Keio University Bachelor's Thesis Academic Year 2010

eMANEMO: An Efficient Multi-path Selection Method for MANEMO Applying to Vehicle-to-Vehicle Communication Network

Keio University Faculty of Environment and Information Studies

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Abstract of Bachelor's Thesis Academic Year 2010

eMANEMO: An Efficient Multi-path Selection Method for MANEMO Applying to Vehicle-to-Vehicle Communication Network

This thesis proposes eMANEMO, an efficient multi-path selection method for MANEMO system applied to Vehicle-to-Vehicle (V2V) communication network. To answer the demand for a new technology to optimize the performance of V2V communications, the idea of Mobile Gateway with MANEMO technique, which is the convergence of Network Mobility Basic Support Protocol (NEMO) and Mobile Ad-hoc Network (MANET) routing protocols, has been introduced.

Although the parameters of path quality(e.g. available bandwidth, delay, packet loss rate) have been used to evaluate the network performance, a method to calculate a metric for MANEMO system from these parameters has not been taken into consideration. For that reason, eMANEMO proposes a system which utilizes path cost in order to enable Mobile Gateway to choose the best route between MANET and NEMO.

The efficiency of the system was evaluated in the indoor experiments with traffic control tools. Experiment results have shown that eMANEMO system can achieve 7.7% throughput improvement, reduce 85.89% delay and 31.69% packet loss rate. In addition, proper behavior of eMANEMO in the field test was also verified. Path quality based switching execution in eMANEMO is proved to help with preventing the inefficient path switching, achieving the highest performance for V2V communication network.

Keywords:

1 Multi-path Selection   2 Path Quality Metrics   3 MANEMO

4 Mobile Gateway   5 Vehicle to Vehicle Communication

Keio University Faculty of Environment and Information Studies

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卒業論文要旨　　　2010 年度 (平成 22 年度)

eMANEMO:車車間通信ネットワークへ適用した MANEMO の効率的なマルチパス選択手法

本研究では，車車間通信ネットワークにおける効率的なマルチパス選択技術である eMANEMO を提案する．近年，自動車通信環境における無線リンク品質に基づき，NEMO (Network Mobility)，MANET (Mobile Ad-hoc Networks) の二つのネットワークを使い分ける MANEMO 技術が注目を集めている．

MANEMO にはいくつかの既存研究が存在するが，既存システムではバンド幅，遅延，エラーレート等の経路特性パラメータを総合的に判断し，経路コストを計算する手法はまだ考案されていない．本研究では，上記パラメータを考慮した経路コストを動的に算出し，車載ルータにおいて車車間通信時の最適経路を計算する eMANEMO を提案する．

本研究では，模倣環境における机上実験と実自動車環境における動作検証試験を行った．机上実験では，eMANEMO は既存システムと比較して，実効帯域を 7.7%向上させ，遅延を 85.89%，パケットロスを 31.69%削減した．また，実環境における動作検証試験においても，効率的なパス選択を行い，車車間通信ネットワークの性能向上を行えることを示した．

キーワード：

1 マルチパス選択　2 パス特性メトリック　3 MANEMO

4 車載モバイルゲットウェイ　5 車車間通信

慶應義塾大学環境情報学部

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Chapter 1

Introduction

1.1 Background

In the recent years, Intelligent Transport Systems (ITS) application(i.e. traffic incident management, traffic jam avoidance, road weather management) has been developed and has become an important part of the human life. According to World Health Organizations(WHO), an estimated 1.2 million people are killed in road crashes each year and as many as 50 million are injured worldwide. Projections indicate that these figures will increase by about 65% over the next 10 years unless there is new commitment for prevention [16]. In Japan, traffic jams take the cost of approximately 12 billion Japanese Yen (14 million USD) every year and cause serious problems, i.e. human fatigue, environmental damages, global air pollution, and an increase of the number of traffic accidents.[17] The ITS is proposed to bring safety improvements for personal transportation.

Nowadays, Vehicular Communication System is developed as a part of the ITS. It is an emerging type of network in which vehicles and roadside units are communicating nodes; exchanging information with each other to solve traffic problem. Beside the advantage in terms of safety improvements, vehicular communication network will bring several other benefits. For example, it provides the better route among vehicles, transferring not only the traffic information, but also many other real time data(i.e. chat, phone, file exchange).

The vehicular communication has two types: Vehicle-to-Vehicle(V2V) communication and Vehicle-to-Infrastructure(V2I) communication. In V2I communication, NEMO protocol (standardized by IETF [7]) is introduced ; meanwhile, V2V communication is well-known with MANET routing protocol, which supports the non-infrastructure communication for mobile nodes.

Although both NEMO and MANET are available to support real-time mobile network, each of them has its benefits and drawbacks. NEMO has the advantages of the reachability and the global Internet connection provision but no standardized routing optimization mechanism. MANETs frequently change their network topologies, but it could provide the shorter routes to the vehicular destinations without depending on network infrastructures. From these facts, an idea of combining two mentioned methods is raised in order to make vehicular communication more flexible and faster. This architecture is called MANEMO.[9]

MANET and NEMO are designed as two independent technologies[1]. There are many types of MANEMO system to support mobile connection in various network environments. One of them is the in-vehicle Mobile Gateway with two routing functions: MANET and NEMO. In this system, the routing policy is used to switch between MANET and NEMO paths for V2V communication. Beside the weakness in the requirement of infrastructure, using the in-vehicle Mobile Gateway in V2V communication network has a plenty of advantages, such as: the benefit of address assignment, providing efficient communication, fault tolerance, always-on internet connectivity, and the system scalability [2].

The mobility of vehicles often causes changes in the network topologies of MANEMO systems. The route which serves high quality at that moment may become disconnected after several seconds. Thus, a flexible route selection method is required to achieve the highest performance path, to forward packets to destination.

In order to prevent the decrease of throughput when MANET link is going down, the existing MANEMO system [2] uses available bandwidth to make switching decision. However, other important metrics of the path quality estimation, such as: network delay and error rate, was not considered comprehensibly.

1.2 Research Goal

This thesis introduces eMANEMO, a multi-path selection method for in-vehicle Mobile Gateway MANEMO system by creating a path cost calculating formula from the path quality metrics(available bandwidth, delay, and error rate) between the mobile routers.

eMANEMO method is proposed to achieve the highest network performance: serve a high throughput path to transfer data, reduce the error rate and latency of system, and ensure that the vehicle is always able to communicate with others and to the global internet.

1.3 Thesis Outline

The rest of this thesis is structured as follows: Chapter 2 describes the technologies used in vehicular communication network, the MANEMO network system topologies, and the advantages of using Mobile Gateway as well as the problems of current routing methods. Chapter 3 presents the proposed eMANEMO method. In Chapter 4, the design and the operation of eMANEMO based system is described. The detailed implementation of the system is presented in Chapter 5. Chapter 6 describes the testing environment, the system evaluation method and results. Finally, the conclusion and future works are presented in Chapter 7.

Chapter 2

Related Protocols and Related Works

This chapter presents the configuration and operation of MANET and NEMO protocols. Afterwards, the topologies of MANEMO system will be analyzed to show why we should use the two-function Mobile Gateway for MANEMO system. Lastly, the problems of current two-function Mobile Gateway routing policies are also addressed in the end of this chapter.

2.1 Routing technologies in vehicular communication network

2.1.1 Mobile Ad-hoc Network Routing Protocols

This section presents two representative routing protocols of MANET technology that are adopted by the IETF: Optimized Link State Routing (OLSR) [10] [11], and Ad-hoc On-Demand Distance Vector (AODV).[**?**]

- **Ad-hoc On-demand Distance Vector(AODV)**

  Ad-hoc On-demand Distance Vector (AODV) is a reactive routing protocol. In AODV, a node only establishes route to the destination just before transmitting data. AODV uses three message types to exchange the routing information: Route Requests (RREQs), Route Replies (RREPs), and Route Error(RERRs).

In order to prevent the unnecessary network-wide dissemination of RREQs, AODV proposes an expanding ring search technique for all of the nodes running this protocol. This technique limits the Time-to-Live value for RREQs before sending, and set a timeout for receiving the RREPs from others. (Figure 2.1)

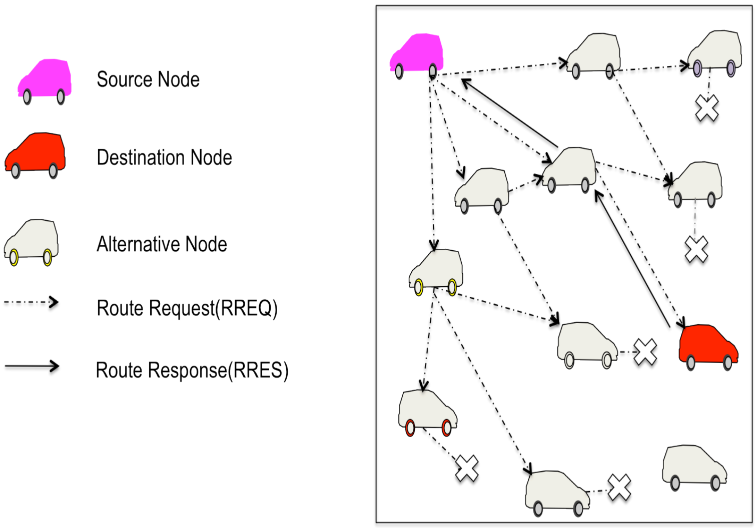


Figure 2.1: AODV On-demand Route Discovery(TTL = 2)

By this technique, AODV can provide a low control overhead for the network system. However, because the route to destination is only established on-demand, it causes a delay when transmitting packets if the routing data is not maintained in the routing buffer.

- **Optimized Link State Routing(OLSR)**

  Optimized Link State Routing(OLSR) is one of the MANET proactive routing protocols, which uses principals from Link State routing. Mobile nodes which run OLSR routing protocol are able to get an over-view of the whole network. Archive this, Mobile Nodes select Multi-Point Relay (MPRs) from its one-hop neighbors by the willingness values, and use MPRs to transmit all of its routing messages. This is to control messages flooding and reduce the overhead of the network protocol.

