rebroadcast for SBF-2 is fewer than that of SBF-1. Both SBF-1 and SBF-2 have fewer packet transmissions than pure flooding and GeoFlood, whereas PRCSPR has almost the same effectiveness as SBF-2. In general, an increased number of packet transmissions consumes more wireless bandwidth. Therefore, SBF-2 is the best flooding method among the five in terms of bandwidth consumption.

Figure 5.5 shows the results of each protocol in terms of packet reachability, while varying the number of stations in a communication area. It can be seen from this figure that the packet reachability of SBF-2 drops when the number of stations in a communication area is lower than 25, regardless of the number of sectors. Similarly, the packet reachability of SBF-1 is lower than pure flooding and GeoFlood when the number of stations in a communication area is lower than 6, regardless of the number of sectors.

SBF has an advantage that the number of packet transmissions generated in the flooding process is very small compared with other flooding methods. However, SBF also has a drawback in that packet reachability drops in low station-density situations. An ideal flooding method is to select SBF-2 at densities over 25 stations in the communication area, SBF-1 at densities from 6 to 25 stations, and pure flooding at densities smaller than 6 stations. This is the motivation for adaptive SBF (ASBF), described next.

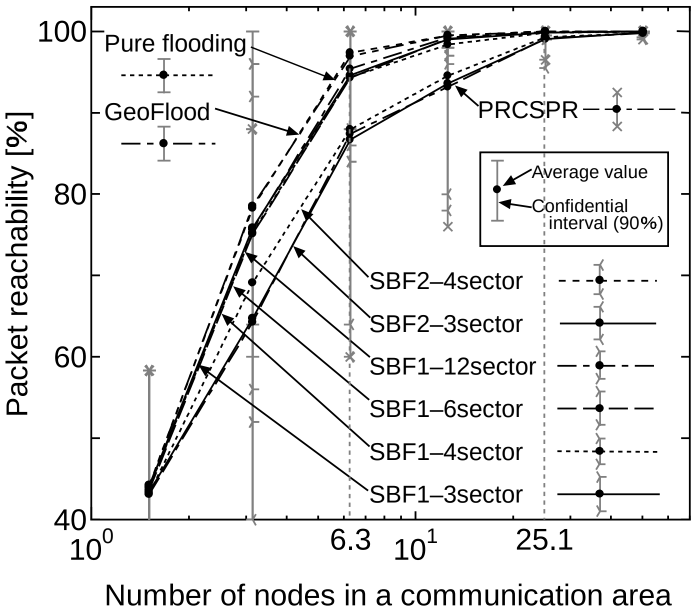


Figure 5.5: Relationship between the number of stations in a communication area and packet reachability.

5.4 Adaptive Sector-Based Flooding (ASBF)

The goal of ASBF is to achieve the same reachability as pure flooding with a small number of packet transmissions, regardless of station density. The idea of ASBF is to make each station select a flooding method from among SBF-1, SBF-2, and pure flooding, adaptively and autonomously, according to its local station density. The thresholds to switch flooding methods are 25 and 6, which are the number of stations in the communication area. The key issue in ASBF is how to obtain the number of neighbor stations without using periodical hello packets. By definition, the number of sectors used in SBF-1 and SBF-2 in ASBF is fixed to three because the number of sectors has a strong influence on the number of packet transmissions and little influence on packet reachability.

The number of neighbor stations can be obtained using the distance between the receiver station and the sector representative position specified in flooding packets. In SBF, only

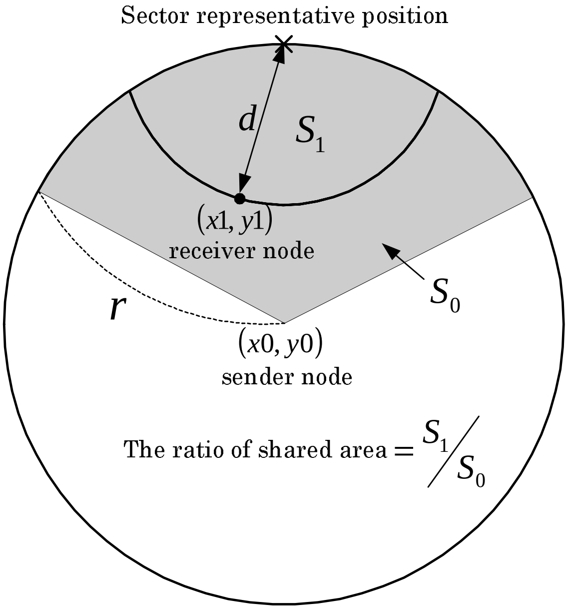


Figure 5.6: Distance from sector representative position and the ratio of shared area.

the station nearest the sector representative position in each sector can rebroadcast a packet. Therefore, station density can be assumed to be high when the distance in the packet is short. Conversely, the station density can be assumed to be low when the distance in the packet is long.

The following two steps are executed to determine the number of neighbor stations. First, the ratio of shared area between the sector area and the area formed by the distance from the sector representative position is obtained. Figure 5.6 illustrates a sector area (S_0), the area formed by the distance from the sector representative position (S_1), and the ratio of shared area (S_1/S_0). The method of calculating the ratio of shared area is described in Appendix A.1. Second, the relationship between the number of neighbor stations and the distance from the sector representative position to its nearest station is derived from the ratio of shared area. Figure 5.7 shows the relationship between the ratio of shared area (S_1/S_0) and the distance from the sector representative position.

