HoWL: An Efficient Route Discovery Scheme Using Routing History in Mobile Ad Hoc Networks

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Abstract of Bachelor's Thesis

HoWL: An Efficient Route Discovery Scheme Using Routing History in Mobile Ad Hoc Networks

In this thesis, we propose an efficient route discovery scheme for mobile ad hoc networks called Hop-Wise Limited broadcast (HoWL). Since nodes do not identify the location of other nodes, some of the routing protocols proposed for mobile ad hoc networks use network-wide broadcasts to discover a route. In contrast, HoWL limits the area of a route discovery by predicting current location of the destination node using history of hop counts of previously used routes.

Furthermore, we introduce Characterized Environmental Indicators (CEI) which characterize real world environments for networks of mobile nodes. The purpose of CEI is to extract key points of the environments. Specifically, environments can be characterized by three indicators: node density, average hop count of utilized routes, and frequency of link failure. We then verify that CEI can also be applied to simulation environments.

We have implemented HoWL as an extension to DSR, which uses network-wide broadcasts as a means of sending route request messages, on GloMoSim network simulator.

Quantitative and qualitative performance comparisons were evaluated between HoWL and its related work, expanding ring search and LAR. The simulations show that HoWL exhibits the highest effectiveness when mobility is high.

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HoWL: An Efficient Route Discovery Scheme Using Routing History in Mobile Ad Hoc Networks

「モバイルアドホックネットワークにおける使用経路履歴を利用した経路探索機構の設計と実装」

携帯端末の急速な普及や無線通信技術の発達に伴い、移動通信端末同士を自律的に、かつ動的に接続するモバイルアドホックネットワークが、広く注目を集めている。

アドホックネットワークでは、すべての端末が無線ルータとなって他の端末へのパケット転送を行うという特徴を持つ。この特徴を利用して、想定するネットワーク内のすべての端末にパケットを転送する手法を”フラッディング”と呼ぶ。アドホックネットワーク用に提案されたいくつかのルーティングプロトコルでは、経路探索時にフラッディングを行って宛先端末を見つける。しかし、フラッディングは宛先端末の位置を考慮しない単純な方式であるために、電力や帯域などのネットワークにかかるオーバヘッドが高い。そこで本研究では、特定の端末と通信している際に使用経路の通信リンクが切断して再度経路探索を行う際に、使用経路のホップ数の履歴を基に経路探索範囲を制限する経路探索機構を提案する。

また、アドホックネットワークの環境はノード数やノードの移動速度などの様々なパラメータで表せられる。本稿では、これらの可変パラメータを三つの指標にまとめる。具体的には、環境はノード密度、使用経路の平均ホップ数、リンク切断頻度の三つの指標で特徴付けられる。これはシミュレーション環境にも応用可能である。

本経路探索機構をネットワークシミュレータ上に実装し、評価を行った結果、経路探索範囲を制限することにより、フラッディングを用いる場合に比べ、ネットワークにかかる負荷の減少と経路探索にかかる遅延の短縮が見られた。また、関連研究との比較評価を行い、本機構がモビリティの高い環境で特に有効であることを示した。

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Chapter 1

Introduction

1.1 Background

The recent advances in radio technology and spread of wireless devices have been remarkable. The radio technology enhance existing wired networks by providing convenient access to network resources for people carrying portable computers and handheld devices. Figure 1.1 shows the examples of radio technology (e.g., Bluetooth [2], 802.11b [10], UWB [27]) and their characteristical positions in the matrix of the maximum throughput and the maximum coverage area. The appropriate technology to use depends on the purpose of usage.

In Figure 1.2, trends in the number of subscriptions to cell phones and the access to the Internet by cell phones are presented. It exhibits that the mobile access to the Internet is becoming increasingly popular. Not only in Japan, but throughout the world, the number of mobile internet users are rapidly increasing. Table 1.1 lists the worldwide PDA (e.g., iPAQ [4], Palm [21]) shipments in number of units for the third quarter of 2002. It shows that more than 2.5 million PDAs were sold in a quarter of a year, meaning the use of wireless devices is becoming widespread.

With these growing availability of wireless network components, the deployment of mobile ad hoc networks has become possible. Mobile ad hoc networks are networks which do not rely on a pre-existing infrastructure. Rather, they are formed dynamically between mobile

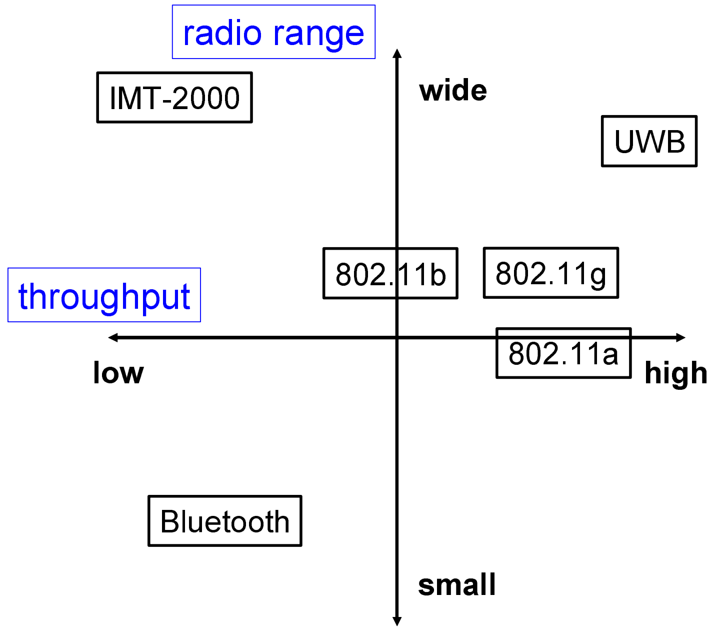

Figure 1.1: Positions of Radio Technology.

nodes, often via multihop where each node in the network can act as a router and forwards data packets to other nodes.

Mobile ad hoc networks have an important role to play in several scenarios. Since mobile ad hoc networks do not require pre-existing infrastructure, it is useful for scenarios such as an emergency communication in a disaster area or a military-use communication in a battlefield, where no infrastructure is available or a centralized configuration is difficult. Also, since mobile ad hoc networks construct network instantly and autonomously, it is suitable for scenarios such as information sharing during a meeting or a conference. Furthermore, there has been research interest in supporting sensor networks and intelligent transport systems (ITS).

However, since nodes in mobile ad hoc networks are mobile, the topology of the network changes dynamically, and since wireless networks have fluctuating link characteristics, the

Figure 1.2: Trends in the Number of Subscriptions to Cell Phones and the Mobile Internet. *Source: Ministry of Public Management, Home Affairs, Posts and Telecommunications, Japan*

network characteristics are subject to change over time. Thus, the network functions such as routing, address allocation, authentication, and authorization must be able to cope with the dynamics of the network. Additionally, since wireless nodes often have limited power supply, the network functions are required to be resource effective. Lastly, internet protocol operability and service discovery are required before the potential of mobile ad hoc networks can be realized.

In this thesis, we propose **an efficient route discovery scheme** for mobile ad hoc networks which is one of the most fundamental mechanisms of a routing protocol for mobile ad hoc networks.

1.2 Motivation

With the growing availability of wireless network components, mobile ad hoc networks are becoming an attractive technology. Mobile ad hoc networks are networks which are formed dynamically and autonomously between mobile nodes, often via multihop where each node in

Table 1.1: Worldwide PDA Unit Shipment Estimates (Units).

Note: Does not include smart phones such as Kyocera 6035, Samsung I-300, and Handspring Treo 180.
Source: Gartner Dataquest (October 2002)

Company	Estimated Shipments
Palm	808,805
Sony	344,963
Hewlett-Packard	292,850
Toshiba	144,391
Handspring	100,100
Others	863,823
Total Market	2,554,932

the network can act as a router and forwards data packets to other nodes. A key challenge to realize deployment of mobile ad hoc networks is to conduct network resource efficient routing which takes node mobility into account.

Since nodes move around in mobile ad hoc networks, a route must be discovered accordingly. One way to discover a route is to send route request messages using flooding where every node within the network under consideration receives messages [11]. Since nodes do not identify the location of other nodes, flooding is the simplest way to discover a feasible route to the destination, and some protocols proposed for mobile ad hoc networks (e.g., AODV [3], DSR [14]) use flooding to discover a route. However, flooding imposes high overhead on network since it is a simple method which does not consider the location of the destination and which relies on usage of link level broadcasts.

Resulting from frequent and unpredictable changes to network topology caused by node mobility in mobile ad hoc networks, research have shown that minimizing the routing overhead is extremely effective in terms of an efficient resource utilization, due to limited available bandwidth and limited power supply.

In this thesis, we propose Hop-Wise Limited broadcast (HoWL) which reduces the overhead of route discovery in mobile ad hoc networks by predicting current location of destination node using history of hop counts of previously used routes and limiting the area to which route request messages are broadcasted based on predicted location information. HoWL achieves two major purposes: **(i) to reduce the overhead of route discovery and (ii) to shorten the latency of route discovery**.

Furthermore, we introduce Characterized Environmental Indicators (CEI) that characterizes real world environments for networks of mobile nodes with constraint that parameters such as speed or transmission range are similar for every node in the network which we refer to as "uniform" environments. The purpose of CEI is to extract key points of the environments. Specifically, uniform real world environments can be characterized by three indicators: node density, average hop count of utilized routes, and frequency of link failure. CEI is also applicable to simulation environments.

We have implemented HoWL as an extension to DSR, which uses flooding as a means of sending route request messages, on GloMoSim network simulator [6].

From quantitative and qualitative comparison between HoWL and its related work, the environments in favor of HoWL and expanding ring search differ. Namely, HoWL has the highest effectiveness when mobility is high, and under high density and low mobility environments, expanding ring search exhibits higher efficiency. LAR can improve its performance by implementing similar optimizations done to DSR, though based on simulation results, HoWL will still be more effective both in quantitative and qualitative ways.

1.3 Structure of the Thesis

This thesis is organized as follows.

The next chapter describes the overview of mobile ad hoc networks, and present the related work of limited broadcast. In Chapter 3, the design and implementation of HoWL is described. In Chapter 4, we introduce CEI. In Chapter 5, we exhibit the simulation results to show CEI is effective under simulation environments, and evaluate the probable variable to be used for the limiting value of HoWL. In Chapter 6, we demonstrate the simulation results for the quantitative performance comparison between HoWL and its related work and state its analysis, and then we exhibit qualitative evaluation. Finally, we state our conclusions and discuss some future work in Chapter 7.

Chapter 2

Mobile Ad Hoc Networks

In this chapter, we first describe briefly about underlying wireless technology. Then, we describe the overview of mobile ad hoc networks, and present the detailed descriptions for the four prominent routing protocols proposed for mobile ad hoc networks. Finally, we define the problem we focus on mobile ad hoc networks, and present the related work of the problem.

2.1 Wireless Technology

Before we describe the overview of mobile ad hoc networks, we review the underlying wireless technology related to this thesis in this section.

2.1.1 Overview

The scale of the wireless networks spread from personal area networks to worldwide satellite networks. The target of our research is the conventional campus-area wireless LAN networks consisting of tens or hundreds of nodes.