Since OLSR maintains the information for routing tables of systems, it supports data transmission without waiting to discover the destinations. Therefore, it is suitable to reduce latency in real-time V2V communication . (Figure 2.2)

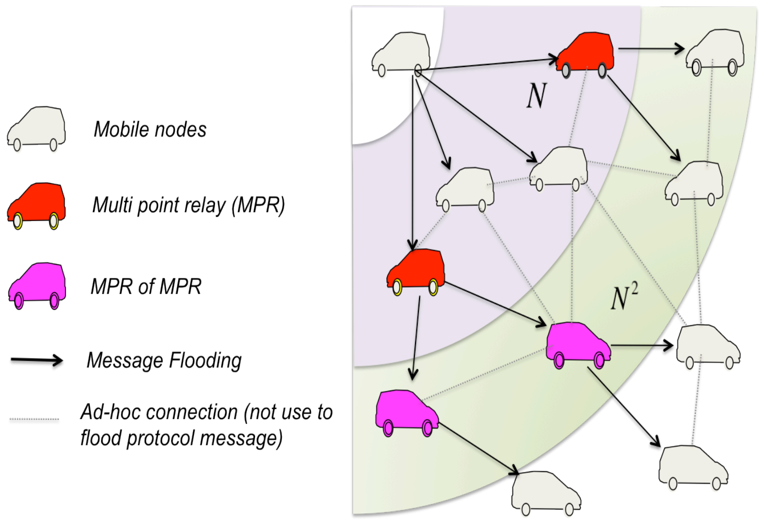


Figure 2.2: OLSR protocol

In RFC 3626, OLSR (version 1) forwards Multiple Interface Declaration(MID) messages to advertise multi-interface information and (HNA) messages to advertise the attached mobile network [10]. However, in order to simplify the operation of Multiple Interface support mechanism and improve the effectiveness of IPv6 support function, OLSR has been upgraded currently to version 2 (defined in Internet-draft). OLSRv2 retains the basic algorithms and mechanisms, while using a more flexible and efficient signaling framework, and include some simplification of the messages that has exchanged. HNA and MID messages are no longer existing in the OLSR version 2. Instead, only Topology Control(TC) message type is used to advertise Link state, for both MANET and hybrid.[11]

2.1.2 Network Mobility Basic Support Protocol

NEMO basic support protocol is defined in RFC 3963, to enable support for Network Mobility [7]. Fig.1 shows the operation of NEMO.(Figure 2.3)

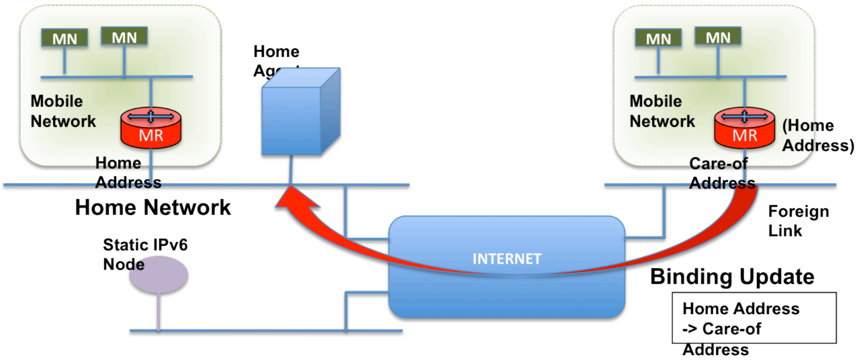


Figure 2.3: NEMO protocol

In a NEMO network, each mobile router, which provide local network for mobile nodes(i.e. cell phone, personal computer, vehicles embedded computers), has its own specific home agent and home link prefix. When the mobile router leaves its home network and moves to another network (foreign link), it is assigned a new care-of-address on the foreign network, and creates a bidirectional tunnel to communicate with the home agent. However, when the mobile router is communicating through foreign link, bi-direction process with the packet header encapsulation and decapsulation will increase the network overhead, the risk of packet fragmentation and the transmission latency. Furthermore, forwarding data packets through a home agent may also lead to either the home agent or the home link becoming a bottleneck for the aggregated traffic from/to all the mobile network nodes. Congestion at home would lead to additional packet delay, or even packet loss [7]. From these points, NEMO network requires an optimized routing mechanism to reduce the network system overhead and the risks mentioned above.

2.2 MANEMO technique based system

MANEMO has been defined as a combination of MANET and NEMO to produce a solution, which benefit from the positive characteristics of both technologies [5]. There are many topologies of MANEMO system which are designed to support mobile connection in various network environments. (Figure 5.1)

[4] analyzed the network system topologies which investigate MANET and NEMO function in separated nodes as well as in one mobile gateway node. However, the implementation of MANEMO with separated node seem not to be suitable because of the requirement of system infrastructure. In addition, as mentioned before, the two-function Mobile Gateway (mobile router) is proved to have a plenty of advantages to routing packets for Mobile Nodes inside vehicle. It is introduced in many current studies [2][1][3][6]

In this system, all of the packets will be sent to the Mobile Gateway. Next, the routing table will determine the interface(MANET, NEMO), and will continue forwarding the packets to the next hop. This is aimed to reduce the latency of network system, which could be caused by going through multiple routers inside vehicle of the packet before it is forwarded to the next hop.

The experiment results of [2], [4], [3] and [6] have shown that in the Mobile Gateway, switching routes from NEMO to MANET immediately is a great way to reduce latency if a directed link exists between vehicles, as a result achieving further the network performance. However, in mobile network environments, the mobility of vehicles often causes the change in the network topology of MANEMO systems. Though MANET could provide shorter routes to vehicular destinations without depending on network infrastructures, recent studies have shown that the qualities of MANET paths are not always higher than the NEMO paths[2][1]. As a result, the priority of the MANET paths in traditional MANEMO systems may cause inefficient path switching decisions. In order to make the routing decision when multi-paths is available, the Mobile Gateway is able to establish a policy based

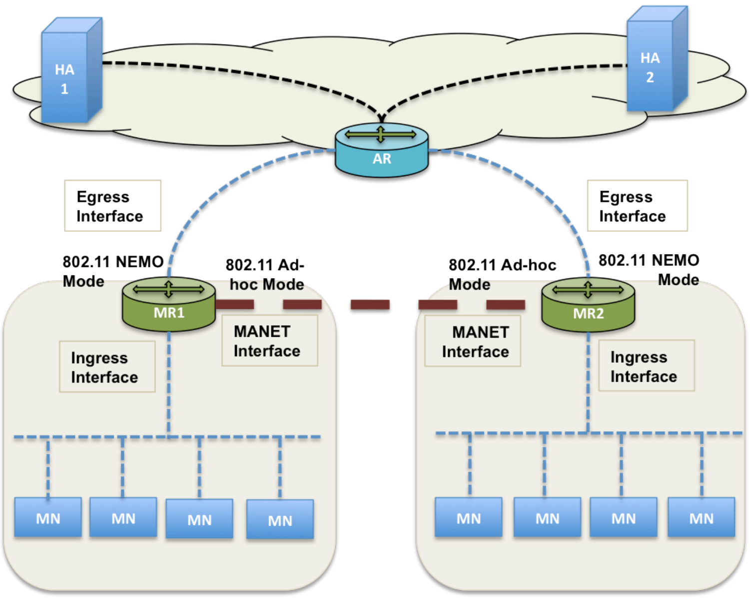


Figure 2.4: Two-function Mobile Gateway based MANEMO system

routing to create and update its Routing Table. For that reason, several path selection methods have been introduced in order to achieve the highest performance for V2V communications.

[2] has proposed available bandwidth, delay and hop count to make the switching decision. However, they only proved the system with the available bandwidth, and has not defined the general calculation formula to show the role of these parameters. In addition, although reducing the packet loss rate is necessary in real-time vehicular network, it is not considered in the existing system to make the switching decision.

In [1], the system uses Route Policy Database (RPDB) to build multiple independent routing tables for forwarding data. Based on the marks (type of flow) which are defined in the header of the packet, it can be routed according to MANET, NEMO, or the main routing table. In other words, it is based only on the flow characteristics and does not considering the fluctuating wireless path qualities.

The routing policy, which establishes the route discovery from the mobile router to its home agent by AODV, one reactive protocol of MANET, is defined in [6]. When a mobile router has moved to a foreign link and is going to send binding update messages to the home agent, system will initialize a route discovery by broadcasting a RREQ message through intermediate routers. If RREQ reaches the target home agent, a RREP message would be send back to the mobile router. Of course, before the RREP message reaches the source node, it has to be transferred through the intermediate routes again. Each intermediate router gets a RREP from the predecessor ones, and stores the information of the route to the target home agent in the routing table. Since every router has the information of each other, AODV is proposed to provide the routes from mobile router to its home agent bypass the home agents of immediate routers. However, although the mobile router could bypass the immediate home agents, it still communicates with others through their home agents. It means that the problem of the bottleneck in home agent is not considered to be completely solved in this system.

2.3 Summary

This chapter introduced two routing protocols of MANET technology, AODV and OLSR, and analyzed the advantages and disadvantages of each protocol. The operation of NEMO and the requirement for optimizing routing mechanism to reduce the network system overhead was also explained. MANEMO technique and the existing MANEMO systems have been reviewed in depth to understand the basic idea as well as their problems: 1) The incomplete consideration of the path quality metrics to make switching decisions. 2) The requirement of a flexible path selection method based on the path cost for MANEMO to achieve the highest performance for V2V communications. Considering these, the next chapter will describe the proposed method to solve these problems.

Chapter 3

eMANEMO method

This thesis proposes eMANEMO - a flexible multi-path selection method for in-vehicle MANEMO mobile gateway using the path quality metrics. In detail, eMANEMO creates a path cost calculation formula for multi-path from quality parameters and use the result values to decide the best route to forward packets to destination. This is proposed to achieving the highest throughput, reducing the latency and error rate of data transmission in the real-time vehicular communication.

This chapter proposes the path quality metrics, which are used as parameters to calculate the multi-path cost. Next, the switching decision mechanism with path cost calculation formula will be presented.

3.1 Path Quality Metrics

In order to estimate the multi-path performance, the three following quality metrics are chosen: bandwidth, delay, and error rate.

- **Available Bandwidth**

  First, unlike in connections between stable routers, the link in mobile network always changes. It seems impossible to use the interface bandwidth to estimate the quality of the link. In order to choose usable routes, the router should dynamically calculate the available bandwidth to make decision.

- **Delay**

  Second, delay is an important performance metric of network system. In addition to determine the path cost, delay is used as a parameter in our calculation formula. It specifies how long it takes for a bit of data to travel across the network environment from the mobile router to another.

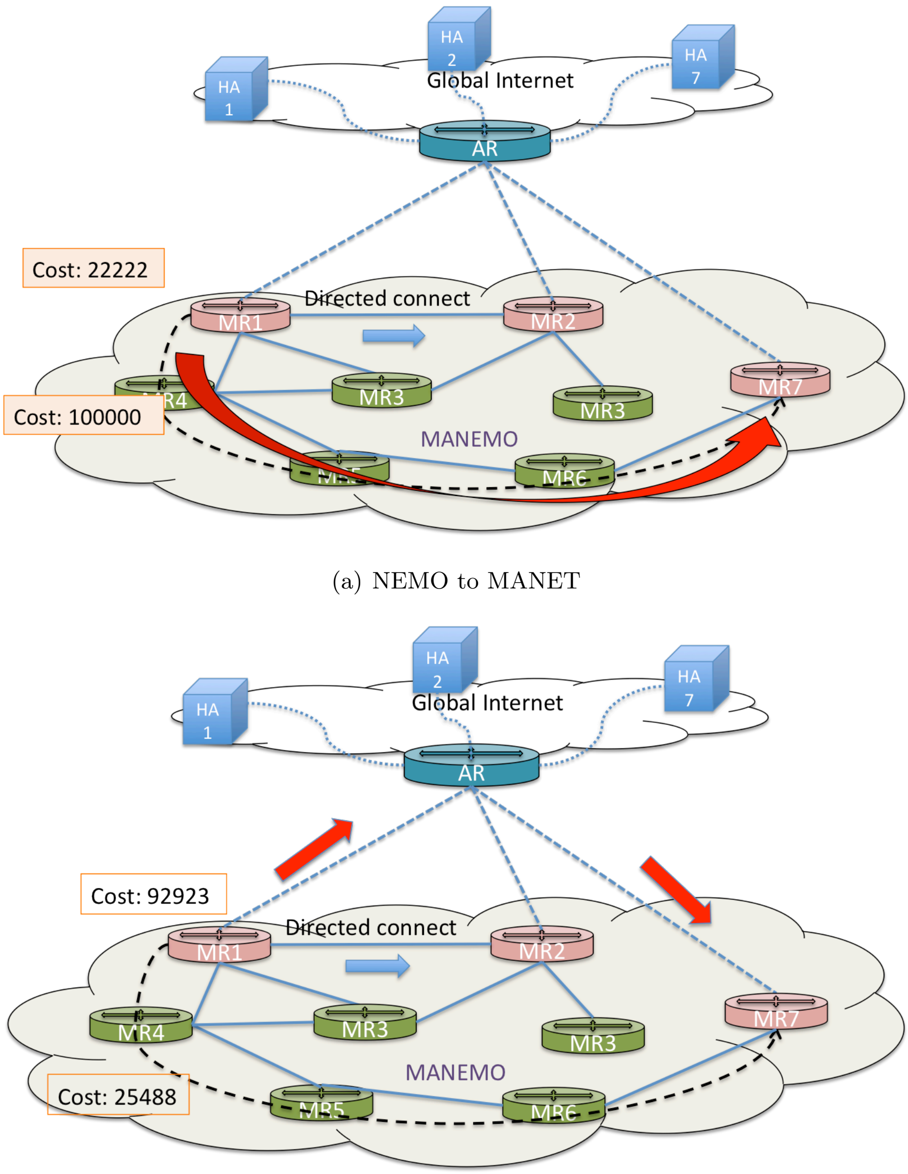
- **Error Rate**

  Third, in high-speed mobile network, packet retransmission causes waste of system resources. Since reducing the error rate is extremely important in the real time V2V communications, it should be considered in the relationship with the available bandwidth and delay to estimate the cost for the path switching decision.