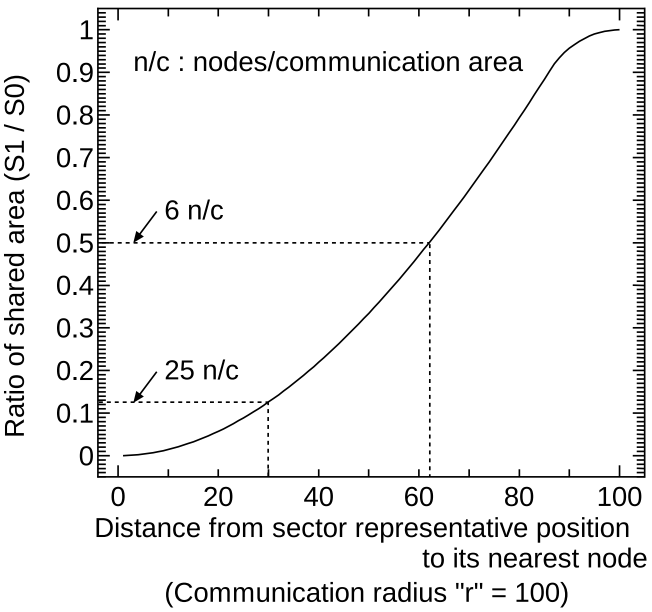


Figure 5.7: Relationship between the distance from sector representative position and ratio of shared area.

When more than 25 stations exist in a communication area, more than an average of 8 stations exist in each sector, which means that each station shares less than 12.5% of the sector area. Then, theoretically the mean distance from the sector representative position to its nearest station is less than 30 m. Similarly, when 6 stations exist in a communication area, the distance from the sector representative position is around 60 m. Therefore, each station should switch the flooding method using the distance specified in flooding packets as a threshold, namely 30 or 60 m. A comparison between this theory and the results of simulation is described in Appendix A.2.

Each station switches the flooding method as illustrated in Figure 5.8. The initial flooding method is pure flooding. When a station receives three packets that include the same originator ID, sequence No., and sector ID in the pure flooding mode, it decides that the station density of its neighbor increases and switches the flooding method from pure flooding to SBF-1. A station using SBF-1 switches its flooding method to SBF-2 when it receives un-

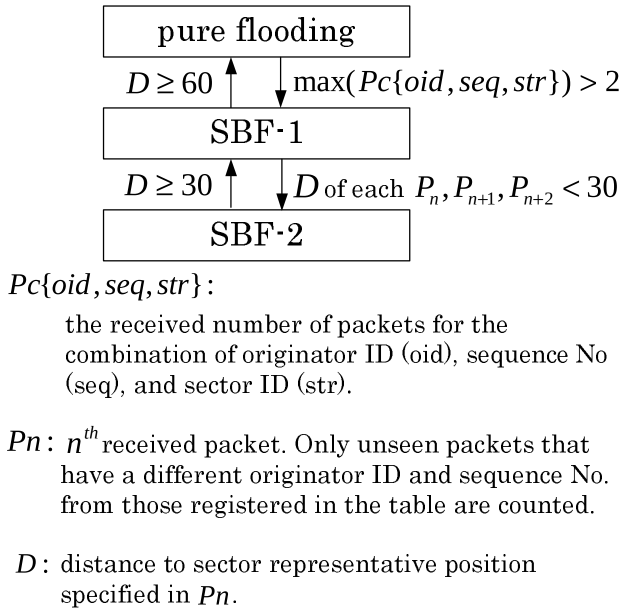


Figure 5.8: Criteria for switching flooding method.

seen packets three consecutive times, each of which indicates that the distance to the sector representative position is less than 30 m. A station using SBF-1 switches its flooding method to pure flooding when it receives an unseen packet whose distance is equal to or more than 60 m. Then, all $Pc\{oid, seq, sec\}$ registered in the table are cleared. A station using SBF-2 switches its flooding method to SBF-1 when it receives an unseen packet whose distance is equal to or more than 30 m.

5.5 Evaluation

The effectiveness of the ASBF was evaluated by simulation. The parameters used in the simulation were the same as those in Table 5.1. The packet reachability, the number of packet transmissions, and the propagation delay time were evaluated compared with three-sector SBF-1 and SBF-2, pure flooding, GeoFlood, and PRCSPR.

Figure 5.9 shows the results of each protocol in terms of packet reachability, while varying

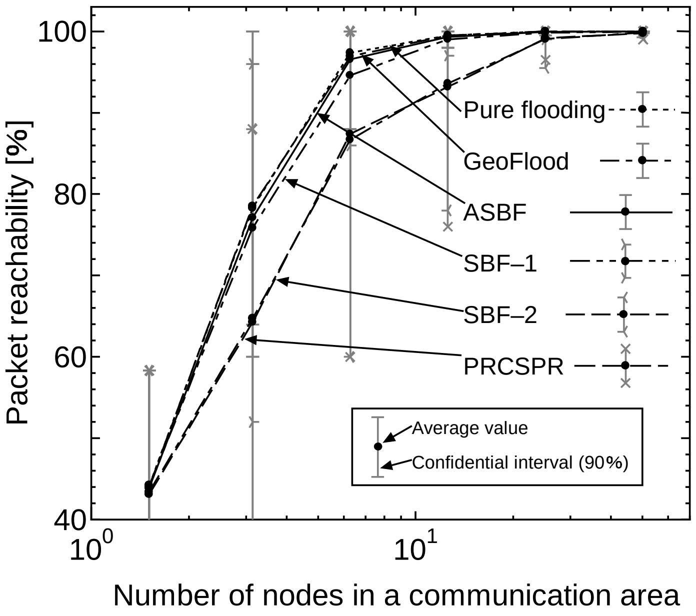


Figure 5.9: Packet reachability.