Wireless LANs are mainly in-room and in-building networks. The examples of the radio technology used to construct it includes IEEE 802.11b, IEEE 802.11a, IEEE 802.11g, Bluetooth, and HyPerLAN/2. The technology mentioned above operate in the unlicensed Industrial, Scientific and Medical (ISM) bands at 2.4 GHz and 5 GHz which have been set aside by the national regulations for experimental purposes.

In the following subsection, we briefly describe IEEE 802.11b which is related to this thesis, and other family of 802.11.

2.1.2 IEEE 802.11

802.11 is a family of specifications for wireless LANs developed by a working group of the Institute of Electrical and Electronics Engineers (IEEE). We briefly describe the four specifications in the family: 802.11, 802.11a, 802.11b, and 802.11g. All four use the Ethernet protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for path sharing.

Among the wireless LAN technology, availability of standards-based 802.11b wireless network components are rapidly growing. The 802.11b standard, often called Wi-Fi, is backward compatible with the earlier 802.11. The modulation used in 802.11 has historically been Phase-Shift Keying (PSK). The modulation method selected for 802.11b is known as Complementary Code Keying (CCK) which allows higher data speeds and is less susceptible to multipath-propagation interference.

802.11g offers wireless transmission over relatively short distances up to 54 Mbps compared with the 11 Mbps of the 802.11b standard. Like 802.11b, 802.11g operates in the 2.4 GHz range and is thus compatible with 802.11b. In contrast, 802.11a operates at 5 GHz with data speeds up to 54 Mbps, which does not have compatibility with 802.11b.

Wireless networks characteristics differ from those of traditional wired networks. Namely, wireless transmission range and wireless link quality both change dynamically depending on the surroundings.

2.2 Mobile Ad Hoc Networks

This section describes the overview of mobile ad hoc networks and the four prominent routing protocols proposed for mobile ad hoc networks. Then, we define the problem we focus on mobile ad hoc networks.

2.2.1 Overview

Mobile ad hoc networks consist of a group of mobile, wireless nodes which cooperatively and spontaneously form a network independent of any pre-existing infrastructure or centralized administration. Rather, a node communicates directly with nodes within its wireless range and indirectly with all other destinations using a dynamically-determined multihop route where each node in the network can act as a router and forwards data packets to other nodes. An image of multihopping is illustrated in Figure 2.1.

The mobile ad hoc networks are often characterized by energy constrained nodes, bandwidth constrained, fluctuating variable capacity wireless links, and dynamic topology, leading

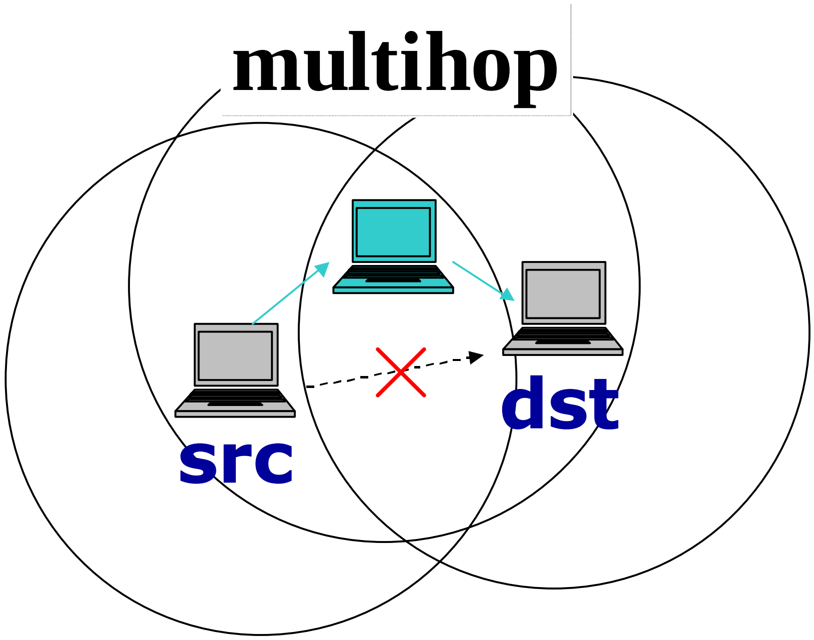

Figure 2.1: Multihop

to frequent and unpredictable connectivity changes.

Prior to now, numerous routing protocols have been proposed for mobile ad hoc networks (e.g., AODV [3], ZRP [7], OLSR [12], DSR [16], TORA [22], CEDAR [24], ABR [26]). These routing protocols can be classified in three ways. Firstly, table-driven, on-demand, and hybrid. Secondly, flat and hierarchical. And lastly, topology-based and destination-based.

Firstly, table-driven protocols attempt to maintain routing information for all known destinations at every source, so that when initiating traffic to a destination, the route is already known and can be used immediately. On the other hand, on-demand protocols discover routes only when needed. Hybrid protocols are mixture of table-driven and on-demand schemes.

Secondly, in flat protocols, none of the nodes take on a distinguished role in the routing scheme, namely, every node sends and responds to routing control messages the same way. In contrast, hierarchical protocols limit the number of nodes participating in a route computation.

And lastly, topology-based protocols maintain large-scale topology information, meaning source routing is conducted. On the contrary, destination-based protocols maintain a hop count and a next hop to the destination.

Some comparisons between these protocols have been published (e.g., [13], [15]). Both papers exhibit simulation results showing on-demand protocols performing significantly better than table-driven protocols in most situations. The key advantage behind on-demand protocols is the reduction of routing overhead resulting from on-demand basis route discovery and maintenance. Reducing the routing overhead under dynamic mobile ad hoc networks, where frequent connectivity changes occur, is especially effective due to limited available bandwidth and limited power supply.

2.2.2 Routing Protocols

We now describe the four prominent routing protocols proposed for mobile ad hoc networks. We especially describe DSR in detail since it is closely related to this thesis, and since vanilla version of DSR is the most simple protocol which includes the fundamental mechanisms common to all four protocols.

- DSR

  Dynamic Source Routing (DSR) is an on-demand, flat, and topology-based protocol. DSR is composed of two mechanisms: route discovery and route maintenance. When a source node has no route to a destination, it broadcasts a route request. Each intermediate node that receives the request appends its address to the request and re-broadcasts it (silently ignoring duplicate requests and any request in which its address already appears). When the route request reaches the destination, the destination sends a route reply containing the complete route back to the source. Route request and route reply put together is called route discovery. When the source node receives a route reply, it caches the source route and will include it in the header of each data packet addressed to the destination. Upon detecting a link failure, invalidated routes are removed from the cache, and this process is called route maintenance.

The above is only the vanilla version of DSR. The specification of DSR Internet Draft [16] states many optimizations including promiscuous learning of routes, non-propagating route requests, replying from cache at intermediate nodes, and salvaging of packets by intermediate nodes.

- AODV

  Ad hoc On-demand Distance Vector (AODV) is an on-demand, flat, and destination-based protocol. In AODV, nodes receiving a request record a "reverse" destination vector back toward the source, using the node from which the broadcast was received as the next-hop. When a route request reaches the destination, route reply is sent along the reverse path back to the source, and the corresponding "forward" destination vector is created at each intermediate node.

  Since destination vector algorithms are subject to routing loops, AODV manages a sequence number per destination to ensure the freshness of each route.

- OLSR

  Optimized Link State Routing (OLSR) is a table-driven, hierarchical, and topology-based protocol, in which each node includes only a subset of its neighbors in a link-state protocol. In link-state protocols, each node distributes its link-state information to every other node in the network each time its connectivity changes. OLSR reduces the cost of this operation by defining a multi-point relay (MPR) set for each node. MPR is the minimal subset of its one-hop neighbors which must rebroadcast a message so that it is received by all of its two-hop neighbors.

- CEDAR

  Core Extraction Distributed Ad hoc Routing (CEDAR) is an on-demand, hierarchical, and topology-based protocol. CEDAR partitions nodes using minimum dominating set. That is, the minimum subset of nodes such that all nodes are at most one-hop away from a dominating "core" node. A core consists of a dominator and "tunnels", unicast paths which connect each core node with nearby core nodes. During route discovery, source node forwards a route request to its dominator. Instead of using link level broadcast to disseminate the request, CEDAR uses a unicast mechanism, the "core broadcast", in which a core node tunnels the message to each of its core neighbors.

2.2.3 Problem Definition

Since nodes move around in mobile ad hoc networks, a route must be discovered accordingly. One way to discover a route is to send route request messages using flooding where every node within the network under consideration receives messages [11]. Since nodes do not identify the location of other nodes, flooding is the simplest way to discover a feasible route to the destination, and some of the routing protocols proposed for mobile ad hoc networks (e.g., DSR and AODV mentioned in Subsection 2.2.2) use flooding to discover a route. However, flooding imposes high overhead on network since it is a simple method which does not consider the location of destination and which relies on usage of link level broadcasts. The following problems associated with link level broadcasts of flooding is mentioned in detail in literature [25].

- Redundant rebroadcasts: Nodes presumably receive duplicate messages.

- Contention: Neighboring nodes potentially try to rebroadcast at the same time.
- Collision: Rebroadcast messages possibly collide.

An example of search area for a route discovery using flooding and HoWL is illustrated in Figure 2.2.

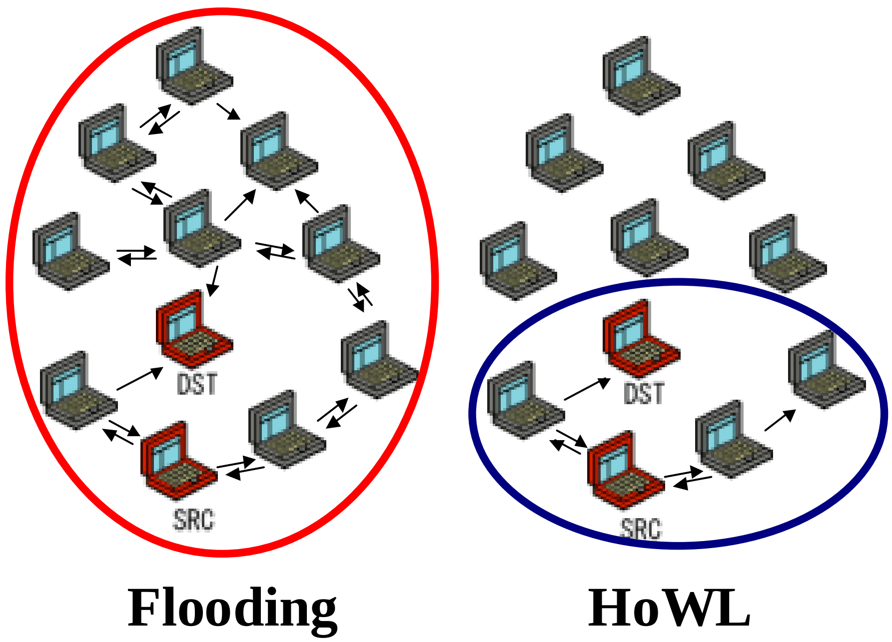

Figure 2.2: Search area of route discovery using Flooding and HoWL

2.3 Related Work of Limited Broadcast

This section briefly describes existing limited broadcast schemes in mobile ad hoc networks, where only a subset of nodes in the network receives route request messages.