3.2 Switching Decision

As mentioned in the previous chapter, current studies have shown that switching from NEMO path to directed MANET link is a useful way to reduce the latency of network system, provide a high throughput route to vehicles bypass the home agents. However, if the distance of the vehicles are not close enough to make the stability of MANET link lower than the NEMO link, the unnecessary switching will cause overhead for the system. Therefore, when MANET links become up, there is a need to measure and calculate the cost of paths to decide which is the best one for transferring data.

Figure 3.1 shows the switching strategies of eMANEMO system. The distance of vehicle-to-vehicle and vehicle-to-HA causes the costs of paths to always change (both NEMO and MANET links) when vehicles are moving. If the cost of in-use main path becomes higher than the alternative one, the system would switch the two paths to optimize network performance.



(a) NEMO to MANET

(b) MANET to NEMO

Figure 3.1: eMANEMO system and multi-path switching strategies

To achieve the highest performance of 2V2 communications, the path cost is calculated in inverse proportion to the available bandwidth, and direct proportion to the delay and error rate of path. The best path will be the one which provides the lowest cost for the data transfer.

Here is the formula that we use to calculate path cost:

$$C = f(B, D, E) = \frac{w_b}{B} + w_d \times D + w_e \times E \tag{3.1}$$

In this formula, B, D, E presents the available bandwidth, delay, and error rate of path respectively; w_b, w_d, w_e are weight vectors of parameters.

$$f(n) = \begin{cases} \text{MANET, if } C_{manet} < C_{nemo} \\ \text{NEMO, if } C_{manet} >= C_{nemo} \end{cases} \tag{3.2}$$

If the cost of the OLSR path becomes smaller than NEMO's, the OLSR is chosen. Conversely, if it becomes greater than the NEMO cost, NEMO one will be chosen. IN eMANEMO system, the internet default gateway should be the NEMO route if available. If the mobile router disconnected from the infrastructure, it would update the routing table with MANET default gateway and send a message to register care-of-address to the Default Gateway's HA [13]. However, because global Internet connection support of MANET nodes is not the main problem in this project, the NEMO link should always be up on this system.

3.3 Summary

The eMANEMO method, which utilizes path quality metrics for V2V system, was proposed in this chapter. Three parameters, available bandwidth, delay, and error rate, were raised to estimate the multi path cost. The switching operation was also described with detailed cases. The system design which reflects our idea will be presented in the following chapter.

Chapter 4

System Design

This chapter presents a design of eMANEMO method based system. The first section gives an overview of the whole system and how it works in the interaction of module parts. In the next section, the requirement sets for our system will be detailed.

4.1 Overview of eMANEMO method Based System

Figure 4.1 shows the overview of eMANEMO system and its performance.

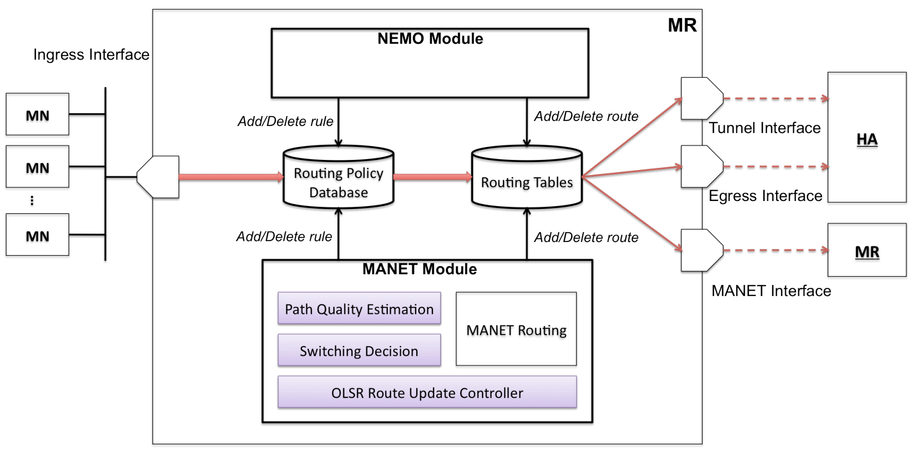


Figure 4.1: Overview of eMANEMO system

There are two main modules in eMANEMO system, NEMO and MANET, which work in parallel to periodically update the system routing database. NEMO module provides routes by connecting to the home agent of the mobile router. In parallel, MANET module provides the shortcut routes to the other mobile routers by ad-hoc connection. Besides the normal MANET routing performance, it also plays the role of calculating the cost of multi-paths to decide route to the destination attached mobile networks.

The mobile router has three output interfaces: tunnel interface, egress interface and ad-hoc interface. Packets from mobile nodes which came through the ingress interface will be processed by the mobile router, and then the router will forward it to the correct interface to the destination.

4.2 System Requirements

4.2.1 NEMO module

In this system, NEMO module is designed to support the mobile router to connect to the internet by going through its home agent. It supports not only the normal internet service(such as: web, mail, file uploading, etc), but also the communication with other mobile routers through home agents.

Technically, when the mobile router is in the home network, it uses the egress interface to advertise the routing information of the attached mobile network. However, when the vehicle left the home link, the mobile router sends the information of its CoA to the home agent to create a tunnel and stops sending routing advertisement through the egress interface. All of the routing advertisements and packets will be sent and received by this tunnel. The NEMO module is assumed to support the mobile router to be connectable everywhere.

4.2.2 MANET module

MANET module is one of the important parts of eMANEMO system. The function of MANET module is to provide shortcut routes for a mobile router to the others by ad-hoc connection and establish eMANEMO routing method by the MANEMO routing decision.(Figure 4.2)

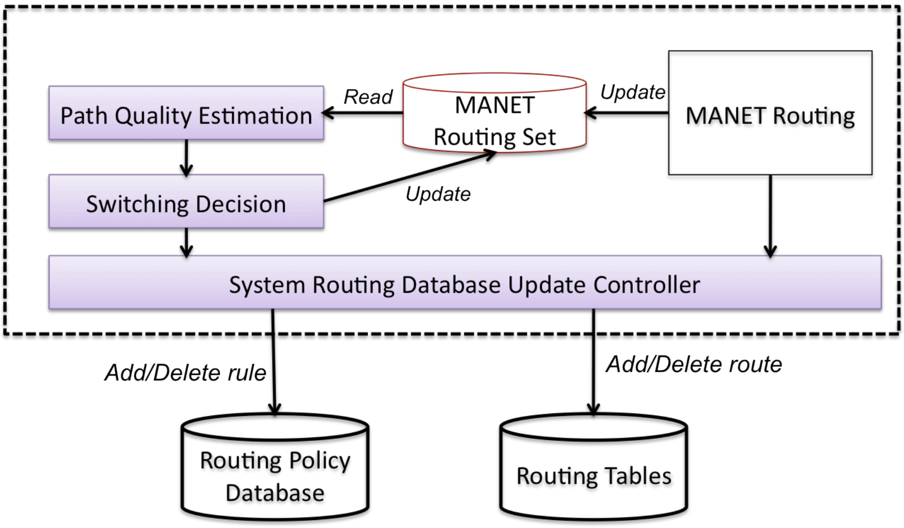


Figure 4.2: MANET module operation

There are many existing ways to build routing database for a router. However, in our system, because of the mobility of routers, to serve a fast routing performance, the routes to all destinations within the mobile ad-hoc network should be known and maintained before use in transmission.

In order to implement eMANEMO method, apart from the ad-hoc routing information, the MANEMO module also need to exchange the NEMO interface address. Thus, the routers can reach all of the destination attached networks by two ways, MANET and NEMO. The next job of MANET module is to solve the multi-paths routing problem.

MANET needs a path quality estimation mechanism to estimate the quality of multi-path. As mentioned before, three following path quality parameters are proposed to calculate the cost of paths to make the switching decision. They are Available Bandwidth, Error Rate and Network Delay. This mechanism should periodically check the data of routing set, which is updated by MANET routing mechanism, in return establish the estimation.

Switching decision mechanism is required to calculate the path cost from the estimated results. If a router has any decision to make network topology changes, this information should be reflected to the routing data set of MANET routing before updating to the System Routing Database by the routing update controller mechanism.

4.2.3 System Routing Database Management

In the IP network, the mobile router needs a flexible route management mechanism to forwarding the packets to the destinations. Since the priority of the OLSR link is consider to be higher than the NEMO link, the system needs to clarify this when managing and updates the routing database.

4.3 Summary

This chapter has explained the design of eMANEMO system. The requirements of modules, when implementing the system with MANEMO routing method, were stated in detail. The next chapter will present the detailed implementation of eMANEMO system according to this design.

Chapter 5

System Implementation

This chapter describes the implementation of the prototype eMANEMO system. In order to satisfy the system requirements , which were stated in the previous chapter, the modules are divided to smaller units and conduct the prototype implementation of the system.

5.1 Overview

In this system, a set of mobile routers and home agents is used as a element of the vehicular communication network. Each mobile router acts as a gateway for all mobile nodes inside the vehicle.

A detail architecture of the set is showed in Figure 5.1.

The home agent uses two interfaces: one to serve the home network, and the other to provide the connection to the internet, managing the mobile routers.

The mobile router has three interfaces:

- Egress Interface runs in NEMO mode, stores the home address, and connects to the home agent.
- MANET Interface runs in Ad-hoc mode, plays the role of connecting with other mobile routers by ad-hoc connection.
- Ingress Interface connects to mobile nodes inside the vehicle.

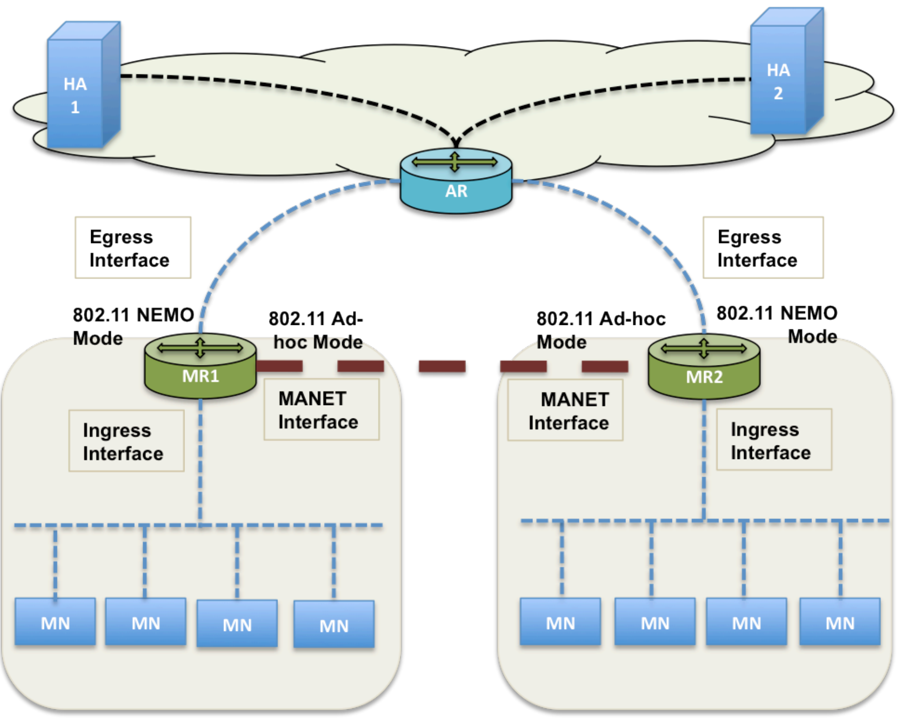


Figure 5.1: Implementation Architecture

Figure 5.2 shows the eMANEMO model system which is implemented in the mobile router.