the number of stations. Though SBF-1 and SBF-2 have low packet reachability in low station-density situations, ASBF has almost the same packet reachability as pure flooding. Pure flooding is the simplest method; thus, no flooding method can surpass pure flooding in terms of packet reachability. GeoFlood also has the same packet reachability as pure flooding. However, PRCSPR has reduced packet reachability in low station-density situations, namely about 10% lower. The purpose of flooding is to deliver a packet to all stations in a network. Therefore, reduced packet reachability is a critical drawback of a flooding method.

Figure 5.10 shows the performance of the protocols in terms of the number of packet transmissions while varying the number of stations. The number of packet transmissions in ASBF is very low compared with pure flooding and GeoFlood. However, ASBF has more transmitted packets per communication area than SBF-1 and SBF-2, namely, one packet more than SBF-1 and two packets more than SBF-2, because of the following two reasons. One is that some stations cannot receive rebroadcast packets even if the packet has rebroadcasted in

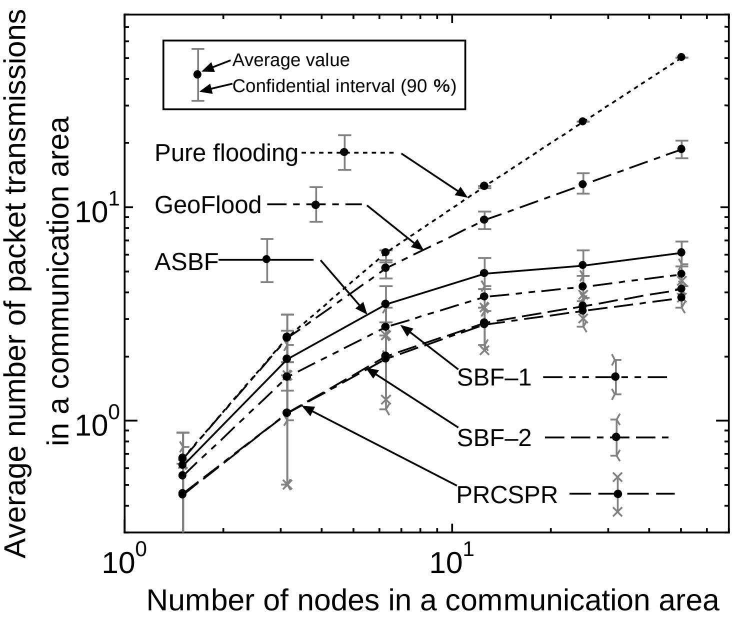


Figure 5.10: The number of packet transmissions.

the same sector. See station B at the left of Figure 5.11 as an example. In this case, station B in Figure 5.11 uses pure flooding at the next flooding process. The other reason is that some stations existing near the edge of the simulation area select pure flooding despite the high station density because these stations judge that the number of neighbor stations is few (see stations A and B at the right of Figure 5.11).

Figure 5.12 shows the performance of the protocols in terms of the propagation delay time while varying the number of stations. SBF-1, SBF-2, and ASBF have long propagation delay compared with pure flooding, GeoFlood, and PRCSPR. This is because stations located away from the sector representative position rebroadcast the packet after a long delay time has passed. In SBF or ASBF, some stations may not be able to receive a rebroadcasted packet in the same sector. Then, the stations rebroadcast the packet after their delay time has passed, the period of which is proportional to the distance from the sector representative position. Pure flooding can complete the flooding within a short propagation delay regardless

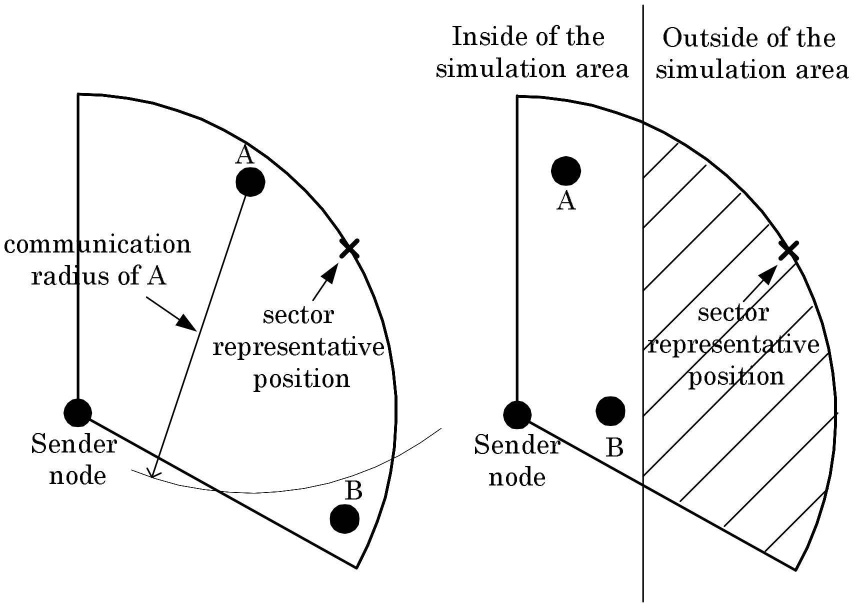


Figure 5.11: The cause of the increase of transmission on ASBF.