Location-Aided Routing (LAR) [17] protocol limits the search for a route to the so-called request zone determined based on the expected location of the destination node. This protocol requires location information from global positioning system (GPS) and needs to know average moving speed of nodes. Relative Distance Micro-discovery Ad hoc Routing (RDMAR) [1] protocol also uses location-based limited broadcast. It utilizes relative distance to the destination node, last time the cache was updated, and average speed of nodes to compute maximum distance to the destination. It also needs to know transmission range in order to convert distance to hop count. Unlike LAR or RDMAR, HoWL does not require any special system such as GPS and utilizes only locally acquired information.

Threshold-based protocols [25] introduce threshold to limit the number of nodes that forward route request messages. For instance, in distance-based scheme, if a node receives a route request message from a node that exists closer than threshold value, it does not forward the route request message any further. However, the recommended threshold value is not specified. In contrast, the effective limiting value of HoWL is achieved dynamically based on the history of hop counts of previously used routes.

Hierarchical protocols such as [5, 18, 24] also reduce the number of nodes that can forward route request messages. In such protocols, only core nodes can involve in disseminating route request messages. This protocol requires algorithm to elect core nodes and reelection of core nodes as topology changes. HoWL has lower computational overhead than CEDAR.

Finally, the expanding ring search mechanism is specified in the protocol specifications of DSR [14] and AODV [3]. A node using this technique first sends route request messages to only its neighbors, and if no route reply is received, the node keeps doubling the hop limit used on the previous attempt. However, when partitions occur, this has effect of high overhead and high latency of route discovery. Unlike the expanding ring search, the worst case of HoWL is tolerable since HoWL attempts limited broadcast only once or twice for each route discovery.

2.4 Summary

In this chapter, we have described briefly about underlying wireless technology IEEE 802.11 assumed in this thesis. Then, we have described the overview of mobile ad hoc networks and classified routing protocols in three ways. Furthermore, we have presented detailed description for the four prominent routing protocols proposed for mobile ad hoc networks, DSR, AODV, OLSR, and CEDAR. Finally, we have defined the problem of using flooding, and presented the related work of limited broadcast.

Chapter 3

Design and Implementation of Hop-Wise Limited broadcast (HoWL)

In this chapter, we first state the goals and purposes of HoWL. Then, we describe the design and implementation of HoWL in detail.

3.1 Goals and Purposes of HoWL

This section states the goals and purposes of HoWL.

3.1.1 Goals

HoWL achieves the following three design goals that were not solved by related work mentioned in Section 2.3.

- Low cost: HoWL does not require any special system such as GPS.
- Simplicity: HoWL requires only locally acquired information, and does not assume any special knowledge such as speed of nodes.
- Generality: HoWL is effective in various environments.

3.1.2 Purposes

HoWL also accomplishes the following three purposes.

1. To reduce the overhead of route request phase by limiting the area which receives route request messages.
2. To reduce the overhead of route reply phase by eliminating route reply messages for long, detouring routes.
3. To shorten latency by limiting the area where routes are searched.

3.2 Design of HoWL

In this section, design of HoWL is described.

3.2.1 Overview

Figure 3.1 illustrates the way HoWL is invoked when trying to find a route to the destination. The section surrounded by dotted line is HoWL.

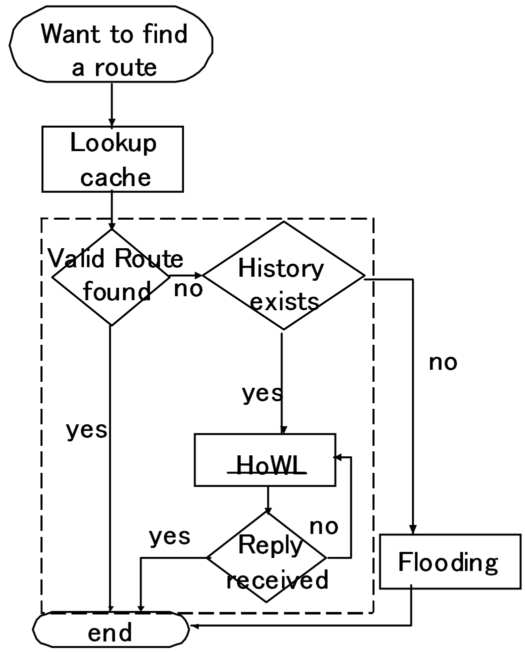

Figure 3.1: HoWL invocation method

3.2.2 Invocation Method

The basic functions of HoWL is as follows:

1. When data must be sent to a destination, it checks for a route to the destination in the cache. If a valid route is found, that route is used to send data. Otherwise, HoWL checks the history of previously used routes to the destination. If valid history is not available, flooding is conducted to discover a route to the destination. Otherwise, HoWL computes the hop count of limited search area based on the history.

2. A HoWL failure detect timer which is calculated based on hop count of limited search area is set when HoWL functions. The HoWL failure detect timer is reset when a route reply message arrives. When the HoWL failure detect timer expires, HoWL assumes the destination was outside of limited search area and repropagates route

request messages for a wider serach area.

3.3 Implementation of HoWL

There are two versions of HoWL. The first one merely utilizes the hop count of previously used route and the other one utilizes hop counts of previously used routes. In this section, we present the detailed description of implementations of the both versions of HoWL.

3.3.1 Overview

HoWL is designed to be effective for all protocols which use flooding as a way to propagate route request messages. We have implemented HoWL as an extension to DSR because of their prominence in research community of mobile ad hoc networks and ready availability of implementation code.

3.3.2 Utilizing the Previously Used Route

The first version of HoWL utilizes merely the previous route.

- Route invalidation flag

  When a link failure occurs and a route is no longer valid, insted of deleting a route from the cache, it sets a route invalidation flag to indicate the route can no longer be used.

- Limiting value of HoWL

  When HoWL functions, the time to live (TTL) field of new route request messages will be calculated based on the hop count of previously used route. Specifically, TTL value will be the hop count of previously used route plus the constant α. (The desired value for α depends on the pattern of hop counts of previously used routes. If the hop count between the same source-destination pair varies greatly as time passes or if a destination seems to be departing from the source node, α should be large and vice versa.)

When this route discovery fails, HoWL doubles the limited search area and repropagates route request messages. When the second route discovery also fails, flooding is conducted. Conducting limited broadcast twice was decided based on experimental results.

The expression executed is as follows:

$TTL = hop\_old + \alpha$

where TTL, hop_old, and α are hop count of limited search area, hop count of previously used route, and a constant value added to hop_old, respectively.

We represent HoWL with different constants α as H(α). For example, HoWL that limits search area of route request messages to one hop further than hop count of previously used route is H(+1).

3.3.3 Utilizing History of Previously Used Routes

The second version of HoWL utilizes history of previously used routes.

- Hop Table

  Hop Table is illustrated in Figure 3.2.

  1. When data must be sent to a destination and a valid route to that destination is not found, HoWL examines the Hop Table. If there is no entry for the destination, this is the first attempt to discover a route to the destination, thus, flooding is conducted. If there is an entry for the destination, check whether history is valid, and compute the hop count of limited search area based on sufficiently valid hop

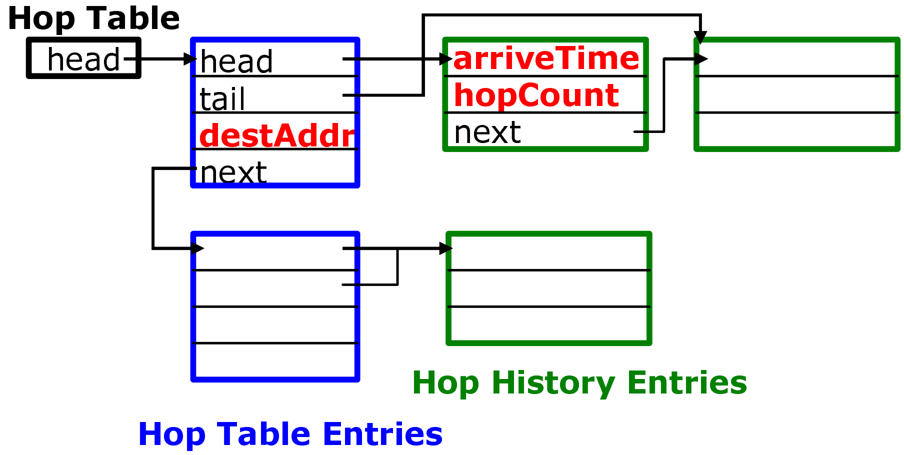

Figure 3.2: Hop Table

counts of previously used routes. If a Hop History Entry is expired, the entry is deleted and the head pointer in Hop Table Entry is changed accordingly.

2. When a route reply is received, construct Hop Table Entry for the destination if it does not already exist, and insert hop count of the route and the time of reception into the Hop History Entry.

The pseudo code for route request handling and calculation of a hop count of limited search area is presented in Figures 3.3 and 3.4, respectively. The variables and functions that appears in the code is described in Table 3.1.

In Figure 3.4, for the first limited search of routes, HoWL calculates weighted average of valid hop counts of previously used routes. Weighted average is an average that takes into account the proportional relevance of each component, rather than treating each component

Table 3.1: Description of Variables and Functions that appears in Pseudo Code

```
Variables:

reqEntry: Request Table Entry of the destination
backoffInterval: used to limit the rate of route discovery process
lastRequest: time of the last route request
times: used to limit the use of limited route requests
hops: hop count of first limited search area

destAddr: address of the destination node
hopEntry: Hop Table Entry of the destination
history: Hop History Entries
a: used to calculate weighted average
newTtl: hop count of the next search area
DSR_MAX_LEN: max hop count is 16, which is defined by DSR specification


Functions:

currenttime: gets current time.
CheckHopTableEntryExists: checks if hop table entry for the destination exists
InsertHopTableEntry: inserts hop table entry for the destination
CheckHistory: checks arriveTime in Hop History Entries, and
              deletes entries when expired.
```

Want to find a route to the destination.

```
void SendRouteREQ(RequestTableEntry *reqEntry, HopTableEntry *hopEntry){
    if((currenttime() - reqEntry->lastRequest) > reqEntry->backoffInterval)){
    // check if backoff interval has expired for the destination
        if (CheckHopTableEntryExists(destAddr)){
            if (reqEntry->hops != DSR_MAX_LEN && reqEntry->times == 1){
            // limited search is conducted only twice for each route discovery
                newTtl = ReCalcTtl(reqEntry);
            }
            else if (reqEntry->hops != DSR_MAX_LEN && reqEntry->times == 0){
                newTtl = CalculateTtl(hopEntry);
            }
            else{
                newTtl = DSR_MAX_LEN; // flooding
            }
        }
        else{ // first attempt for route discovery
            InsertHopTableEntry(destAddr);
            newTtl = DSR_MAX_LEN; // flooding
        }
    }
```

Figure 3.3: Pseudo Code for Handling Route Request

First Limited Search of Routes.

```
int CalculateTtl(HopTableEntry *hopEntry){
    float a = 0.8; // conducts weighted average
    float newTtl = (float)(hopEntry->head->hopcount);
    HopHistoryEntry *history;

    CheckHistory(hopEntry); // delete expired entries

    if(history->next){ // if there's more than one hop count
      for(history = hopEntry->head; history->next != NULL;
          history = history->next){

        newTtl = ((1-a) * newTtl) + (a * history->next->hopcount);
      }
    }

    return((int)(newTtl));
}
```

Second Limited Search of Routes.

```
int ReCalcTtl(RequestTableEntry *reqEntry){
    int newTtl;
    int hops;

    hops = reqEntry->hops;

    newTtl = hops * 2; // double the search area

    if(newTtl > DSR_MAX_LEN){ // should not exceed maximum TTL
        newTtl = DSR_MAX_LEN;
    }

    return(newTtl);
}
```

Figure 3.4: Pseudo Code for Calculating Hop Count of Limited Search Area

equally. Namely, when a is lower, newer component has higher importance. Similar to HoWL which utilizes merely the previously used route, HoWL doubles the limited search area and repropagates route request messages when this route discovery fails. When the second route discovery also fails, flooding is conducted.