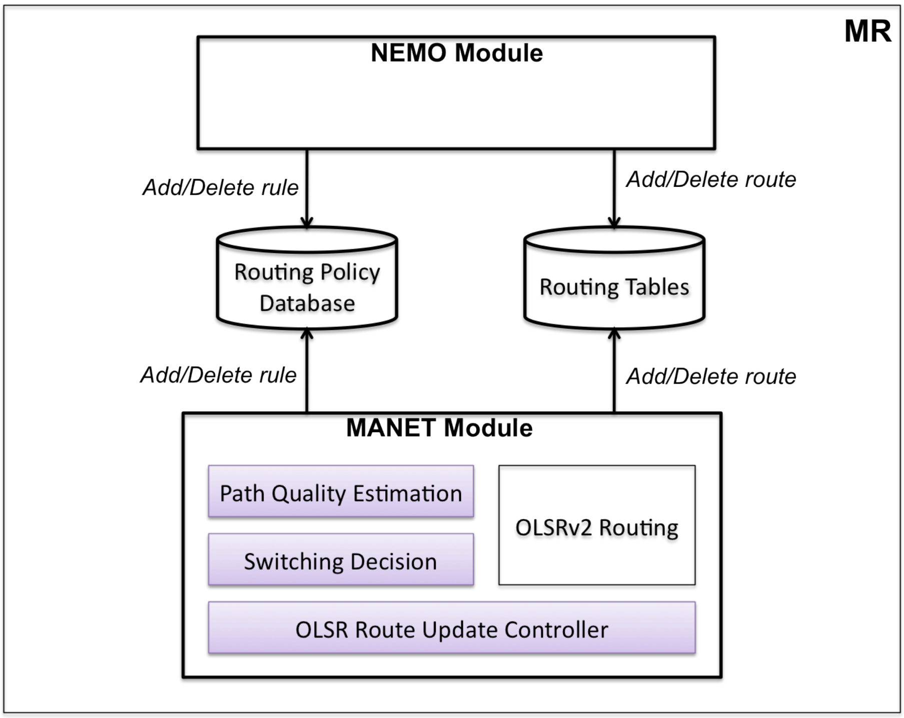


Figure 5.2: Overview of eMANEMO system

As mentioned in the previous chapter, there are two main modules in our system: the NEMO module and the MANET module. Especially, in the MANET module, each required function is divided into smaller sub-modules. In detail, it includes four sub-modules, MANET routing, Path Quality Estimation, Switching Decision, and Route Update Controller. Routing database is updated and maintained in the routing database of the system.

This chapter is presented as follows: First, we explain the setup and the configuration of NEMO module. Second, the implementation of MANET module with sub-modules is detailed next. Last, the system routing database management will come up in the third section.

The system is implemented in Linux Ubuntu 10.04 environment by C/C++ Language.

5.2 NEMO Module

In our system, we use UMIP, an USAGI-patched Mobile IPv6 for Linux to setup the NEMO function in both of the mobile router and the home agent. The installation and configuration is detailed in UMIP documentation page. (See [18])

Since the default installed Linux kernel does not support mobility services, we need to re-compile and install the kernel with some required packages.(See [18] [19].)

The home link is assumed to be not used in the prototype system. However, the home agent still has to advertise Router Advertisements with the home link prefix. Thus, we create a dummy interface and advertise the Home Link prefix on it.

5.3 MANET Module

Since the requirement of the MANET module is to maintain the routing information before it is used, we choose the proactive OLSRv2 routing protocol, which is introduced by the IETF[11], to perform the MANET function in our system.

5.3.1 MANET Routing

The modified nOLSRv2 daemon of Niigata group is used. This is an implemenation on Linux platform of OLSR protocol version 2, which is proposed as an update for the current OLSR.[11] The implementation of this daemon is available to support both of the IPv4 and the IPv6 network configuration.

In order to support link quality estimation and path cost calculation, which we will present later, the mobile router should have not only OLSR routes, but also the information of NEMO routes to the destination network. In other words, the mobile router should notify to its OLSR neighbors the NEMO interface information.

Fortunately, OLSRv2 protocol is designed with TC message to advertise the attached network information. By using TC messages, we can also advertise the NEMO interface information as an attached network of the mobile router. The receivers will process this message, and recognize this information by parsing the attached network address (Figure 5.3).

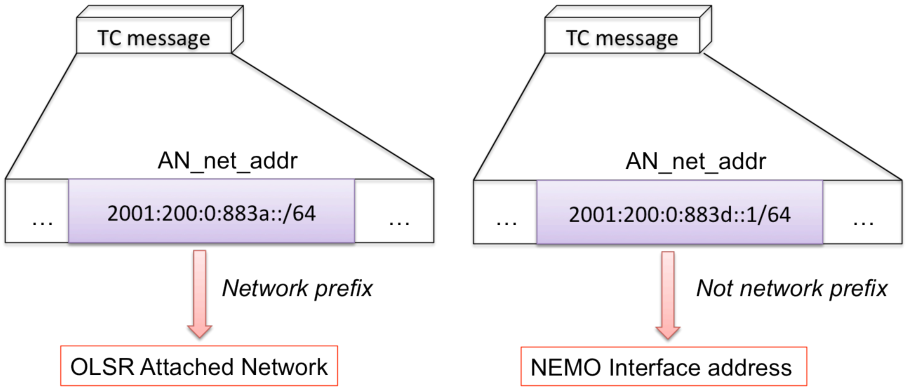


Figure 5.3: Extra NEMO information in TC message

We modified the nOLSRv2 daemon, which was developed by Niigata group, to perform the OLSR routing module. Then, we added the network type as an element of the attached network tuple. Specifically, the NEMO type is declared for NEMO network address, and the OLSR type is for the normal one. When OLSRv2 reads the attached network information to build the routing set, it will know which is the NEMO route and does not add the NEMO route to the routing table.

- Old Attached Network Tuple:

  (AN_net_addr, AN_prefix_length, AN_orig, AN_dist, AN_seq_number, AN_time)

- New Attached Network Tuple:

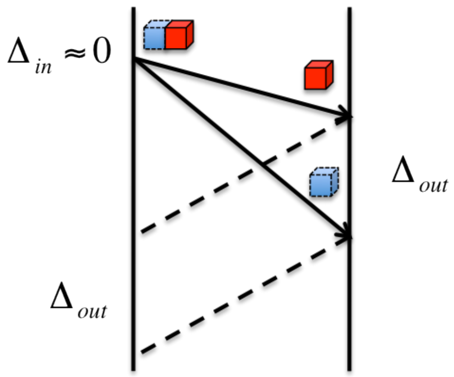
  (AN_net_addr, AN_prefix_length, AN_orig, AN_dist, **AN_type**, *AN_seq_number, AN_time)*

AN_type will have the value of *NEMO* if the received information is the address of NEMO interface. The value of AN_type will be *OLSR* if the received information is belong to the mobile network, which is attached to mobile router by the ingress interface.

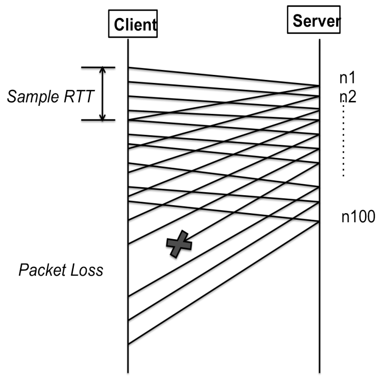
By this way, mobile routers could grasp both of the OLSR path (by the original address) and the NEMO path (by NEMO attached network address) to the destination network from the view of the MANET module.

5.3.2 Link Quality Estimation

Since available bandwidth, delay and error rate are dynamic in properties, characterizing these parameters is a very difficult problem, especially in the dynamic environment like vehicular networks. In this thesis, we propose the method of using packet pair technique[14] to estimate the parameters.(Figure 5.4)



(a) Bandwidth



(b) Delay and Error Rate

Figure 5.4: Packet Pair Technique

The idea behind the packet pair technique is to send groups of back-to-back packets to a receiver which echoes them back to the sender[**?**]. By sending a number of probe packet pairs, we can measure all of three parameters at once time.

- **Available Bandwidth (B)**

The bandwidth is measured by the following formula:

$$B = \frac{L}{\Delta_{out}} \tag{5.1}$$

L presents the size of packet number i. Δ_{out} is the time out spacing of the packet pair.

- **Delay (D)**

By taking the sample round trip time of each packets, we estimate the delay parameter D as the estimated round trip times of all sending packets:

$$Sample\_RTT = Send\_Time - Receive\_Time \tag{5.2}$$

$$Diff = Sample\_RTT - estimated\_RTT \tag{5.3}$$

$$estimated\_RTT_{(t)} = estimated\_RTT_{(t-1)} + \alpha \times Diff \tag{5.4}$$

The weight of difference between the sample_RTT and the estimated_RTT is assumed to $\alpha = 0.25$. Since the unit of estimated_RTT, Diff, and Sample_RTT is microsecond(us), the estimated_RTT is increased 1000 times to convert to millisecond(ms) before being used as the delay parameter in the path cost calculation. 3.1

$$D = estimated\_RTT \times 1000 \tag{5.5}$$

- **Error Rate (E)**

Error rate E is the rate of lost packets during each time estimation.

$$E = \frac{N_{lost\_pkt}}{N_{total}} \times 100 \tag{5.6}$$

In this system, the sending packet number, packet length are changeable and can be redefined by the administrator. By default:

- Packet Number = 50 packets (25 packet pairs)
- Packet Length = 800 bytes

Unit of parameters are: Available bandwidth: bps, Delay: ms, and Error Rate: %.

We implemented the prototype system with the above three parameters. In addition, we also implemented options to choose parameters to calculate the path costs, which we will present in the next section.

The interval default for Link Quality Estimation is setup to 7s.

5.3.3 Switching Decision

In eMANEMO system, from the parameters estimation results, the mobile router will make the switching decision by calculating and comparing the cost of available paths.

We implemented the path cost calculation as designed in the previous chapter. (Formula 3.1)

In the formula to calculate the path cost, we set the weight to be rechangable. The decision to make which parameter more important than others is up to the network administator. By default, the weight is defined as follows:
$w_1 = 54 \times 10^6, w_2 = 1, w_3 = 100$. This means that in the path cost, Available Bandwidth is the dividing value of $54 \times 10^6 bps$(54Mbps), Delay is the value of 1 microsecond, and the Error rate is 100 times the 100% value.

5.3.4 OLSRv2 Route Update Controller Module

The route update controller module plays a role in managing OLSRv2 routing tuples and updates the routing information to the system database.

We devide OLSR routing tuples into 6 types and define their status as: OLSR_INT, NEMO_NET_ADDR, NEIGBOR_ATTACHED_NET, OTHER, DELETED_ROUTE, RE_ADDED.

- OLSR_INT is the route which has the destination on the OLSR interface.
- NEMO_NET_ADDR is the route which has the destination on the NEMO interface.
- NEIGBOR_ATTACHED_NET is the route which has the destination on the attached mobile network of 1-hop neighbor.
- OTHER is the route which has the destination on the attached mobile network of more-than-2-hops neighbor.
- DELETED_ROUTE is the route which was deleted after calculating the path costs.
- RE_ADDED is the route which was deleted before and re-added after calculating the path costs.