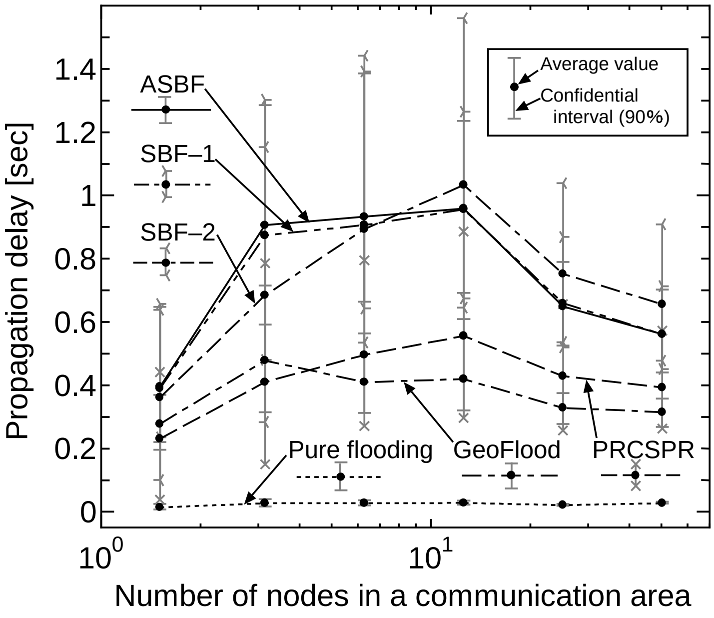


Figure 5.12: Packet propagation delay.

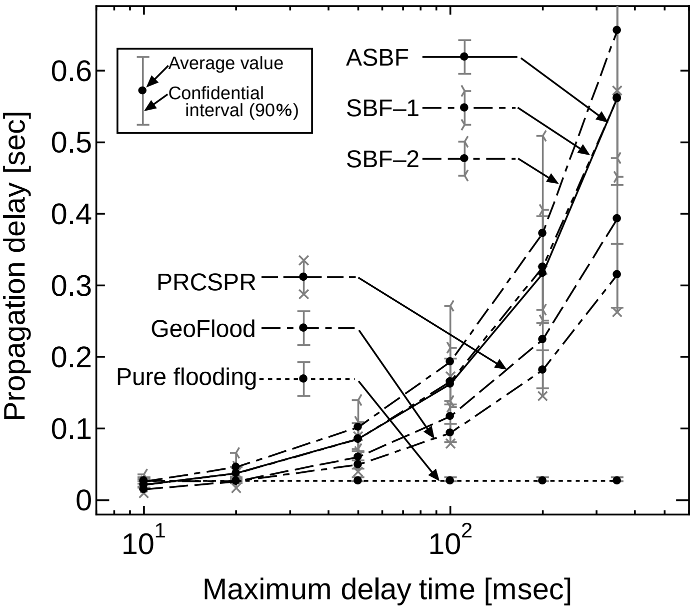


Figure 5.13: Relationship between propagation delay and the maximum delay time.

of station density. The propagation delay of three flooding methods other than pure flooding is less in high station-density situations because the possibility of station existence at the most effective flooding relay position in each method rises. On the other hand, the propagation delay is also less in extremely low station-density situations. In these situations, some stations have no neighbor stations in their communication area. Therefore, the hop count becomes small, thus reducing the propagation delay time.

Not only ASBF but also GeoFlood and PRCSPR need to define the maximum delay time. Shortening the maximum delay time leads to a short propagation delay. However, it increases the packet collision possibility. Therefore, the influence of the variation of the maximum delay time on the propagation delay and the number of packet transmissions were examined in 400 stations.

Figure 5.13 shows the performance of the protocols in terms of the propagation delay, while varying the maximum delay time. All protocols other than pure flooding complete

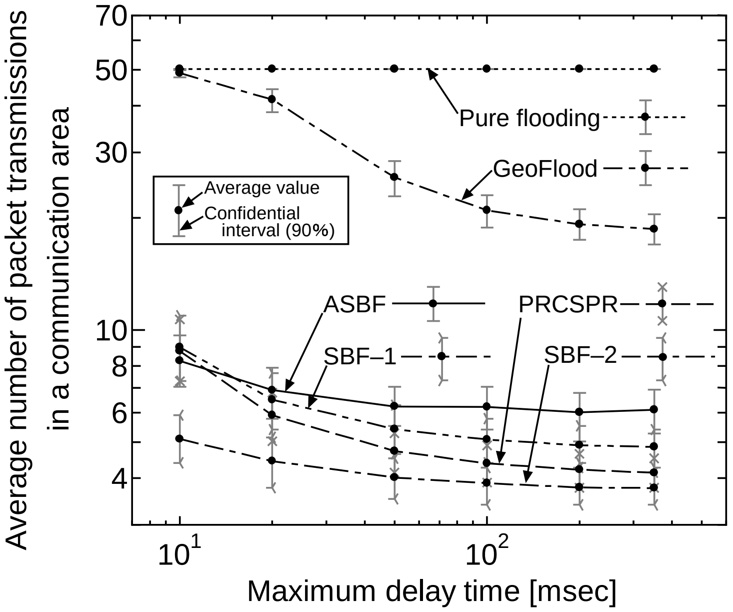


Figure 5.14: Relationship between the number of packet transmissions and the maximum delay time.

flooding with less propagation delay when the shorter maximum delay time is used. All flooding methods have almost the same propagation delay as pure flooding at the maximum delay time of 10 ms.