3.3.4 Common Parameters

- HoWL failure detect timer

  A HoWL failure detect timer is calculated based on the following equation.

  $time\_out = 30 * ttl$

  where time_out and ttl are the timeout value set to HoWL failure detect timer and hop count of limited search area, respectively. The time unit is milliseconds, and 30 milliseconds is the one hop request timeout value provided by the simulator code.

- Preserved duration of the history

  The hop counts of previously used routes are considered valid for 600 seconds. This is based on the route cache timeout value of 300 seconds specified in the draft [16], and for the reason that cache is still valid as history even after route is no longer valid.

3.4 Summary

In this chapter, we have stated the goals and purposes of HoWL. Then, we have described the design of HoWL. Finally, we have presented the detailed description of implementations of the two versions of HoWL. The first version utilizes merely the previous route, and the second version utilizes history of previously used routes.

Chapter 4

Characterization of Environments

In this chapter, we present purpose and description of CEI. Then, we introduce CEI applied to simulation environments, and state advantages of using CEI.

4.1 Purpose of Characterized Environmental Indicators (CEI)

CEI accomplishes the following purpose.

- To characterize real world environments for networks of mobile nodes with fewer parameters.

  CEI has constraint that parameters such as speed or transmission range are similar for every node in the network which we refer to as “uniform” environments.

  That is, scenario where nodes carried by cars and people are intermingled, implying that speed of nodes differ, is out of scope of CEI.

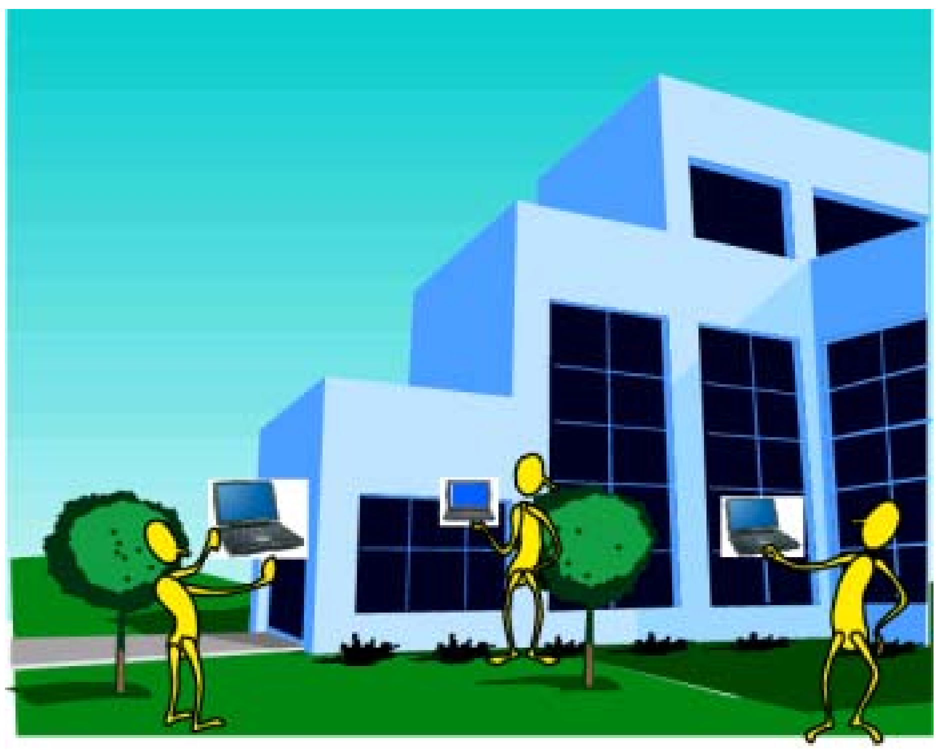

Figure 4.1: An Example of Real World Scenario

For example, in Figure 4.1, variable parameters for the scenario include number of nodes, moving speed of nodes, transmission range of wireless device, area of the network, traffic rate, traffic pattern, and so on. Since more parameters mean longer time is needed for evaluation and analysis, the purpose of CEI is to extract key points and **characterize environments** to reduce variable parameters. An image of this is illustrated in Figure 4.2.

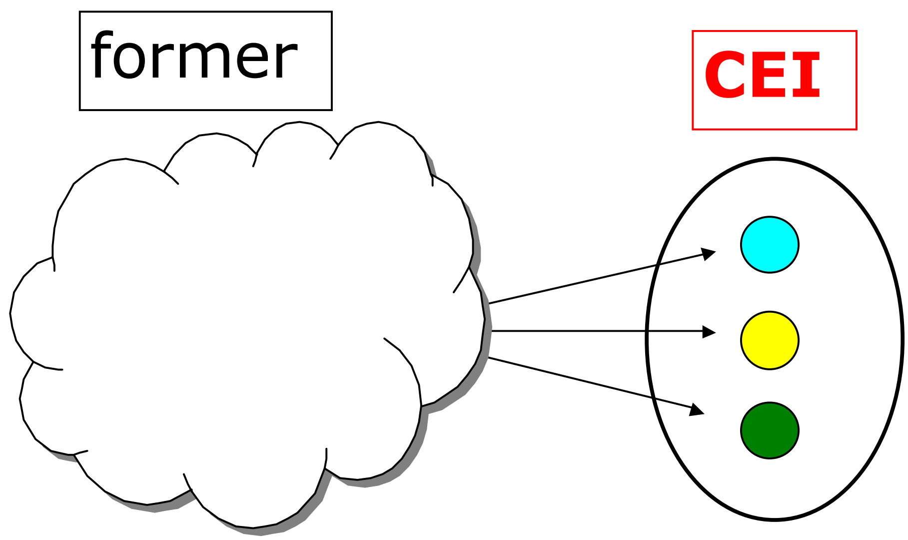

Figure 4.2: Characterization of Environmental Parameters

4.2 Detailed Description of CEI

CEI consists of the following three indicators.

1. Node Density (ND): an indicator for number of nodes that can be reached directly.

   ND=$\frac{area\ of\ transmission\ range}{area\ of\ the\ network} \times\ number\ of\ nodes$

   A larger ND value represents a higher density of nodes.

2. Average Hop count of routes (AH): an indicator for average hop count of routes that were actually used.

   AH = $\frac{length\ of\ diagonal\ of\ the\ network}{radius\ of\ transmission\ range}$

   The actual distance between source and destination is shorter than length of diagonal of network, yet route detours, thus AH serves as an indicator for average hop count of routes.

   A higher AH value exhibits that longer routes are being utilized.

3. frequency of Link Failure (LF): an indicator for frequency of link failure occurrence.

   LF = $\frac{speed\ of\ nodes}{radius\ of\ transmission\ range}$

   LF is an indicator for frequency of a node going out of transmission range of another node, indicating frequency of initiation of a new route discovery.

   The higher the LF, the more often the link breaks, resulting in more route discovery.

4.3 CEI Applied to Simulation Environments

CEI can also be applied to simulation environments.

The expressions for the above mentioned three indicators are as follows:

$$ND = \frac{\pi r^2 n}{xy} \tag{4.1}$$

$$AH = \frac{\sqrt{x^2 + y^2}}{r} \tag{4.2}$$

$$LF = \frac{s}{r} \tag{4.3}$$

where number of nodes, maximum speed of nodes, size of simulation field, and radius of transmission range are n (nodes), s (m/s), x $*$ y (m), and r (m), respectively with meter abbreviated as m.

4.4 Advantages of CEI when Applied to Simulation Environments

First, CEI simplifies an evaluation through simulations by reduces the amount of simulations to be conducted.

Moreover, CEI facilitates stating the advantageous and disadvantageous conditions for a simulation target. That is, in a case where field becomes wider and other conditions remain the same, node density becomes smaller and average hop count of routes becomes longer. When two indicators that affect the the behavior of environments are changed at the same time, performance comparison becomes difficult. In contrast, CEI enables to focus on one indicator that has impact on behavior of environments at a time.

Finally, CEI absorbs various scaled environments. The explanation for this is mentioned below. The following "realistic" scenarios and values of generally used parameters adopted for these scenarios are referred from [13].

The realistic scenarios are as follows:

- Disaster Recovery

  The disaster recovery scenario represents a vehicle network used for rescue operation at a disaster area.

- Conference

  The conference scenario models people attending a conference, a seminar session, or a similar indoor activity.

- Event Coverage

  The event coverage scenarios express outdoor activities such as reporters covering a sport event.

Table 4.1: Values of generally used parameters adopted for realistic scenarios

Parameter	Disaster Recovery	Conference	Event Coverage
r (m)	250	25	250
n (nodes)	50	50	50
x ∗ y (m)	1500 ∗ 900	150 ∗ 90	1500 ∗ 900
s (m/s)	20	1	1

Table 4.2: Values in Table 4.1 converted to CEI values

Parameter	Disaster Recovery	Conference	Event Coverage
ND	7.27 ($\frac{125\pi}{54}$)	7.27 ($\frac{125\pi}{54}$)	7.27 ($\frac{125\pi}{54}$)
AH	7.00 ($\frac{6\sqrt{34}}{5}$)	7.00 ($\frac{6\sqrt{34}}{5}$)	7.00 ($\frac{6\sqrt{34}}{5}$)
LF	$\frac{2}{25}$	$\frac{1}{25}$	$\frac{1}{250}$

The values of generally used parameters for the realistic scenarios described in Table 4.1 become easy to compare when CEI is introduced. As seen in Table 4.2, by using CEI, the only difference between above three scenarios is the value of LF which is the frequency of a new route discovery. Specifically, the above mentioned scenarios are listed in descending order of LF. The explanation for LF being high in disaster recovery scenarios is since moving speed of vehicles are fast, and LF is higher in conference scenarios than event coverage scenarios because indoor communication utilizes smaller range radios. Other CEI indicators, ND which indicates the number of nodes that can be reached directly and AH which implies the average hop count of routes, remain the same which results from the fact that transmission range and size of field are similarly magnified. Thus we can conclude that CEI absorbs various scaled environments in a sense that differences in parameters values between different scenarios are reduced.

4.5 Summary

In this chapter, we have present purpose of CEI. Then, we have described CEI in detail. CEI consists of three indicators, for node density, average hop count of routes, and frequency of link failure occurence. Finally, we have introduced expressions for the three indicators of CEI when applied to simulation environments, and stated advantages of using CEI.