5.4 System Routing Database Management

Since the routing information is maintained in multiple routing tables in Linux system, Routing Policy Database(RPDB) is used to lead the system to look into correct routing tables when forwarding packets.

Both the NEMO and MANET does routing and updates their information to the Routing Database.

NEMO writes in two routing tables: its own table(Table 252) and the main table of the system, to determine the next hop information. Table 252 maintains the tunnel route to the home agent. The route to foreign link and default gateway to the internet is written to the main routing table. To clarify this, it defines rules in the routing policy database from priority 1000 to 1005. (Figure 5.5)

Since this system consider the priority of MANET routes to be higher than NEMO, we insert the MANET routes to the main routing table and define 999 as the priority for MANET. (Figure 5.5)

```
mr2@ubuntu:~$ ip -6 rule
0:      from all lookup local
999:    from all to 2001:200:0:883a::/64 lookup main
999:    from all to 2001:200:1:4444::1111 lookup main
1000:   from all to 2001:200:1:4444::/64 lookup main
1000:   from all to 2001:200:0:883b::/64 lookup main
1001:   from 2001:200:0:883e::1 lookup 252
1002:   from fe80::/64 lookup main
1002:   from 2001:200:0:8805::/64 lookup main
1003:   from 2001:200:0:883e::1 blackhole
1005:   from 2001:200:1:4444::/64 lookup 252
1005:   from 2001:200:0:883b::/64 lookup 252
32766:  from all lookup main
```

Figure 5.5: Routing Policy Database(RPDB)

In the main routing table, the longest matching principle is used. The prefix length of MANET route is always longer than NEMO default gateway(::/0), so certainly MANET route will be used to forward packets if it is available.

5.5 Summary

This chapter has detailed the implementation of eMANEMO system. NEMO module was implemented by using UMIP - an USAGI-patched Mobile IPv6 for Linux. MANET module was implemented by modifying nOLSRv2 daemon of Niigata group and adding three sub-modules: Link Quality Estimation, Switching Decision, and Route Update Controller. Link Quality Estimation sub-module is proposed to implement with the packet pair technique. The multi-path cost is calculated to make routing decision in Switching Decision sub-module. With the routing information received from modified nOLSRv2 and Switching Decision, Route Update Controller module updates the Routing Database of the system. The organization of Route

Database Management of the system was also described in the previous section with two parts: Routing Tables and Routing Policy Database. Next chapter will set up the test environment and evaluate the experiment results for the prototype eMANEMO system.

Chapter 6

Evaluation

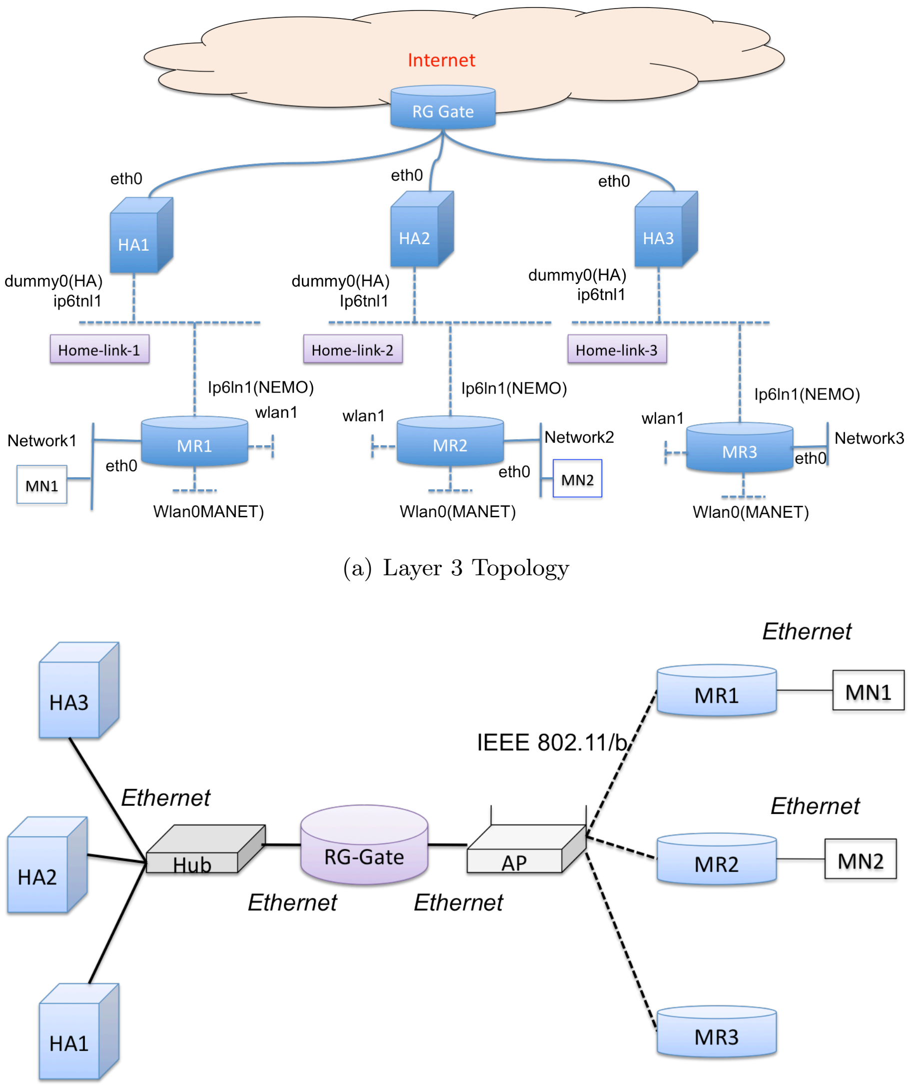
This chapter presents the method and setup of the experiments, which was used to evaluate the performance of eMANEMO method.

6.1 Experimental Setup

This test use three home agents(HAs), three mobile routers(MRs) and two mobile network nodes(MNNs). Figure 6.1 describes the network configuration of our system. The physical environment is presented in Table 6.1. All of nodes(HAs, MRs, and MNNs) are installed the network mobility supported Linux Ubuntu 10.04 Kernel 2.6.27.

The HAs connected to the Internet via a router of the Internet Research Laboratory by their Ethernet interfaces. In this evaluation, the home link was not in use, so dummy interfaces were configured and set up in the HAs for the home link advertisements.

The MRs provide the global internet connection to the ingress mobile network through their Ethernet interfaces. They registered the care of address with the wireless network, provided by the access point of the laboratory. Then, they sent the binding update messages to the home agents to create network tunnels to the home agents by the NEMO interface(*wlan1*). All the packets from the MNNs and binding update messages would be first forwarded to their home agents, then be sent to the destinations through



(a) Layer 3 Topology

(b) Layer 2 Topology

Figure 6.1: Network Configuration

Table 6.1: Nodes Information

Node	CPU	Network Devices
MRs	Intel Core i5-520M 2.4GHz	(wlan0) Intel Centrino IEEE 802.11abgn (wlan1) AtermWL54AG IEEE 802.11abgn (eth0) Ethernet IEEE 802.3
HA1	Intel Core 2 Duo 2.4 GHz	(eth0) Ethernet IEEE 802.3
HA2	Intel Core 2 Duo 1.86 GHz	(eth0) Ethernet IEEE 802.3
HA3	Intel Pentium 1.70 GHz	(eth0) Ethernet IEEE 802.3
MN1	Intel Core 2 Duo 2.4GHz	(eth0) Ethernet IEEE 802.3
MN2	Intel Core i5-520M 2.4GHz	(eth0) Ethernet IEEE 802.3

these tunnels. The mobile routers are able to connect to others through the MANET interfaces - *wlan0*. Then the packets would be directly forwarded to the destination mobile network via MANETs.

6.2 Evaluation method

The performance of eMANEMO system is measured in the indoor experiments and the field test to verify the following three evaluations:

Evaluation 1: Accuracy and effectiveness of the path cost based switching decision

This evaluation is to demonstrate that eMANEMO can considerably improve the performance of V2V communications. It will evaluate the MANEMO system with or without the path cost based routing decision, which is more accurate in choosing the best path to the destination. It will also identify cases where eMANEMO system could promote the highest efficiency.

The following two following scenarios are set to evaluate the performance of the system:

- Scenario 1: The mobile routers are running near the home agents (The communication between vehicles which have the home agents in the same country)

- Scenario 2: The mobile routers are running far from the home agents (The communication between vehicles which have the home agents in different countries)

In order to simulate these situations, Traffic Control software under Linux was used to set the delay of HAs' interfaces. The delay of interface eth0 of HA2 is added by 20ms in order to set up scenario 1, and 100ms to set up scenario 2.

The performance of the system with one-hop MANET connections and multi-hop MANET connections were also evaluated. Ip6tables and TC Linux tools are used to assume the changes in topology and link quality of network.

Below are the measurements and the comparisons that will be done:

- Measure Throughput, Round Trip Time, Packet Loss Rate of the traffic between MN1 and MN2.

- Compare the Throughput, Round Trip Time, and Packet Loss Rate measurement results with the two-function gateway MANEMO system(without the path cost based routing decision) and stand alone NEMO system.

Evaluation 2: Convergence Time

Since mobile routers are independently establishing the path quality estimation and the switching function, the switching time of mobile routers in the same link are different. The measurement and comparison of mobile routers' switching time will verify the convergence time of eMANEMO system.

Evaluation 3: Operation Verification in Field Test

This aims to verify the proper behavior of eMANEMO in real moving environment. The RTT will be measured to confirm the switching performance of the system.

Iperf test tool version 2.05 is used to measure the throughput. Iperf has two modes: the client mode and the server mode. In order to measure the throughput, the client sends TCP data stream through port number 5001. In our test, MNN1 was the client, and MNN2 was the server. The measurement interval was set to i = 10 seconds.

Round Trip Time and Packet Loss Rate are measured by sending 64-bytes ICMPv6 packets each second.

6.3 Results

6.3.1 Accuracy and effectiveness of the path cost based switching decision

In order to evaluate the accuracy and effectiveness of eMANEMO switching decision in different network situations, various indoor experiments with traffic tools have been held.

Experiment 1: One-hop Adhoc Connection (2 mobile routers)

To simulate that MRs and MNNs are moving, this test created and ran tc.sh script to control the traffic rate of the MANET interface of MR1 as table 6.2.

The traffic rate was increased 10 times every 20 seconds. When it reached to the maximum ideal value(50 Mbits/s), the traffic rate was decreased 10 times again with the same interval until to 0.

Through the indoor tests, the RTT between MNNs in the near home agent scenario was set to 40 ms, in the far home agent scenario was 100 ms.

Figure 6.2 and 6.3 show the throughput and RTT comparisons among NEMO, the MANEMO system without path cost based routing decision and eMANEMO system.