Figure 5.14 shows the performance of the protocols in terms of the number of packet transmissions, while varying the maximum delay time. It can be seen from this figure that ASBF can complete flooding as fast as pure flooding with almost as few packet transmissions as PRCSPR. GeoFlood transmits the same number of packets as that of pure flooding when the propagation delay time of GeoFlood is equal to that of pure flooding.

ASBF is the superior flooding method, based on the following three reasons. First, ASBF has the same reachability as pure flooding and GeoFlood. The reachability is the most important criterion because the purpose of flooding is to disseminate a packet to all stations in the network. The reachability of PRCSPR is about 10% lower than that of ASBF in low station-density situations. Second, ASBF can complete flooding with few packet transmissions compared with GeoFlood that has the same reachability as pure flooding. Finally, ASBF can complete flooding as fast as pure flooding by adjusting the maximum delay time. Then, the number of packet transmissions is almost equal to PRCSPR.

5.6 Conclusions

SBF, an efficient flooding protocol using position information for mobile ad-hoc networks, was proposed. SBF can execute flooding with a small number of packet transmissions. SBF is divided into SBF-1 and SBF-2 according to the criteria used for rebroadcast cancellation. ASBF was proposed, too. ASBF makes each station select a flooding method from among SBF-1, SBF-2, and pure flooding depending on its local station density. The station density is determined using the distance between the sector representative position and its nearest station.

Simulation results have shown that ASBF can realize the same reachability as pure flooding and GeoFlood with a small number of packet transmissions. SBF-1 and SBF-2 have lower reachability than ASBF in low station-density situations. However, the number of packet transmissions of SBF-1 and SBF-2 are smaller than that of ASBF by about one or two per communication area. The performance of SBF-2 is almost the same as PRCSPR in terms of both packet reachability and the number of packet transmissions. The proposed SBF-1, SBF-2, and ASBF methods have different performances in terms of packet reachability, the number of packet transmissions, and simplicity of implementation. Therefore, manufacturers or engineers should decide which method is the best for the target system according to the required specifications, such as the application or limitations of the system.

Chapter 6

Conclusions

6.1 Conclusions and future works of this study

Routing protocols for vehicle ad-hoc networks that are considered as a key technology to realize ubiquitous networks were discussed in this thesis. Specifically, following three routing protocols were treated: routing protocols for short distance inter-vehicle communications; routing protocols for inter-vehicle communications via established networks; and flooding methods that are needed to realize long distance inter-vehicle communications.

As a routing protocol for short distance inter-vehicle communications, relative speed-based routing (RSR) was proposed. The main feature of RSR is to construct a stable route without periodical beacons. The topology of inter-vehicle networks changes dynamically. Therefore, unless the stability of routes is considered, control packets for route reconstruction are transmitted frequently and precious wireless bandwidth is wasted much. RSR is divided into RSR-1 and RSR-2 according to the metric used. RSR-1 uses the relative speed between vehicles as the metric; RSR-2 uses the cumulative change of the distance to neighboring vehicles as well as the relative speed as the metric. Simulation evaluation showed that both RSR-1 and RSR-2 have better packet reachability and overhead reduction compared with existing routing protocols.

As a routing protocol for inter-vehicle communications via established networks, another new metric, the consecutive wireless hop counts, was proposed. It was shown by simulation that the consecutive wireless hop counts is more important than simple hop count from the viewpoint of throughput in ad-hoc network combined with established networks. The idea was formulated; the way to build the formula into reactive routing protocols was explained, too. The performance of our proposed routing protocol, which was realized as an extension of ad hoc on-demand distance vector (AODV), was evaluated by simulation. The results showed that the proposed routing protocol is effective especially under a high data rate situation compared with AODV.

In vehicle ad-hoc networks using mobile IP protocol, periodical flooding of agent advertisement packets is required. In order to reduce the overhead, two new flooding methods were suggested: sector-based flooding (SBF) and adaptive sector-based flooding (ASBF). Both SBF and ASBF uses position information to realize efficient flooding. Simulation results showed that SBF reduces the number of packet transmissions generated in flooding and ASBF has high packet reachability and few packet transmissions.

The routing protocols suggested in this thesis help manufacturers or engineers to develop target network system. Some prototypes can be developed in no time by combining these proposed routing protocols and existing wireless equipment, such as wireless LAN. I hope this study serves as a foundation of future study and development.

There are still many subjects to be solved in order for vehicle ad-hoc network to be used widely in daily life. Above all, gaining the sense of stability and assurance for users and telecommunication carrier is the essential subject. From this point of view, the quality of service (QoS) and security are one of the most controversial subjects.

In near future, most of all communication will be connected with so-called next generation network (NGN), in which all information are transferred through IP networks. In NGN, not only e-mail or World Wide Web (WWW) but also quality-strict applications, such as voice over IP (VoIP) and video on demand (VoD) will be served on IP networks. Consequently, some sort of new methods must be implemented in ad-hoc networks to satisfy QoS elements, such as bandwidth, delay, jitter, and so on. QoS issue includes scheduling method, queuing method, traffic control method, fault tolerant method. Each issue is related to media access layer, routing layer, and session layer. These issues will be future work of ad-hoc networks. Security for ad-hoc network is another important subject. If security is unreliable, ad-hoc network will not be used for commercial purpose. From now on, I would like to tackle above issues.