Chapter 5

Fundamental Experiments

In this chapter, we first verify that CEI is effective under simulation environments through simulations on the ns-2 network simulator [20]. Then, we show simulation results to evaluate the probable variables to be used for the limiting value of H(α). Finally, we demonstrate the performance evaluation of H(α)s as the preliminary evaluation.

5.1 Simulation Environment

This section briefly describes about the network simulator and the simulation model being used for the verification of CEI and the preliminary performance evaluation of HoWL.

5.1.1 Simulation Model

The ns-2 network simulator was extended by the Rice Monarch Project to enable accurate simulation of mobile nodes connected by wireless network interfaces, including the ability to simulate multihop mobile ad hoc networks. Some of the features include complete implementation of the IEEE 802.11 Distributed Coordination Function (DCF) MAC protocol, wireless network interface modeling the Lucent WaveLAN Direct Sequence Spread Spectrum (DSSS) radio, modeling of signal attenuation, collision, and capture, and two ray ground reflection radio propagation model. Implementations of the mobile ad hoc network routing protocols, AODV [3], DSR [16], TORA [22], and DSDV [23], are also included.

5.1.2 Mobility and Traffic Model

Throughout this thesis, the Random Way Point Model is being used as the mobility model. In the Random Way Point Model, nodes randomly select a destination from a specified simulation field, move towards the destination at a speed uniformly distributed between zero and a maximum speed, and on reaching the destination, stay still for pause amount of time before repeating the whole process.

The following is the simulation parameters used for the verification of HoWL. Each simulation ran for 60 seconds of simulated time with pause time of zero second, meaning nodes were constantly moving. We chose our traffic source to be constant bit rate (CBR). We experimented with sending rate of four packets per second from one source to one destination all through the simulation.

Although we chose Random Way Point Model for verification of CEI, CEI is also effective with other movement models [28].

5.2 Verification of CEI by Simulation

An example of the simulation environments which have the same CEI values, with one being a conference scenario mentioned in Section 4.4, is shown as follows.

1. n: 50 nodes, s: 1 m/s, x,y: 150 m by 90 m, r: 25 m
2. n: 50 nodes, s: 10 m/s, x,y: 1500 m by 900 m, r: 250 m
3. n: 57 nodes, s: 1 m/s, x,y: 123.69 m by 123.69 m, r: 25 m

For each of the same CEI valued environments, 100 trials of route change were conducted, and difference in number of hop counts of routes to the destination before and after a route change occurred, which we refer to as hop variance, was compared.

Hop variances are the key to HoWL since a hop count of the previously used route plus a hop variance is the optimized value for the hop count of limited search area for a route discovery.

The distributions of hop variances are shown in Figure 5.1. It demonstrates that results for the environments which have the same CEI values are similar.

We have also discovered that traffic rate is correlated with LF, such that when moving slower, sending proportionally less traffic will gain similar results. However, time also needs to be changed accordingly to retain same amount of route changes. Thus, we have eliminated this from CEI, and simulation time and traffic rate were kept constant for all simulations.

Similarly, other generally used parameters are thought to be related to one of the three indicators of CEI. For example, pause time of nodes is thought to be related to LF, such that when pause time is long, LF is low, and vice versa.

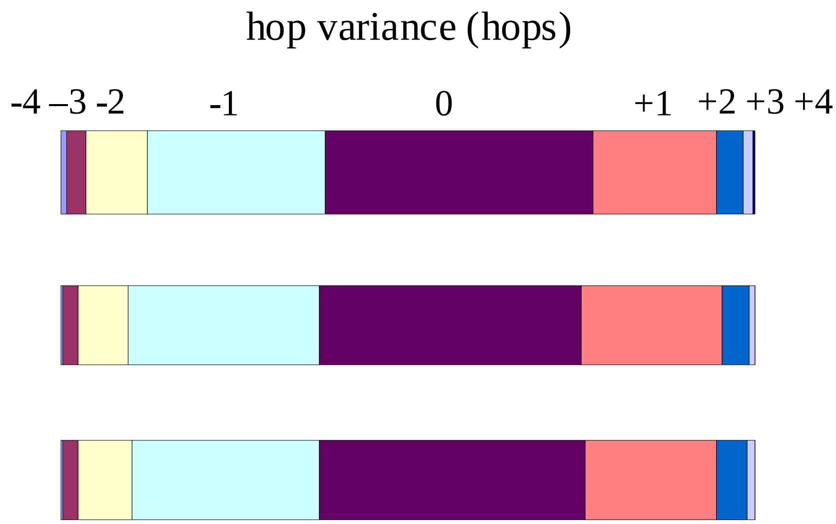

Figure 5.1: Hop variance of the environments with the same CEI values

From the reason mentioned above, we conclude that environments can be **characterized** by the three indicators of CEI, node density, average hop count of routes, and frequency of link failure occurrence. Further analysis of CEI is future work.

5.3 Distribution of Hop Variances

When ND is lower, AH is longer, or LF is higher, hop count of route varies more significantly. An example of distribution of hop variances under different CEI values is shown in Figure5.2. As the figure indicates, the first bar graph, which has lower node density, has higher hop variance than the second bar graph.

From Figure 5.2, the best value for α from Subsection 3.3.2 is expected to be around 1. When α is 0, 1, and 2, the probability that HoWL succeeds, in other words, the destination is within limited search area of route discovery, for the second bar graph is approximately

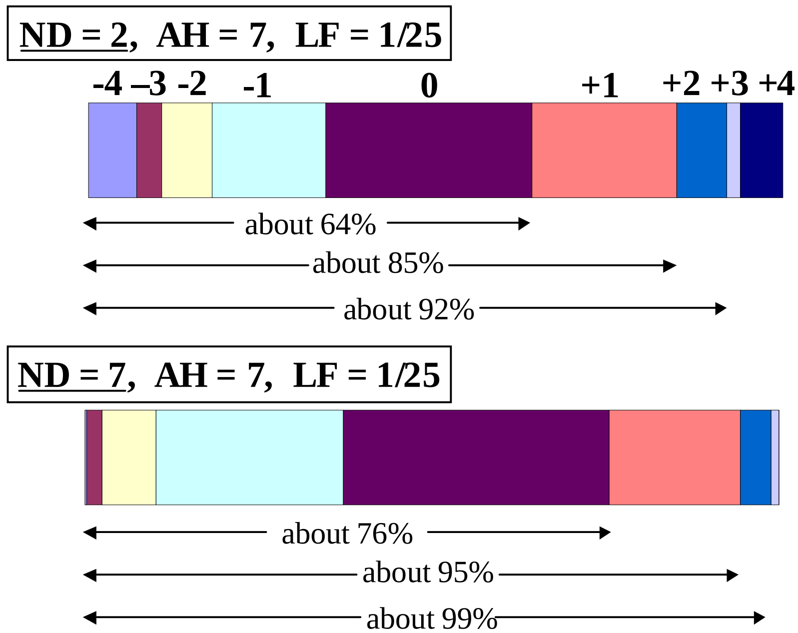

Figure 5.2: Difference in number of hop counts before and after link failure

76, 95, and 99 %, respectively.

5.4 Preliminary Evaluation

In this section, we present some of the results from the preliminary evaluation done on H(α)s.

Based on the analysis presented in Section 5.3, we compare the performance of H(0), H(+1), and H(+2) over vanilla version of DSR.

For performance comparison between HoWL and flooding, we use the following two metrics to verify that the purposes of HoWL stated in Section 3.1 is accomplished.

1. Overhead imposed on the network: we define overhead as the total number of bytes of control packets, namely route request messages and route reply messages.
2. Latency of route discovery: we define latency as the time route request messages are

propagated to the time the last route reply message for that destination is received at the source node.

The simulation environment is the same as described in Section 5.1. We ran 100 simulations for each of the simulation environments and took the average.

In Figures 5.3 – 5.5, the overhead of HoWL against flooding under different ND, AH, and LF values are shown. And Figures 5.8 – 5.13 represent the ratio of the latency of HoWL against flooding when the latency of flooding is regarded as 1. Smaller ND, AH, and LF value indicates lower density, shorter routes, and lower frequency of link failures, respectively. Since large reduction in overhead and small latency mean HoWL is efficient, HoWL is more effective when bar graph is longer for Figures 5.3 – 5.5 and shorter for Figure 5.8 – 5.13. Discussion of the simulation results are presented in the following subsections.

5.4.1 Overhead

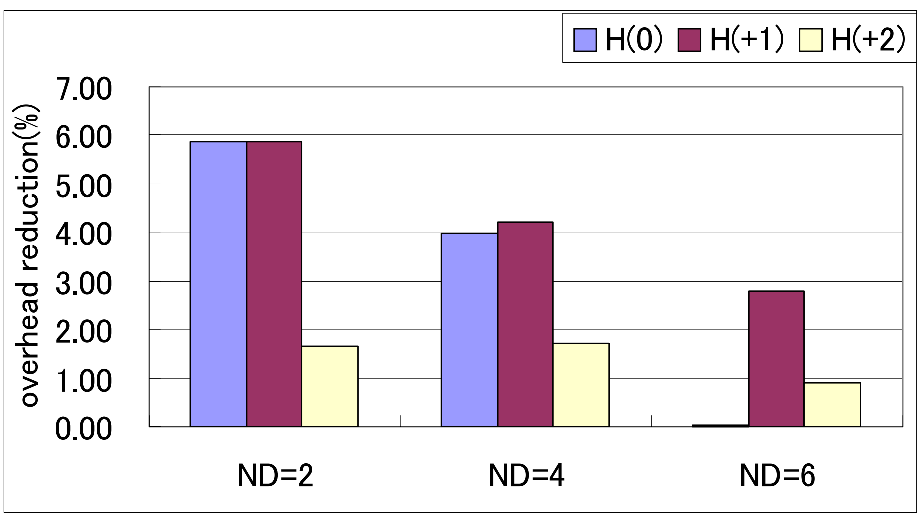

Figure 5.3: Efficiency of HoWL under different ND when AH = 5 and LF = 1/30

First, HoWL enhances its effectiveness when ND is low. This results from the fact that