From t = 0 to t = 19s, the traffic rate of MANET interface of MR1 was configured as disconnected. Therefore, all of three systems used the NEMO

Table 6.2: Traffic Control (Rate Limiting) of MR1 in case running two MRs

Time	Rate
0s - 20s	0 bit/s
20s - 40s	20 kbits/s
40s - 60s	200 kbits/s
60s - 80s	2,000 kbits/s
80s - 100s	20,000 kbits/s
100s - 120s	50,000 kbits/s
120s - 140s	20,000 kbits/s
140s - 160s	2,000 kbits/s
160s - 180s	200 kbits/s
180s - 200s	20 kbits/s
200s - 220s	0 bit/s

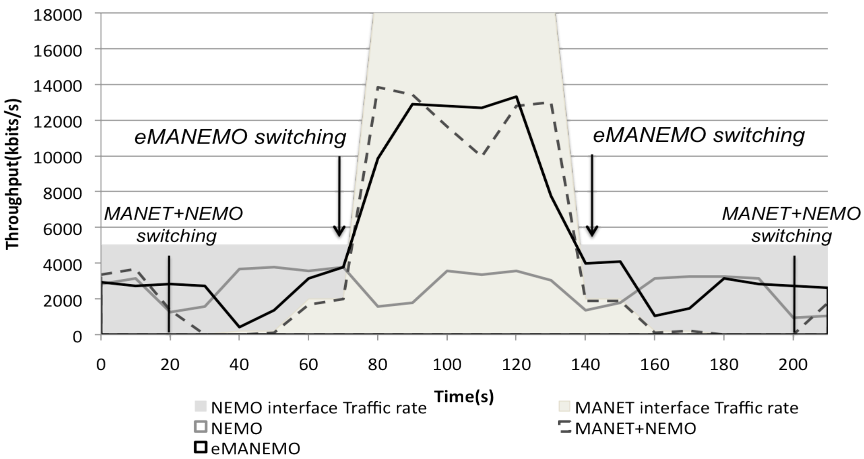


Figure 6.2: Throughput between MMNs in case 2 MRs are near to their HAs (measured by Iperf TCP)

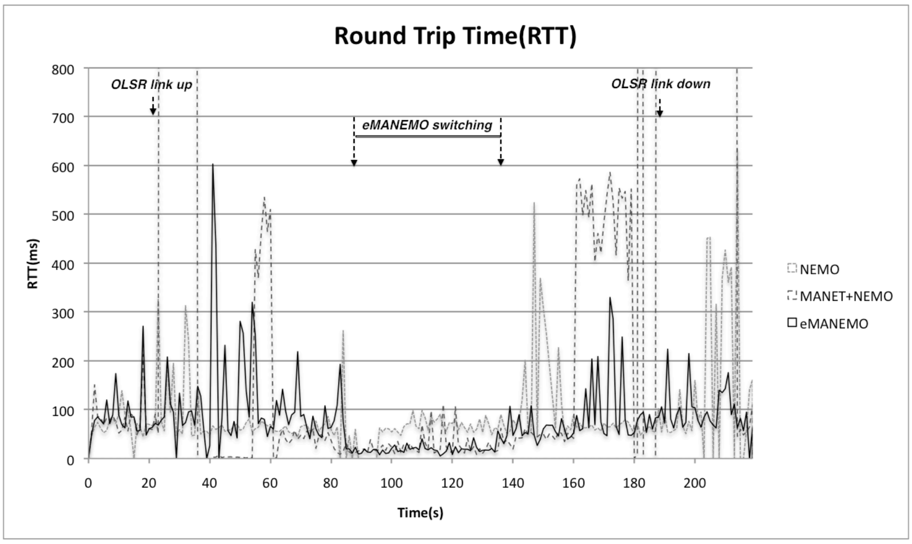


Figure 6.3: Round Trip Time between MMNs in case 2 MRs are near to their HAs during the TCP Stream Transmission

route for their data transfer. When t = 20s, the MANET interface of MR1 was brought up. The MANEMO system without multi-path selection immediately added the available routes to the routing table, caused the decrease of link throughput and the increase of the delay. Setting the traffic rate to 20 kbits/s has made the RTT increase of 5,738 milliseconds(approximately 5.7 seconds) with packet losses occur(7 packets were lost). Different from that, after receiving the routing information from its neighbor, eMANEMO calculated and compared the path costs to the destination(MANET and NEMO) and decided whether to use this route for data transmission or not. Thus, the router continued to use the NEMO route instead of adding the MANET to the routing table.

At t = 40s, the traffic rate was increased to 200 kbits/s, and then to 2,000 kbits/s at t = 60s. The delay of MANET link was reduced to 2.6s. However, the throughput of the MANET link was still lower than the NEMO link.

After 23s, at t = 83s, when the traffic rate was increased to 10 times, the cost of MANET route became lower than NEMO. MR1 added the MANET route to the system routing database. One second later, MR2 switched its connection from NEMO to MANET. The throughput on the link between each end point was increased from 3,775 kbits/s to 9,857 kbits/s, and then to the maximum value 13,317 kbits/s. The RTT was decreased from 75.6s to 20.2s after switching.

At t = 140s, the traffic rate of MANET interface was limited to 2,000 kbits/s again. The MANET link bandwidth decreased to nearly 2,000 kbits/s, and the RTT was increased from 19.4s to 45s. Since the cost of the MANET path has become higher than the NEMO, eMANEMO stopped investigating MANET route and smoothly switched back to the stable NEMO.

Table 6.3 shows the average values of the path quality with three systems: eMANEMO improved the average throughput approximately 90% of the stand-alone NEMO system, 19% of the MANEMO system without the path cost execution. eMANEMO also improved the RTT and Packet Loss Rate for the link between MNNs: reduced 14% RTT and 77% Packet Loss Rate than stand alone NEMO system, reduced 91,5% RTT and 63% Packet Loss Rate than MANEMO system without the path cost execution of eMANEMO.

Table 6.3: Average Parameter Values in case 2 MRs are near to HAs during TCP Stream Transmission)

Method	Throughput	Round Trip Time	Packet Loss Rate
NEMO	2,652 Kbits/s	90 ms	7.73% (17/220)
MANET+NEMO	4,214 Kbits/s	918 ms	5% (11/220)
eMANEMO	5,050 Kbits/s	78 ms	1.82% (4/220)

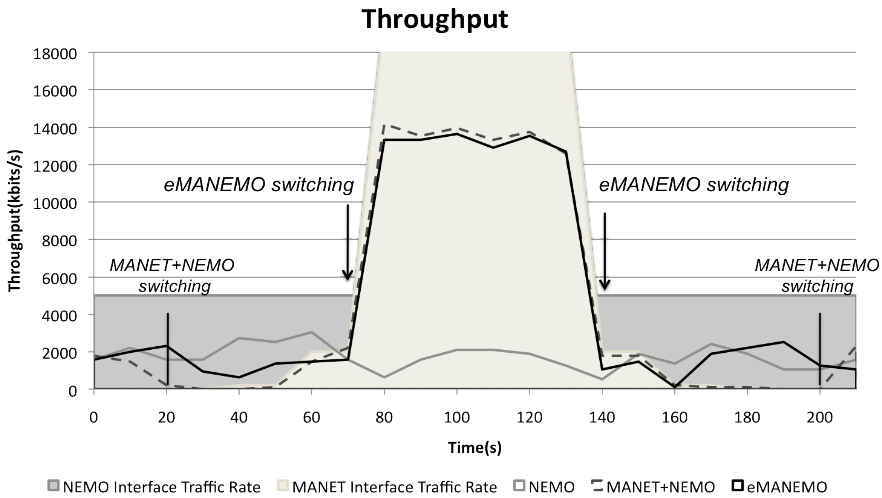


Figure 6.4: Throughput between MMNs in case 2 MRs are far to their HAs (measured by Iperf TCP)

The results in Figure 6.4 and 6.5 show the performance of the system when home agents are far away from mobile networks.

At time t = 75s, when the traffic rate of MANET interface was set to near the NEMO link(rate was about 2,000 kbits/s), because of the effects of delays between mobile routers and home agents, eMANEMO in MR1 made switching decision to use the MANET link instead of the NEMO. Two seconds later, MR2 also changed its route to the MANET link. Like the previous test, in this case, the switching from the NEMO link to MANET link was established smoothly. There was no packet loss occured in this event. This switching action helped to improve the throughput of link from 1,573 kbits/s to 13,317 kbits/s at measurement time t = 80s, the RTT from 208 ms to 50.2 ms, and then finally decreased to 1.64 ms. The ad-hoc connection then became stable with the throughput around 13,300 kbits/s and RTT around 17ms.

At time t = 140s, the traffic rate of the MANET interface was decreased to 2,000 kbits/s. The decrease of traffic rate caused the down of the MANET link available bandwidth. To prevent the decrease of the connection quality,

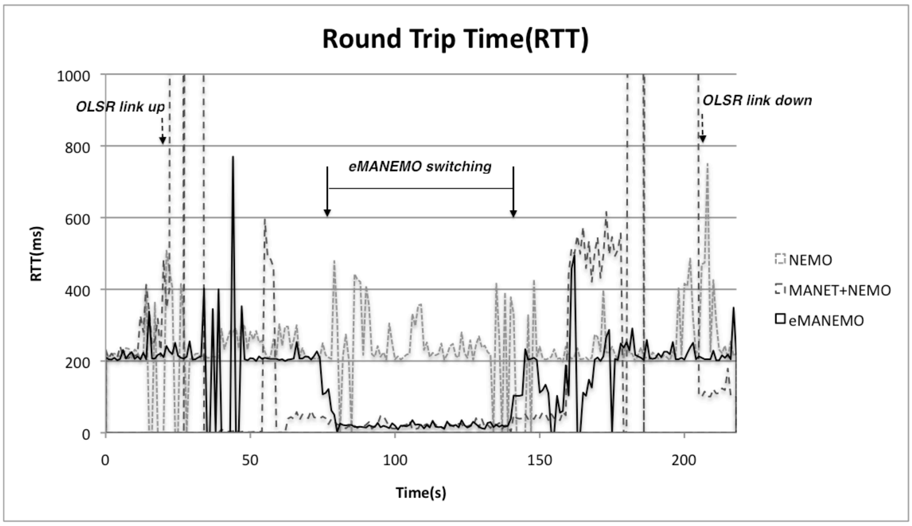


Figure 6.5: Round Trip Time between two MRs in case 2 MRs are far to their HAs during the TCP Stream Transmission

eMANEMO in one MR switched from the MANET and NEMO link. Four seconds later, its partner also established the switching decision. However, since the traffic rate of the MANET link and the NEMO link were almost the same, the unstableness of the wireless link caused the cost of the NEMO link be higher than the MANET link. At time t = 150s, one mobile router has switch from NEMO to the MANET. (The RTT decreased from 203 ms to 112 ms). This action resulted in loss of two ICMPv6 packets. At time t = 160s, when the traffic rate of MANET interface was decreased 10 times again, eMANEMO switched back from MANET to NEMO. The throughput on the MANET link was getting worse at that time. There were two packet losses before the system changed back to the NEMO link.

However, the average values of parameters still shows the efficiency of eMANEMO. The average throughput of eMANEMO was 4,658 kbits/s, providing 169% improvement to the stand-alone NEMO system(1,729 kbits/s), and 8.04% to the MANEMO system without the path cost execution. The average RTT of eMANEMO was 146 ms, while the stand-alone NEMO was 238 ms, and the MANEMO without the path cost execution was 896 ms.

(Table 6.3.1)

Beside the great throughput improvement, this test showed us the highly improvement of the RTT of eMANEMO with the stand-alone NEMO system and the MANEMO without path cost execution. It also showed the performance of eMANEMO in case the cost of the MANET link and the NEMO link were nearly equal.

Table 6.4: Average Values in case 2 MRs far to HAs (during TCP Stream Transmission)

Method	Throughput	Round Trip Time	Packet Loss Rate
NEMO	1,729 kbits/s	238 ms	8.18% (18/220)
MANET+NEMO	4,311 kbits/s	896 ms	4.55% (10/220)
eMANEMO	4,658 kbits/s	146 ms	6.36% (14/220)

Experiment 2: Multi-hop Adhoc Connection(3 Mobile routers)

This test created and ran tc.sh script to control the traffic rate of the MANET interface of MR1 as table 6.5.