6.2 International trends of inter-vehicle communications

The active research on inter-vehicle communication system is pursued in European Countries, United States, and Japan. In European Countries, there exist several public projects and forums. The most famous one is FleetNet project, which was launched in 2000 and finished in 2003, in Germany. In this project, many routing protocols that use wireless LAN (IEEE 802.11 a/b/g) as its MAC protocol were reported. Currently, network on wheels (NOW) project inherits FleetNet projects; further research is pursued.

In United States, manufacturers of electronic toll collection (ETC) system are aggressively developing their business markets. ETC uses designated short range communication (DSRC) of 5.9 GHz. The standardization activity of DSRC is processed in IEEE 802.11 p TG, which is known as wireless access in the vehicular environment (WAVE).

In Japan, Association of Radio Industries and Businesses (ARIB) and intelligent transport system (ITS) forum are processing the standardization activity. ARIB recommends using DSRC of 5.8 GHz for inter-vehicle communications. The purpose of using DSRC is effective frequency use in the places other than toll stations. Ministry of Land, Infrastructure and

Transport (MLIT) supports this idea by placing DSRC equipments on the roadsides. On the other hands, lots of vehicle or communication related manufacturers recommend using wireless LAN. The reason for not using DSRC is the communication speed. The data rate of DSRC is 4 Mbit/s, whereas wireless LAN can achieve several hundreds of Mbit/s. In the future, vehicles will equip various wireless communication devices, such as DSRC, wireless LAN, and WiMAX; vehicles will use each device depends on the situation.

Appendix A

Supplementary information on adaptive sector-based flooding

A.1 Method of calculating the ratio of shared area

As shown in Figure A.1, the shared area $S1$, which indicates the overlapping area of the sector OAB and the circle P, can be calculated by integrating the length of CD, a part of the circumference of the circle P with radius x. The calculation can be divided into the following three methods according to the value of x.

1. $(0 < x < R\sin\frac{\phi}{2})$

   When the radius x is shorter than $PT\,(= R\sin\frac{\phi}{2})$ in Figure A.1, S_1 can be calculated by simply integrating the length of CD, a part of the circumference of the circle P with radius x, as follows (see Figure A.2(a)):

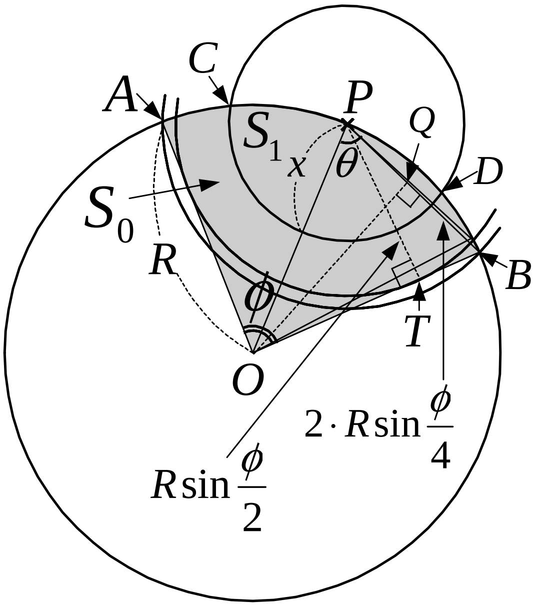
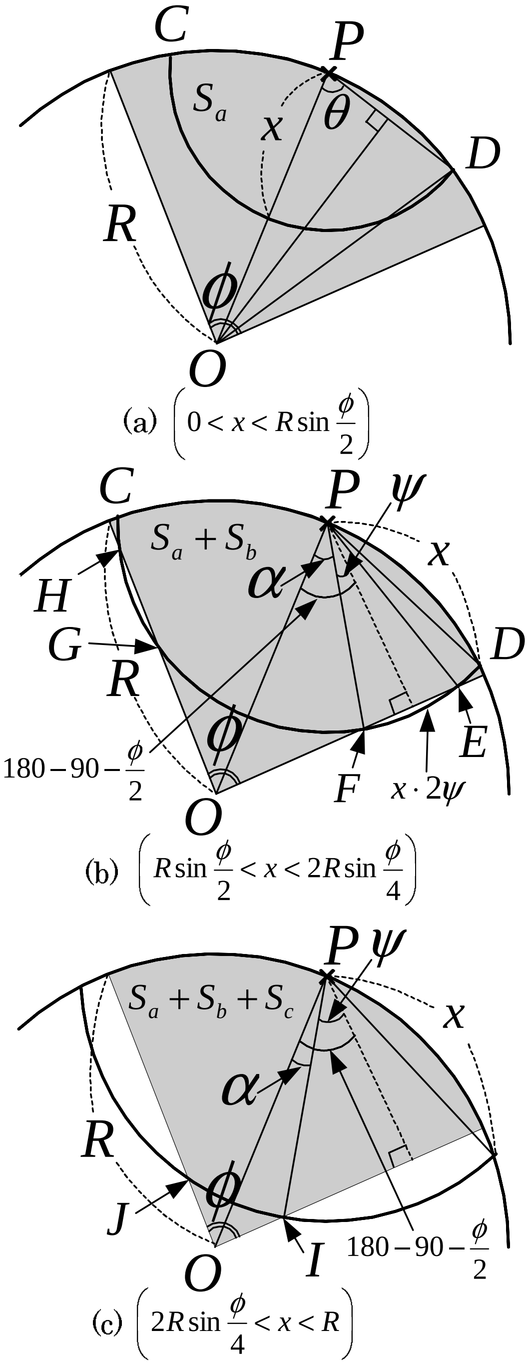