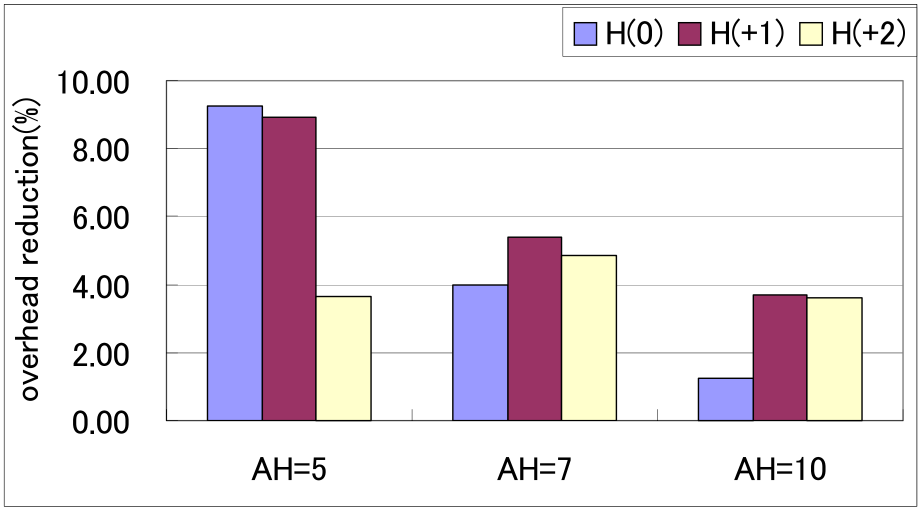

Figure 5.4: Efficiency of HoWL under different AH when ND = 2 and LF = 1/20

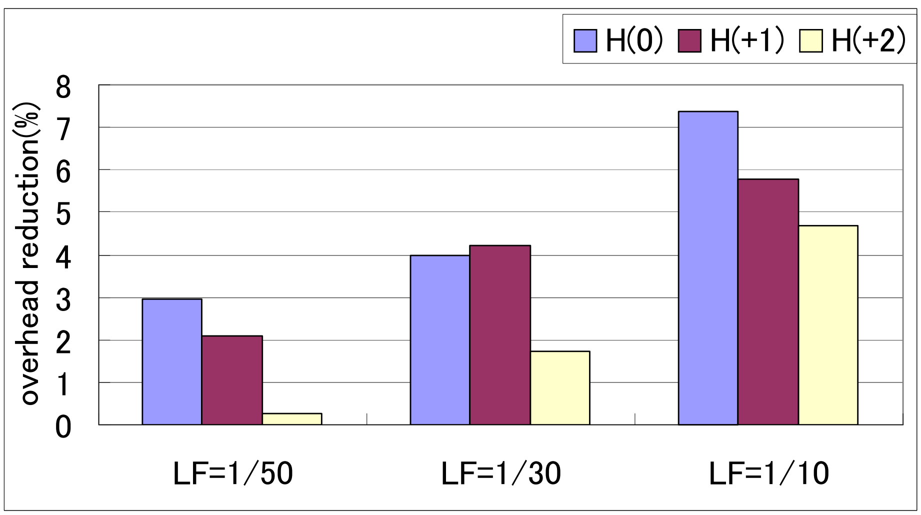

Figure 5.5: Efficiency of HoWL under different LF when ND = 4 and AH = 5

the cost of route request failure increases as the number of nodes which receive route request messages grows. This is demonstrated in Figure 5.3 where difference in overhead of H(0) and H(+1) when ND = 6 is significantly more than when ND = 2 because more overhead is imposed when route request failure occur for higher ND. When ND equals 2, the overhead

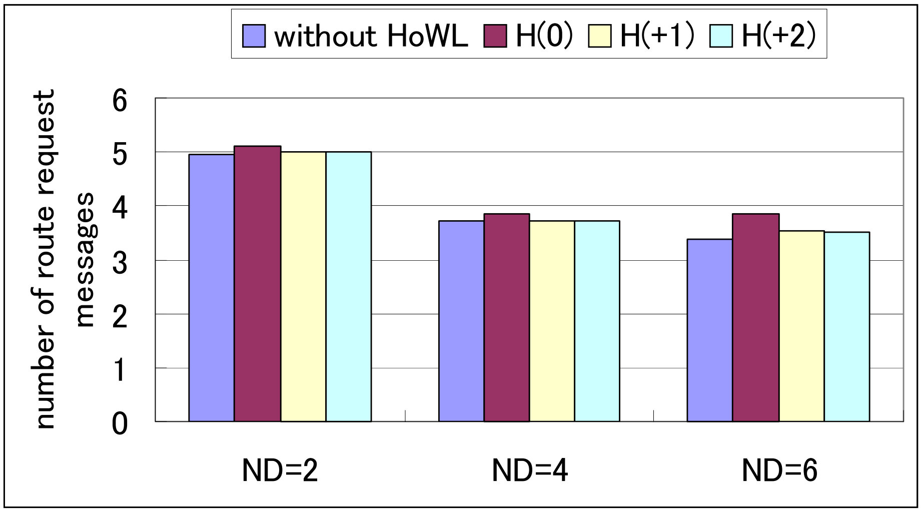

Figure 5.6: Number of route request messages when ND=2

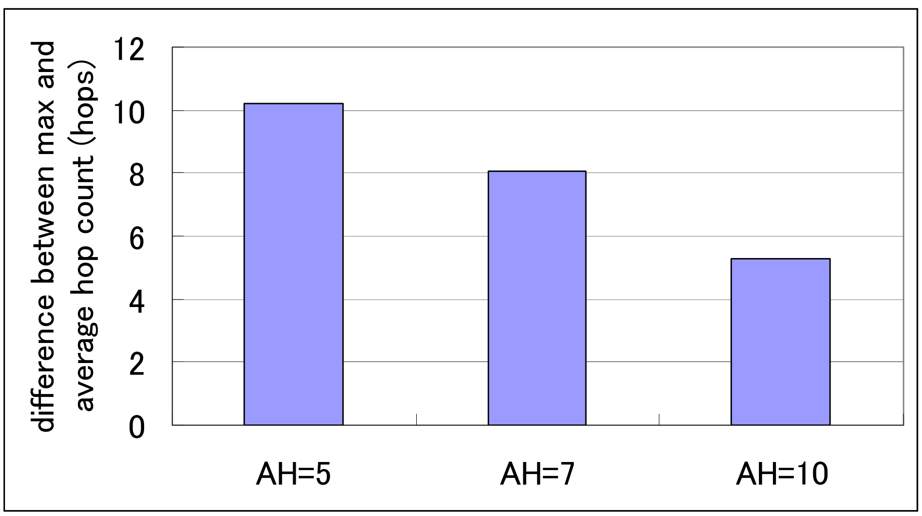

Figure 5.7: Difference between maximum hop count and average hop count of routes

of H(0) and H(+1) are nearly the same. However, from Figure 5.6, since H(0) results in approximately 2 % more route request messages than H(+1) because H(0) has higher probability of searching smaller area than necessarily than H(+1), H(+1) shows the best performance for different node densities.

Next, efficiency of HoWL increases with AH being smaller. This comes from the fact that for different AH values, although average hop counts of routes were different, maximum hop count were 16 which is the limitation of specification of DSR. Figure 5.7 shows the difference between maximum hop count of all routes that were found and average hop count of routes that were actually used. When the difference between maximum hop count and average hop count of routes is large, overhead reduction is high. Additionally, Figure 5.4 demonstrates that when AH is higher, wider search area for route discovery induce more efficiency. The explanation being when average hop count of route is long, search area for route discovery is wide, imposing high overhead when route request failure occur which suggests to utilize wider search area.

Finally, HoWL is more efficient when LF is higher. This is because HoWL has opportunity to show its effectiveness when a link failure occurs.

Thus HoWL exhibits higher performance of up to 10 % reduction in the overhead under environments where ND is lower or AH is shorter, namely when cost of failure of HoWL is not significantly high.

5.4.2 Latency

A latency depends on how limited the search area for route discovery is and a probability of searching smaller area than necessarily which invoke repropagation of route request messages.

First, HoWL is more efficient when more nodes exist such that when ND is higher or AH is higher. The explanation is that the more the node exists, the more the possibility of contention which is caused of neighboring nodes trying to send at the same time. This gives rise to longer latency. The best result in the aspect of latency is shown in Figures 5.9 and 5.11 where up to 13 % reduction was observed. However, this result contradicts with the result demonstrated in Section 6.2. Under lower ND or shorter AH valued environments, up

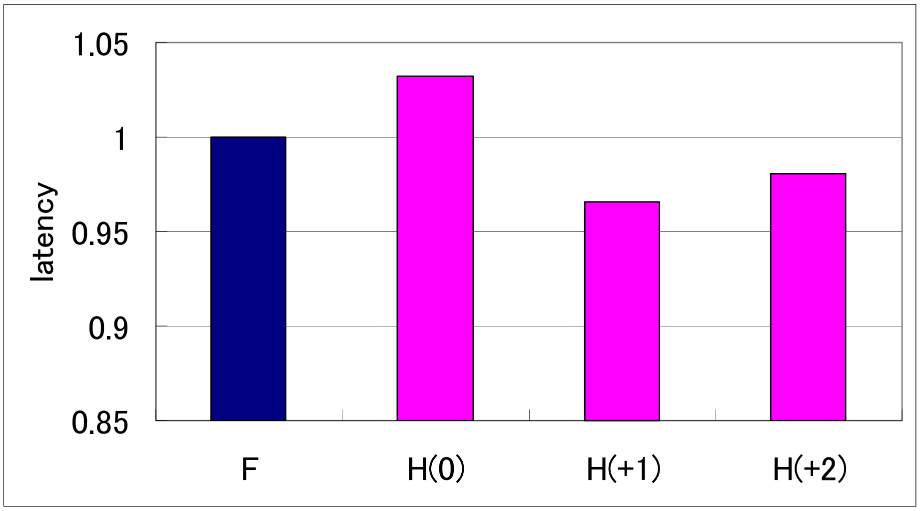

Figure 5.8: Latency of route discovery when ND = 2 (AH = 5, LF = 1/30)

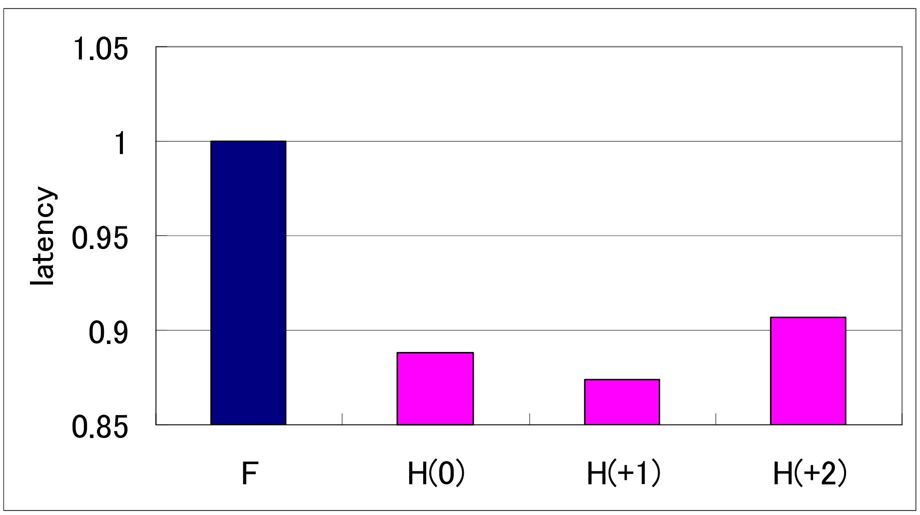

Figure 5.9: Latency of route discovery when ND = 6 (AH = 5, LF = 1/30)

to 5 % reduction in latency was exhibited.