Table 6.5: Traffic Control(Rate Limiting) of MR1 in case running three MRs

Time	Rate
0s - 20s	0 bit/s
20s - 40s	20 kbits/s
40s - 60s	200 kbits/s
60s - 80s	2,000 kbits/s
80s - 100s	20,000 kbits/s
100s - 120s	50,000 kbits/s
120s - 140s	20,000 kbits/s
140s - 160s	2,000 kbits/s
160s - 180s	200 kbits/s
180s - 200s	20 kbits/s
	Drop all packets from MR2
200s - 220s	50,000 kbits/s
220s - 240s	20,000 kbits/s
240s - 260s	2,000 kbits/s
260s - 280s	200 kbits/s
280s - 300s	20 kbits/s
300s - 320s	0 bit/s

Figure 6.6 shows the emulation of vehicles' movement and the adhoc connection state.

In the first 200s, MRs performed as the experiment 1: increased and decreased the traffic rate every 20 seconds. However, from t = 200s, the MR1 was set to drop all packets which have source MAC address from MANET interface of MR2. This intends to make MR1 and MR2 change from 1-hop to 2-hops connection via MR3. We will see how the system performs with directly connected link and also with the multi-hop adhoc connection.

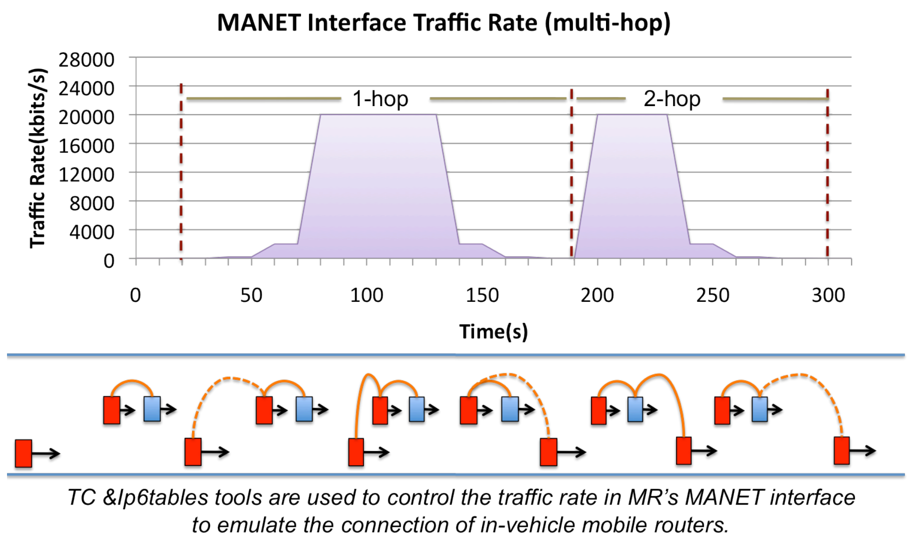


Figure 6.6: Emulation of vehicles' movement and ad-hoc connection state

Figure 6.7, 6.8, 6.11, and 6.10 show performance of the system in the comparison with other methods in two cases: mobile routers are near to the home agents, and are far to the home agents.

In the first case, from t = 0 to t = 200ms, the performance of the network link between MNNs was the same with the case two mobile routers are near to their home agents. At time t = 200s, when the MANET link between MR1 and MR2 changed from 1-hop to 2-hops connection, it took 6 seconds on both of eMANEMO and the MANEMO system without path cost execution to change to the multi-hops connection. At t = 260s, while the MANEMO system without path cost execution continued utilizing the worse MANET link, eMANEMO changed back to the NEMO link to prevent the increase of the network system overload. However, at time t = 278s, MR3 switched the route to MR1 from the NEMO to the MANET link and continuously utility the worse MANET link. At t = 281s, the new path cost calculation was established in MR3 and helped this router to update the routing database.

In the case where the mobile routers were far to the home agents, it took 8 seconds for the MANEMO without path cost execution to start using the

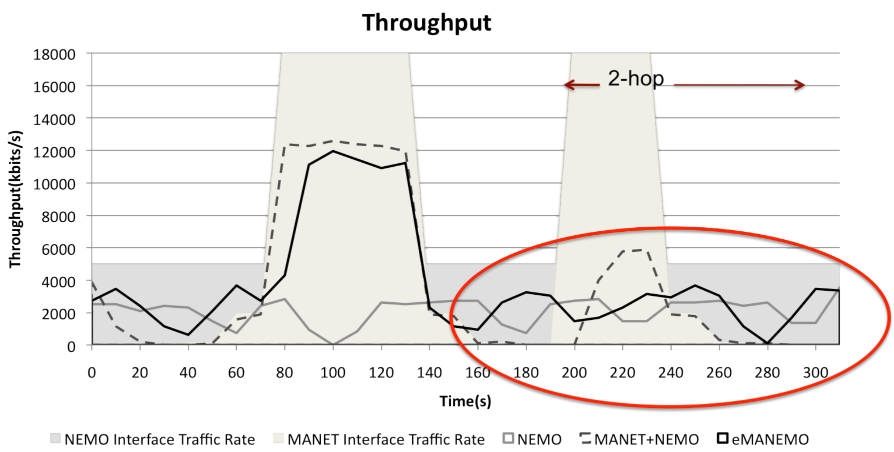


Figure 6.7: Throughput between MMNs in case 3 MRs near to their HAs (measured by Iperf TCP)

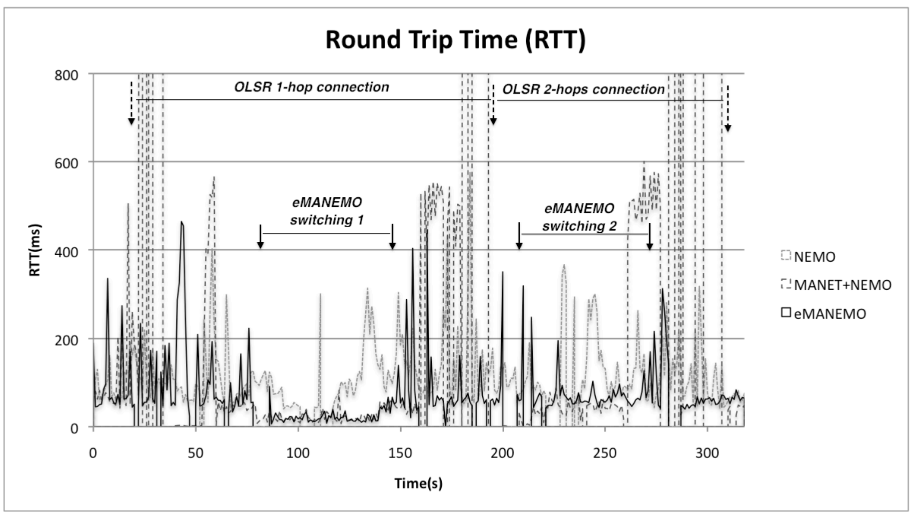


Figure 6.8: Round Trip Time between MMNs in case 3 MRs near to their HAs during the TCP Stream Transmission

Table 6.6: Average Values in case 3 MRs are near to HAs during TCP Stream Transmission)

Method	Throughput	Round Trip Time	Packet Loss Rate
NEMO	2,080 kbits/s	119 ms	5.31 % (17/320)
MANET+NEMO	3,325 kbits/s	918 ms	10.62 % (34/320)
eMANEMO	3,784 kbits/s	75 ms	8.75 % (28/320)

2-hop OLSR connection. The time to switch from NEMO to MANET of eMANEMO system was 6 seconds. At time t = 235s, one mobile router switched from the MANET link to the NEMO link. The switching of one mobile router at t = 235s made the responses of the packets, which were sending from router via MANET interface, returned back the sender by the NEMO link. This continued to t = 263s. At that time, the other mobile router finally made its switching decision.

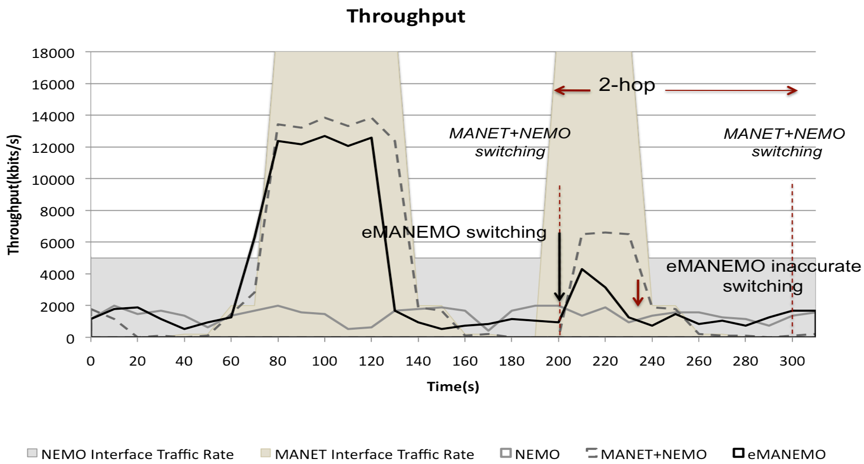


Figure 6.9: Throughput between MMNs in case 3 MRs far to their HAs (measured by Iperf TCP)

In these cases, although the 2-hop MANET path quality is still higher

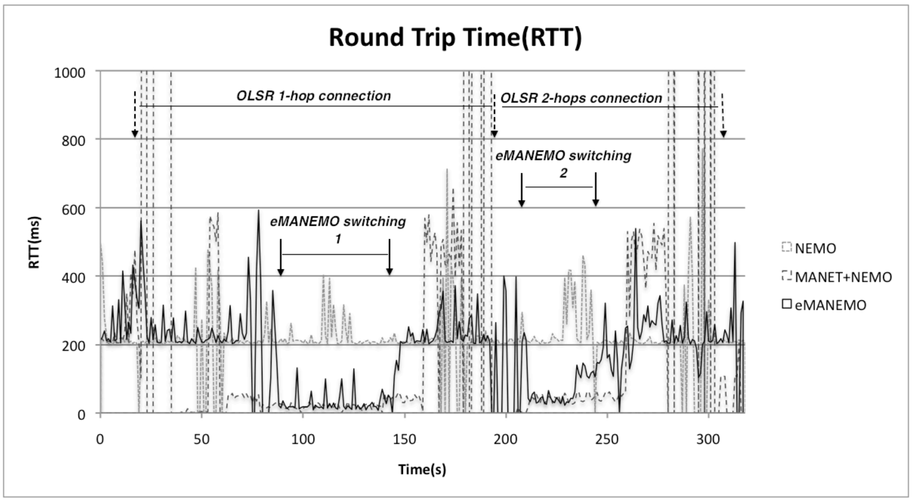


Figure 6.10: Round Trip Time between two MRs in case 3 MRs far to their HAs during the TCP Stream Transmission

Table 6.7: Average Values in case 3 MRs far to HAs during TCP Stream Transmission)

Method	Throughput	Round Trip Time	Packet Loss Rate
NEMO	1418 kbits/s	218 ms	7.19 % (23/320)
MANET+NEMO	3604 kbits/s	720 ms	14.11 % (45/320)
eMANEMO	3214 kbits/s	169 ms	6.88 % (22/320)

than the NEMO path, the system early switched from the MANET path to the NEMO one. The inaccurate path quality estimation due to the unsuitable sending packet size and packet pair number caused this inefficient switching. The experimental results were retaken with the adjustments of sending packet size and pair numbers of the path quality estimation submodule. (Packet Length = 1500 bytes, Packet Number = 20 packets (10 pairs)). The performance of eMANEMO has been improved with correct switching point for 2-hop adhoc connection. The average values of parameters were 4171 kbits/s throughput, 158 ms delay, and 5.36% packet loss rate.