Figure A.1: Shared area.

$$\begin{aligned} S_1 &= S_a \\ &= \int x \cdot 2\theta \, dx \qquad (R\cos\theta = \frac{x}{2}) \\ &= \int 2x \arccos\left(\frac{x}{2R}\right) dx \end{aligned} \tag{A.1}$$

2. $(R\sin\frac{\phi}{2} < x < 2R\sin\frac{\phi}{4})$

When the radius x is longer than PT and shorter than $PB\,(= 2R\sin\frac{\phi}{4})$, the circumference of the circle P overlapping with the sector area is $(CD - EF - GH)$, as shown in Figure A.2(b). Therefore, the overlapping area of this range of x, or S_b, is calculated



(a) $\left(0 < x < R\sin\frac{\phi}{2}\right)$

(b) $\left(R\sin\frac{\phi}{2} < x < 2R\sin\frac{\phi}{4}\right)$

(c) $\left(2R\sin\frac{\phi}{4} < x < R\right)$

Figure A.2: The circumference of the circle P overlapped with the sector area.

as follows:

$$\begin{aligned} Sb &= \int (2x \arccos\left(\frac{x}{2R}\right) - x \cdot 2\psi \cdot 2)\,dx \\ &\qquad (x\cos\psi = R\sin\frac{\phi}{2}) \\ &= \int (2x \arccos\left(\frac{x}{2R}\right) - 4x \arccos\left(\frac{R\sin\frac{\phi}{2}}{x}\right))\,dx \end{aligned} \tag{A.2}$$

where $\phi = \frac{2\pi}{3}$ in the three-sector formation. S_1 is obtained by S_a at the x value of $R\sin\frac{\phi}{2}$ plus S_b.

$$S_1 = S_a + S_b \tag{A.3}$$

3. $(2R\sin\frac{\phi}{4} < x < R)$

   When the radius x is longer than PB, the circumference of the circle P overlapping with the sector area is IJ, as shown in Figure A.2(c). Therefore, the overlapping area of this range of x, or S_c, is calculated as follows:

$$\begin{aligned} Sc &= \int x \cdot 2\alpha\,dx \qquad \left(\alpha = \left(90 - \frac{\phi}{2}\right) - \psi\right) \\ &= \int 2x((90 - \frac{\phi}{2}) - \psi)\,dx \\ &= \int 2x(90 - \frac{\phi}{2} - \arccos\left(\frac{R\sin\frac{\phi}{2}}{x}\right))\,dx \end{aligned} \tag{A.4}$$

   where $\phi = \frac{2\pi}{3}$ in the three-sector formation. S_1 is obtained by S_a at the x value of $R\sin\frac{\phi}{2}$ plus S_b at the x value of $2R\sin\frac{\phi}{4}$ plus S_c.

$$S_1 = S_a + S_b + S_c \tag{A.5}$$

As an example, the shared area S_1 at the radius x of 30 m and the communication radius R of 100 m in the three-sector formation is calculated by:

$$S1 = \int_0^{30} 2x \arccos\left(\frac{x}{200}\right)\,dx = 1323.512714 \tag{A.6}$$

Table A.1: Calculation results for S_1, S_0, and S_1/S_0.

Distance x[m]	$S_1\,(S_a + S_b)$	S_0	$S_1/S_0 \times 100[\%]$
29	1239.6	10472.0	11.8
30	1323.5	10472.0	12.6
31	1410.0	10472.0	13.5
59	4777.2	10472.0	45.6
60	4928.2	10472.0	47.1
61	5081.1	10472.0	48.5
62	5235.8	10472.0	50.0
63	5392.5	10472.0	51.5

Table A.1 shows the calculation results for S_1 at the radii x around 30 m and 60 m. It also shows the sector area $S_0\,(= 100^2\pi/3)$ and shared area ratio S_1/S_0. The calculation results show that S_1/S_0 becomes 12.5% around 30 m and 50% around 60 m, which is identical to Figure 5.7.

A.2 Difference between theory and measurement

This section describes difference between theory and measurement in terms of the distance from the sector representative position to its nearest station. It is assumed that one station exists within 30 m from the sector representative position when 25 stations exist in the communication area in Figures. 5.6 and 5.7. In the same way, it is assumed that one station exists within 60 m from the sector representative position when 6 stations exist in the communication area. In this section, we describe the difference between the above theoretical assumption and simulation measurement.

Table A.2 shows the simulation parameters. The simulation area, that is, an area of 100 m from the fixed station A, is divided into three sectors. In this simulation area, 25

Table A.2: Simulation parameters.

Simulation field	100 [m] from a fixed station A
Number of sectors	3
Number of stations	25, 6
station mobility	0 - 2.2 [m/s]
Flooding packet originator	Fixed station A
Transmission interval	1 [s]
Simulation period	500 [s]

Table A.3: The distance from the sector representative position to its nearest station.