Next, when ND is lower, AH is higher, or LF is higher, H(0) is too limited and tend to consume longer time than flooding. These environments, which are presented in Figures 5.8, 5.10, 5.11, and 5.13, have higher hop variance as stated in Section 5.3. An inefficient H(0)

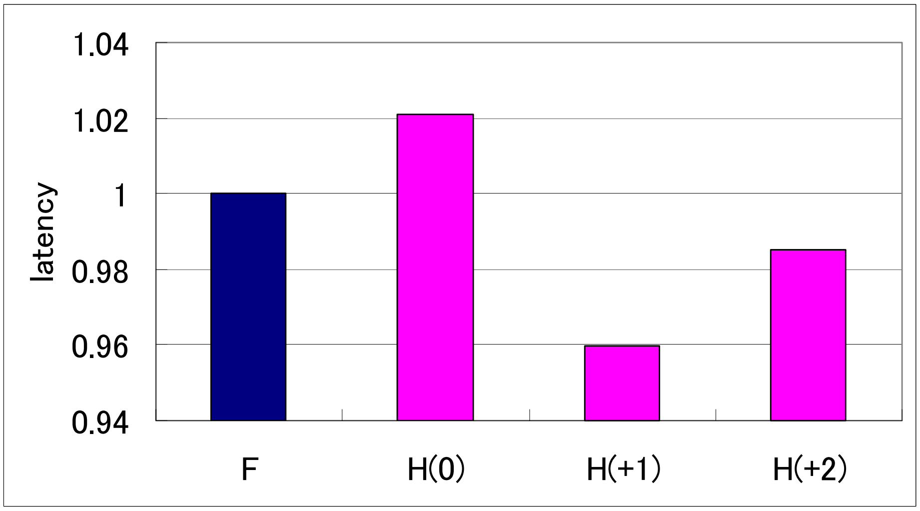

Figure 5.10: Latency of route discovery when AH = 5 (ND = 2, LF = 1/20)

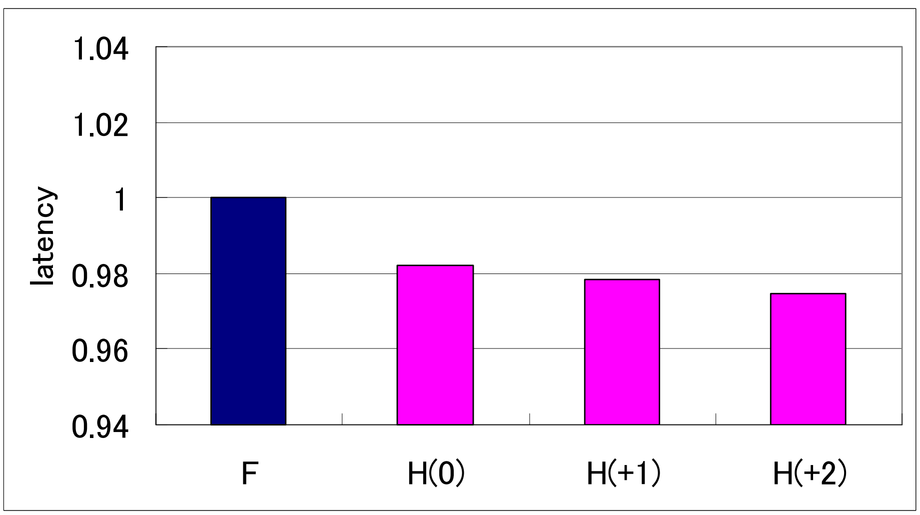

Figure 5.11: Latency of route discovery when AH = 10 (ND = 2, LF = 1/20)

under these environments results from the fact that environments with higher hop variances have a higher probability of the destination not being within the limited search area which invoke repropagation of route request messages.

In Figure 5.9, the search area for route discovery is too limited in H(0) which invoked

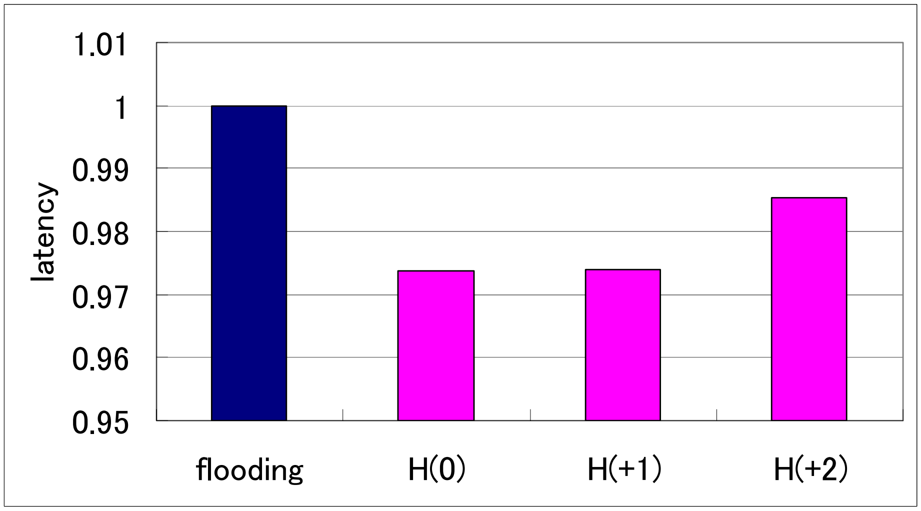

Figure 5.12: Latency of route discovery when LF = 1/50 (ND = 4, AH = 5)

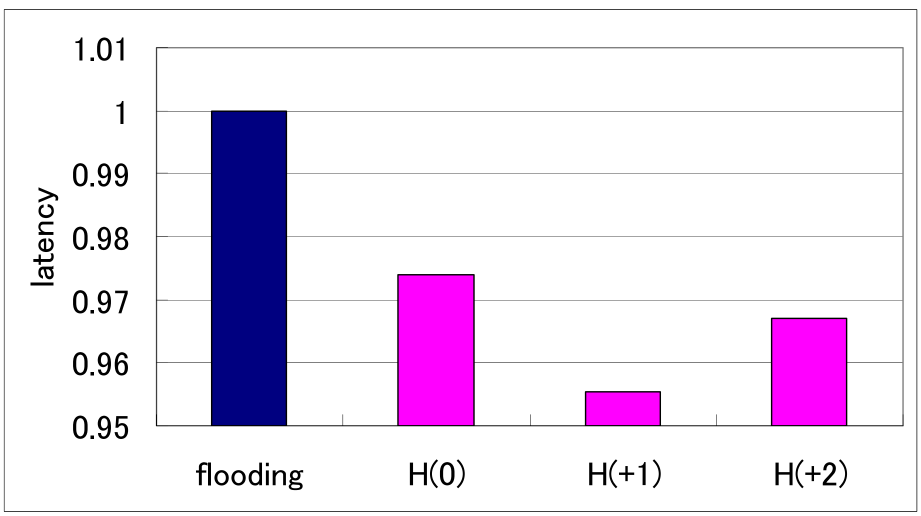

Figure 5.13: Latency of route discovery when LF = 1/10 (ND = 4, AH = 5)

repropagation of route request messages and too wide in H(+2). Thus H(+1) provides the least latency and this accords with the result from Figure 5.3. Similarly, in Figure 5.11, H(+2) provides the least latency and this corresponds with the analysis from Figure 5.4 that when AH is higher, wider search area for route discovery induce more efficiency.

Consequently, HoWL exhibits higher performance of up to 13 % reduction in the latency under environments where ND is higher or AH is longer, namely when more nodes exist.

5.5 Summary

In this chapter, we have verified that CEI is effective under simulation environments through simulations on the ns-2 network simulator. Then, we have shown simulation results to observe hop variance under different CEI values, and decided to use 0, 1, and 2 for constants α by examining the results. Finally, we have exhibited the performance evaluation of H(α)s as the preliminary evaluation.

Simulations have shown that HoWL utilizing merely the previous route is especially effective when node density is low, average hop count of route is short, or frequency of link failure is high where up to 10 % reduction in overhead and approximately 5 % reduction in latency were demonstrated.

Chapter 6

Performance Evaluation

In this chapter, we evaluate the quantitative performance of HoWL over its related work, LAR and expanding ring search, through simulations on the network simulator GloMoSim [6], and we also show the qualitative evaluation.

6.1 Simulation Environment

6.1.1 Comparison of Simulators GloMoSim and ns-2

Table 6.1: Comparison of simulators GloMoSim and ns-2

Simulator	**GloMoSim**	**ns-2**
Radio Model	standard	abstract
Signal Reception	SNRT based, BER based	SNRT based
Radio Frequency	2.4 GHz	914 MHz

The major differences between GloMoSim and ns-2 are shown in Table 6.1.

- Noise (SNR) calculation model

  GloMoSim calculates the power of interference and noise as the sum of all signals on the channel other than the one being received by the radio plus the thermal (receiver) noise. On the other hand, ns-2 calculates pseudo SNR values by treating a signal that has arrived prior to the receiving signal to represent the noise on the channel, which may end up estimating better channel conditions than in GloMoSim.

- Signal reception model

  To determine the probability of successful signal reception for a given frame, ns-2 uses the SNR value directly by comparing it with an SNR threshold (SNRT), and accepts only signals whose SNR values have been above SNRT at any time during the reception. In addition to SNRT based model, GloMoSim supports BER based model, which probabilistically decides whether or not each frame is received successfully based on the frame length and the Bit Error Rate (BER) deduced by SNR and modulation scheme used at the transceiver.

- Radio Frequency

Both GloMoSim and ns-2 radio models are implemented based on the DSSS PHY reference configuration in the IEEE 802.11 standard [10], except that ns-2 (version 2.1b8) used for this thesis set parameters for an old version of WaveLAN whose radio frequency is at 914 MHz, which is currently using 2.4 GHz.

For the reasons mentioned above, we conclude that the implementations of the physical layer and radio model are more realistic in GloMoSim than ns-2. Thus, GloMoSim is being used for the performance comparisons with the related work.

The comparison of the simulators is described in more detail in literature [19].

6.1.2 Mobility and Traffic Model

The Random Way Point Model is used as the mobility model. Each simulation ran for 15 minutes of simulated time with pause time of zero second, meaning nodes were constantly moving. Initial placement of nodes is random. We chose our traffic source to be constant bit rate (CBR). We experimented with sending interval of five seconds between 512-byte packets from one source to one destination throughout the simulation.

6.2 Comparative Targets

- LAR

  In GloMoSim, Location-Aided Routing (LAR) [17] protocol utilizes the exact coordinates in the simulation field as the location information. LAR conducts source routing similar to HoWL. In addition, for the first attempt to discover a route to the destination, flooding is used for the route request, which is also similar to HoWL. From the second time, expected location of the destination node is calculated based on the following equation and the previous location of the destination.

  $radius = velocity * time\_elapsed$

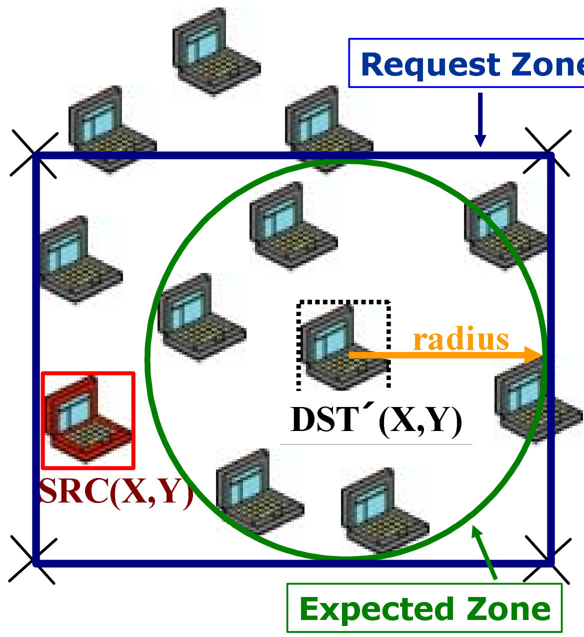

Figure 6.1: LAR

where radius, velocity, and time_elapsed are radius of the expected zone centered at the previous location of the destination, moving speed of the destination, and the time elapsed since the last time route was found, respectively. In LAR, time out of the cache is not executed.