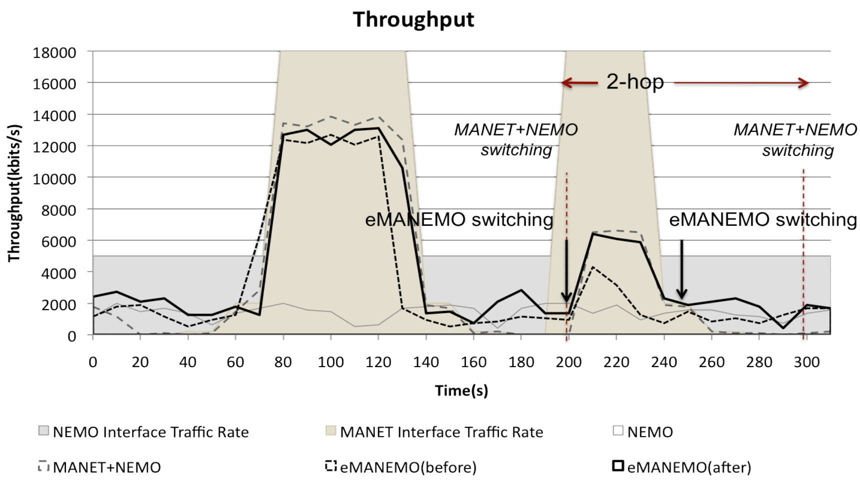
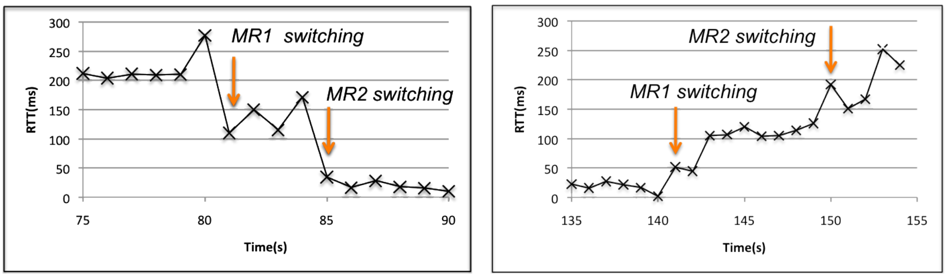


Figure 6.11: New switching points. Throughput between MMNs in case 3 MRs far to their HAs (measured by Iperf TCP)

6.3.2 Convergence Time

Figure 6.12 shows the convergence time results in case one-hop adhoc connection, MRs are far to HAs. Experimental results showed that convergence time was always in the range between 0 to the path quality estimation interval. The default value of the interval was 7 seconds. There was no packet loss occurred in almost all switching events.



(a) NEMO to MANET. $t_c = 4s$ (b) MANET to NEMO. $t_c = 7s$

Figure 6.12: Convergence Time (2MRs far to HAs. NEMO RTT $\approx$ 200 ms)

6.3.3 Operation Verification in Field Test

The proper behavior of eMANEMO system was verified in the field test around the course of Shonan Fujisawa Campus, Keio University.

We set up two access points to provide wireless network for the experiment (802.11 b/g channel 6). (Figure 6.13)

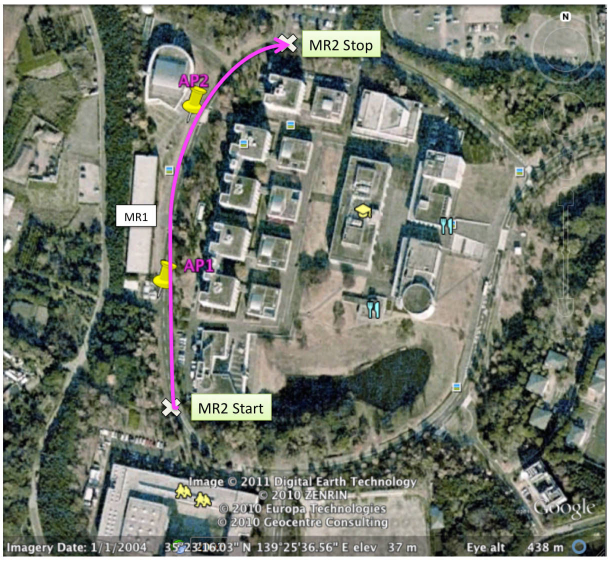


Figure 6.13: Wireless Network Environment Setup

The movement of MRs in our evaluation is set as figure 6.14

We used two mobile routers: MR1, MR2, and their attached mobile network nodes: MNN1, MNN2. MR1 is set to stop at $v_1 = 0km/h$. MR2

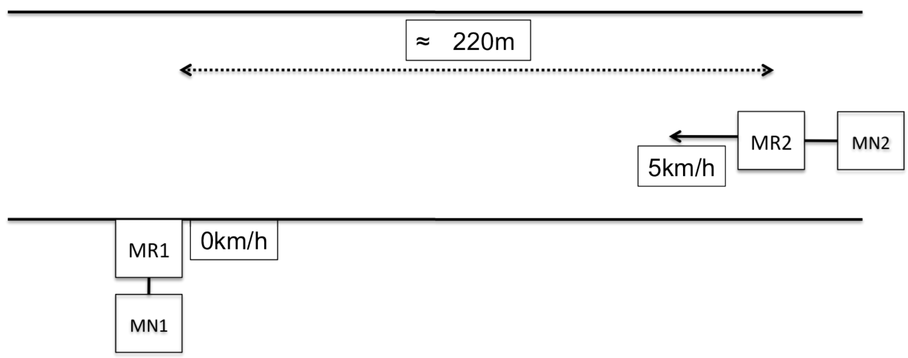


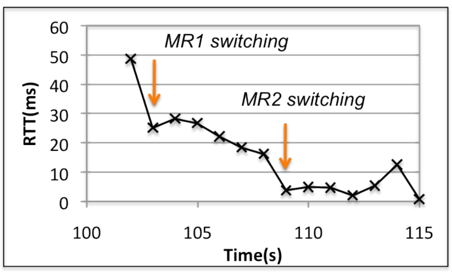
Figure 6.14: Moving of MRs

ran around the course with the speed $v_2 = 5km/h$. The distance of two MRs when starting was d = 220m.

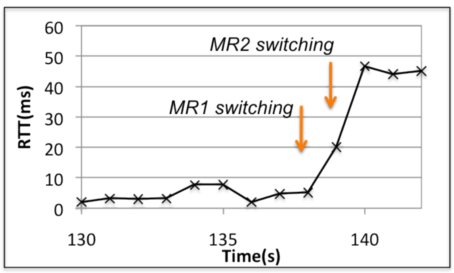
Figure 6.15 shows the switching manner of eMANEMO from the NEMO link to the MANET when MR2 were moving close to MR1.

At time t = 101s, when the cost of the MANET link became lower than the NEMO link, MR1 established the route switching, which made the RTT decrease from 48,1ms to 25,1ms. 7 seconds after, MR2 also switched from the NEMO to MANET to reduce the RTT from 16.7ms to 3.71ms.

At time t= 137s, when the cost of the MANET link became higher than the NEMO link(MR2 were moving far to MR1), MR1 established the path switchingfrom MANET to NEMO. One second after, MR2 also made the path switching decision.



(a) NEMO to MANET



(b) MANET to NEMO

Figure 6.15: Switching performance in real field test

6.4 Summary

This chapter described the testing environment and evaluate the performance of the eMANEMO system. First, the accuracy and effectiveness of the path cost based switching decision has been evaluated in the indoor experiments. The effectiveness of switching decision was confirmed in almost all test cases, especially in the evaluation with 1-hop MANET link connections. While the network overhead, which was caused by the path quality estimation, has made the maximum throughput of eMANEMO lower than the existing MANEMO system, the average values of metrics have proved that eMANEMO had entirely improved the performance for V2V data transmissions: improving 7.7% throughput, reducing 85.89% delay and 31.69% packet loss rate. Next, the convergence time for both of MRs during the path switching decision was verified in the range from 0 to the interval of path quality estimations. Although the switching timings of mobile routers were different, there was no packet loss occurred in almost all path switchings. Last, the proper behavior of eMANEMO system has been also confirmed in the field test. It was proved that eMANEMO could help the network system to prevent the inefficient switching when multi-path is available, achieving the highest performance for the network system. The next chapter will present the conclusion and the future works of this thesis.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

This thesis proposed and implemented eMANEMO, a multi-path selection method based on path quality metrics for in-vehicle MANEMO Mobile Gateway systems. eMANEMO built a path cost calculation formula from three following quality parameters: available bandwidth, delay and error rate. The result value(path cost) is used to decide the best route to forward packets in multi-path selection.

In this thesis, the prototype system was designed and implemented. UMIP package, an USAGI-patched Mobile IPv6 for Linux, and modified nOLSRv2 daemon was used to implement the NEMO function and MANET function of this system. In order to estimate the metrics to make switching decision, the path quality estimation module was implemented with the packet pair technique in the prototype system.

The effectiveness of the proposed eMANEMO was discussed in the comparison with other methods: the stand-alone NEMO and the MANEMO system without path cost based switching decision. The performance of our prototype system has been evaluated in the indoor experiments. Experiment results have shown that eMANEMO system based on path quality metrics can achieve 7.7% throughput improvement, reduce 85.89% delay and 31.69%

packet loss rate. In addition, proper behavior in the field test of the system was also verified. Utilizing path quality metrics achieved the highest performance of the network system, the throughput improvement, the delay and packet loss rate reduction for the data transmission in the real-time V2V network.

7.2 Future work

This section presents future works of the research. These works are focusing on: improving the accuracy of the Path Quality Estimation and the Switching Decision modules, considering the system design, and evaluating the system in the field test.

Improving the accuracy of Path Quality Estimation and Switching Decision modules

The effectiveness of eMANEMO with path quality metrics estimation by packet pair technique was proved through various experiments. The system always performed well in the tests with 1-hop OLSR connection. However, in the test case with multi-hops, though the early switching from NEMO to MANET helped network system to reduce the packet loss rate, it caused the decrease of throughput and the increase of packet delay. That happened because of the inaccuracy of the Path Quality Estimation module in estimating the multi-hop bandwidth availability. Moreover, checking all path quality from router to all MANET destinations existing in this routing data seems not to be suitable for the mobile network system.

In OLSR network, mobile routers select MPR from its one-hop neighbors by the willingness values, and use MPRs to transmit all of its routing messages. This is to control messages flooding and reduce the overhead of the network protocol.[11] Mobile routers can measure the path quality metrics to its 1-hop neighbor, and then use the MPRs to exchange the path quality information to others. Mobile routers, after receiving the path quality information from its selectors, will calculate the available bandwidth to the multi-hop destination. This is purposed to reduce the sending packets in the path quality estimations, and reduce the overload of the network system.

Improving the performance of Route Update Controller

The switching function is now add/delete route information from the system routing database. However, the add/delete information of the routing table causes packet losses occurred, increasing the overload of the system. The method of load balancing between MANET and NEMO interfaces, only changing the priority of paths in data transmission are considered to solve this problem.

Considering the system design

In this system, eMANEMO method was implemented as a part of MANET functionality. In the future, we desire a platform that can handle routing information from both of MANET and NEMO modules. Several methods have been considered, and one of them is utilizing Quagga network routing software suite to support our eMANEMO.

Evaluating the system in the real field test under the consider of moving speed of vehicles

This thesis evaluated the system in the indoor experiments, assuming the change of the traffic rate between mobile routers by ip6tables and Traffic Control tools. The time step was set to 20 seconds for each change. To verify the proper behavior of the system, the field test was also operated. The speed of the vehicle in our test was only 5km/h (speed of pedestrians). It is expected that the vehicles move with higher speed(e.g. 40km/h). However, the connection between mobile routers others will change very fast under the high moving speed. Besides, the noise from other networks, the handover when moving from an access point to connect to the other also has effect to the path quality estimation. Preparing a good test environment is extremely important to evaluate the accuracy and efficiency of the system.

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