	25 stations	6 stations
Minimum distance	0.6 [m]	1.3 [m]
Maximum distance	75.9 [m]	96.3 [m]
Average distance	33.1 [m]	62.1 [m]
Theory	$\leq$30 [m]	$\leq$60 [m]

or 6 stations are deployed at random. Only the nearest station to each sector representative position rebroadcasts the flooding packet originated by the fixed station A. Then, the distance between the sector representative position and its nearest station was measured and compared with the theoretical value.

Table A.3 shows the simulation results. It can be seen from the table that the average distance in the measurement is almost the same as the theoretical length. This means that while the theoretical value assumes that one station exists within the area, the station existence probability within the theoretical distance is about 50% in this measurement. The reason is that stations are not always deployed uniformly in the simulation area. In the simulation period, some bias occurs to the distribution of the station's position even if the initial position and the destination of stations are decided at random.

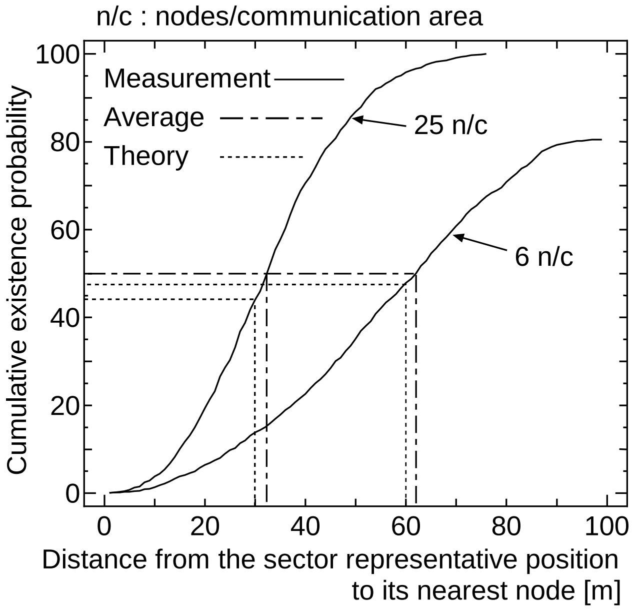


Figure A.3: Cumulative existence probability.

Figure A.3 shows the cumulative existence probability of the nearest station to the sector representative position with a certain distance. The cumulative existence probability for 6 stations cannot reach 100% at 100 m because no stations exist in a sector at the ratio of 20%. The existence probability of a station within the theoretical distance rises if the number of stations is more than 25 or 6.

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Acronyms

ABR	associativity-based routing
AODV	ad-hoc on-demand distance vector
AP	access point
ARIB	Association of Radio Industries and Businesses
ASBF	adaptive sector-based flooding
BC	broadcast
CTS	clear to send
DCF	distributed coordinated function
DSR	dynamic source routing
DSRC	designated short range communication
ETC	electronic toll collection
FA	foreign agent
FORP	flow-oriented routing protocol
GPS	global positioning system
HA	home agent
ID	identification data
IEICE	The Institute of Electronics, Information and Communication Engineers
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
IETF	internet engineering task force
IP	internet protocol
IPSJ	Information Processing Society of Japan
ITS	intelligent transport system
JRC	Japan Radio Company, Ltd.

LAN	local area network
LSI	large-scale integration
MAC	media access control
MANET	mobile ad-hoc networks
MIC	Ministry of Internal Affairs and Communications
MLIT	Ministry of Land, Infrastructure and Transport
MS	mobile station
NGN	next generation network
NS	network simulator
PDA	personal digital assistant
PHS	personal handy phone system
PRCSPR	packet relay control scheme based on priority regions
PRNET	packet radio network
QoS	quality of service
RAD	random assessment delay
RERR	route error packet
RREP	route reply packet
RREQ	route request packet
RTS	request to send
RSR	relative speed-based routing
SBF	sector-based flooding
SSA	signal stability-based adaptive routing
TCP	transmission control protocol
TG	task group
UDP	user datagram protocol
VoD	video on demand
VoIP	voice over IP
WAN	wide area network
WAVE	wireless access in the vehicular environment
WDD	waiting-time driven diffusion
WG	working group
WiMAX	worldwide interoperability for microwave access

WWW	world wide web

Publications

List of publications related to this study

Journals

1. M. Yoshida, K. Arai, S. Asami, and T. Miki, "Relative Speed-Based Routing (RSR) for Vehicle Ad-Hoc Networks," IEICE Trans. Commun. *(Japanese Edition)*, vol.J88-B, No.8, pp.1434-1443, Aug. 2005. (This paper was translated into English in Electronics and Communications in Japan, Part 1, vol.89, No.11, pp.1-11, 2006)

   (Chapter 3 of the thesis)

2. M. Yoshida and T. Miki, "A Routing Protocol for Mobile Terminals in Ad Hoc Network with Established Network," IEICE Trans. Commun. *(Japanese Edition)*, vol.J89-B, No.6, pp.887-896, June 2006. (This paper will be translated into English in Electronics and Communications in Japan, Part 1, vol.90, No.10, pp.47-56, 2007)

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3. M. Yoshida, M. Terada, and T. Miki, "Adaptive Sector-Based Flooding for Mobile Ad-Hoc Networks," IEICE Trans. Commun., vol.E90-B, No.4, pp.788-798, April 2007.

   (Chapter 5 and Appendix of the thesis)

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