Request zone is determined to include both the source node and the expected zone. Search area of the route is limited within a request zone. Figure 6.1 illustrates the expected zone and the request zone for a source and destination pair, where DST' and SRC are the coordinates of the previous location of the destination and the current location of the source, respectively.

Lastly, backoff interval between route requests is defined as two seconds.

- Expanding Ring Search

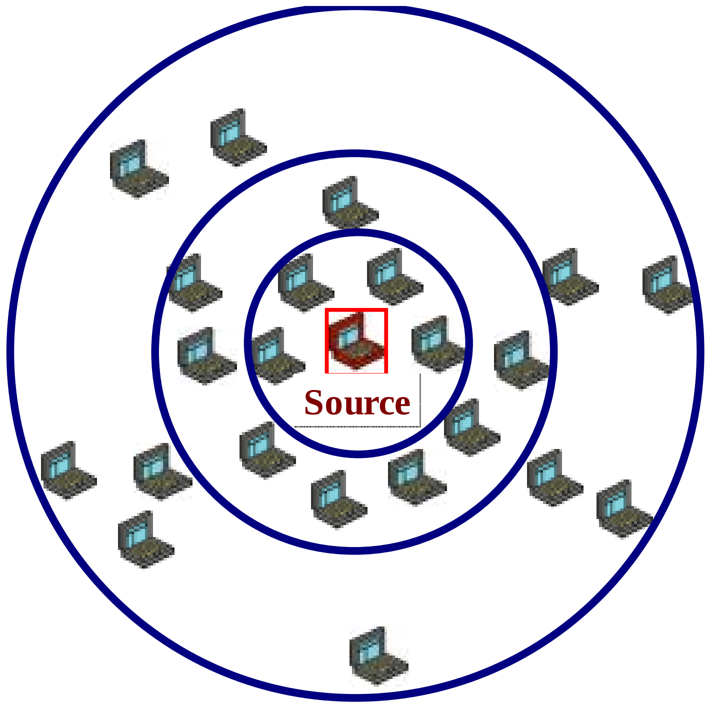

Figure 6.2: Expanding Ring Search

The expanding ring search mechanism is specified in the protocol specifications of DSR [14]. A node using this technique first sends route request messages to only its neighbors, and if no route reply is received, the node keeps doubling the hop limit used on the previous attempt. That is, the search area is gradually expanded from 1, 2, 4, 8, to 16-hops as illustrated in Figure 6.2.

- DSR

In addition to a vanilla version of DSR described in Section 2.2, DSR protocol defines a number of optimizations (e.g., literatures [8], [9], [16]).

In GloMoSim [6], the following optimizations are implemented.

(Promiscuous means a node can gain route information from packets destined to other nodes.)

- Promiscuous learning of source routes
- Discovering shorter routes promiscuously
- All nodes process all of the Route Error messages they receive

  (when the node is the destination of the packet, is the forwarder, or overhears the packet promiscuously)
- Nonpropagating Route Requests

  (This one-hop route request is not implemented in HoWL.)
- Replying from cache at the intermediate nodes
- Gratuitous Route Replies from intermediate nodes
- Salvaging (for data and Route Errors) by intermediate nodes
- Tapping

Furthermore, in contrast to LAR, DSR uses 0.03 seconds for the backoff interval of nonpropagating route requests, and gradually increases backoff interval between route requests from one, two, four, eight to sixteen seconds as a flooded route request fails.

6.3 Quantitative Evaluation

In this section, we exhibit some of the results from the quantitative performance comparison between HoWL and the related work listed in Section 6.2. For the impartial performance comparison between HoWL and LAR, DSR is included in the evaluations to distinguish effectiveness of DSR from the effectiveness of HoWL.

In the following figures and analyses, H(α), H(ave), and RING represent HoWL described in Subsection 3.3.2, HoWL described in Subsection 3.3.3, and expanding ring search, respectively.

For the quantitative comparison, the following two metrics are used to verify that the purposes of HoWL stated in Section 3.1 are accomplished.

1. Overhead imposed on the network

   We define overhead as the total number of bytes of control packets, namely, route request messages and route reply messages.

2. Latency of route discovery

   We define latency as the time route request messages are propagated to the time the last route reply message for that request is received at the source node.

Simulation scenarios expressed by generally used parameters listed in Section 4.3 are shown below:

1. n: 100 nodes, s: 1 m/s, x,y: 1000 m by 1000 m, r: 100 m

   (ND = 1, AH = 10, LF = 1/100)

2. **n: 300 nodes**, s: 1 m/s, x,y: 1000 m by 1000 m, r: 100 m

   (**ND = 3**, AH = 10, LF = 1/100)

3. **n: 25 nodes**, s: 1 m/s, **x,y: 500 m by 500 m**, r: 100 m

   (ND = 1, **AH = 5**, LF = 1/100)

4. n: 100 nodes, **s: 3 m/s**, x,y: 1000 m by 1000 m, r: 100 m

   (ND = 1, AH = 10, **LF = 3/100**)

We ran 100 simulations for each of the simulation environments and took the average.

6.3.1 Overhead

Figures 6.4 – 6.7 show the ratio of the overhead of HoWL against each of the protocols when the overhead of H(0) is regarded as 1, and Figures 6.8 – 6.11 exhibit the results for the same scenarios when HoWL, RING, and DSR does not implement the optimizations listed in Section 6.2. By eliminating optimizations, comparison of HoWL, RING, and LAR is done under same conditions.

In Figure 6.3, meanings for colors of the graphs are explained.

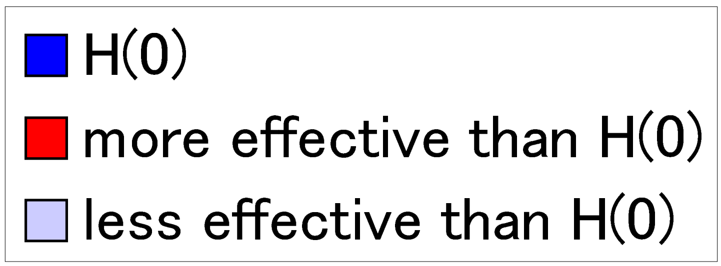

Figure 6.3: Definition for colors of the graphs

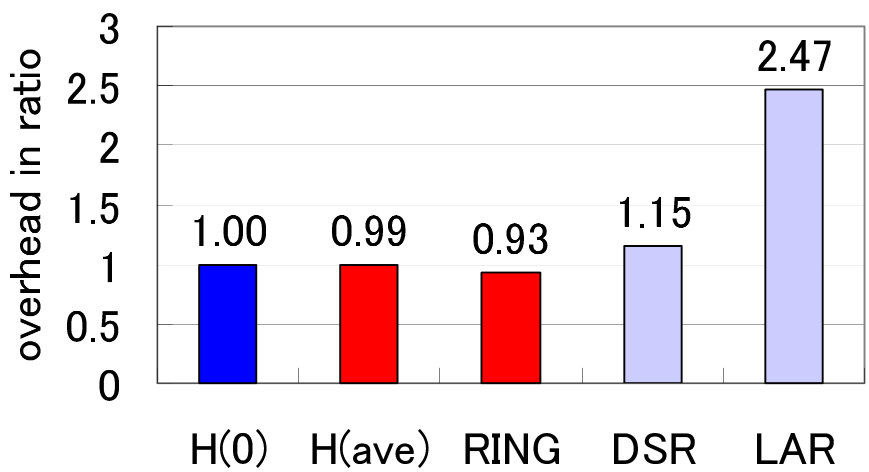

Figure 6.4: Overhead: ND = 1, AH = 10, LF = 1/100

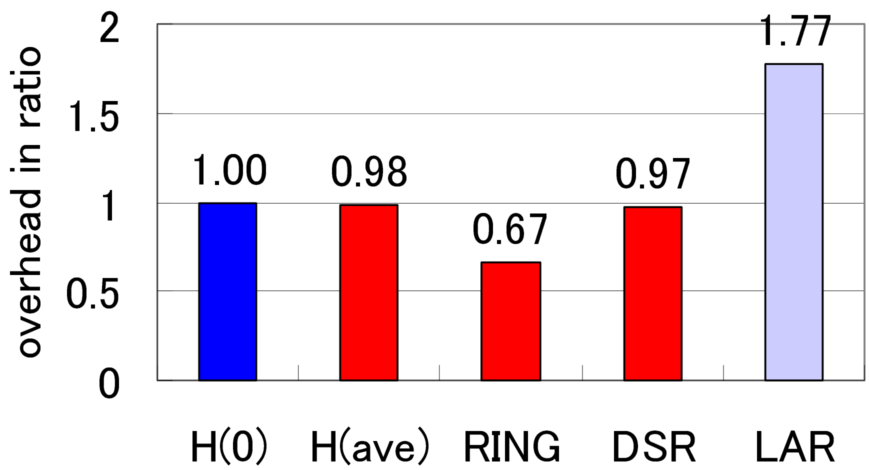

Figure 6.5: Overhead: **ND = 3**, AH = 10, LF = 1/100

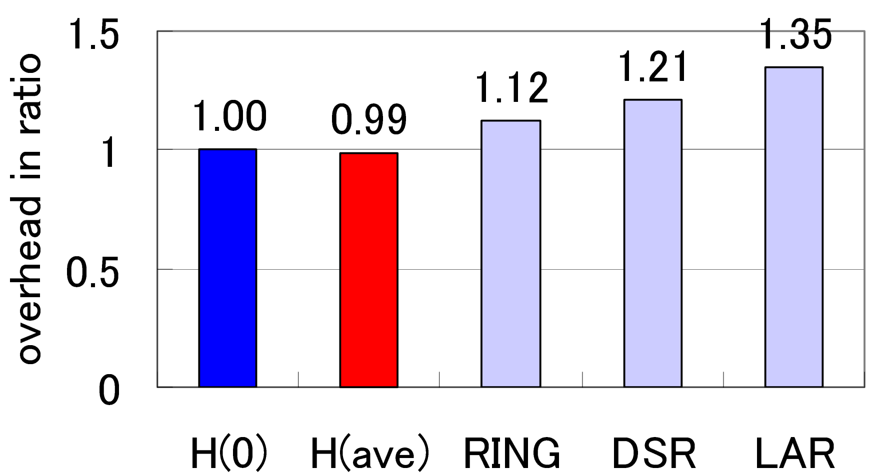

Figure 6.6: Overhead: ND = 1, **AH = 5**, LF = 1/100

With Optimizations:

In Figures 6.4 – 6.7, H(0) and H(ave) are about the same.

RING enhances its effectiveness when route cache of the intermediate nodes are valid.

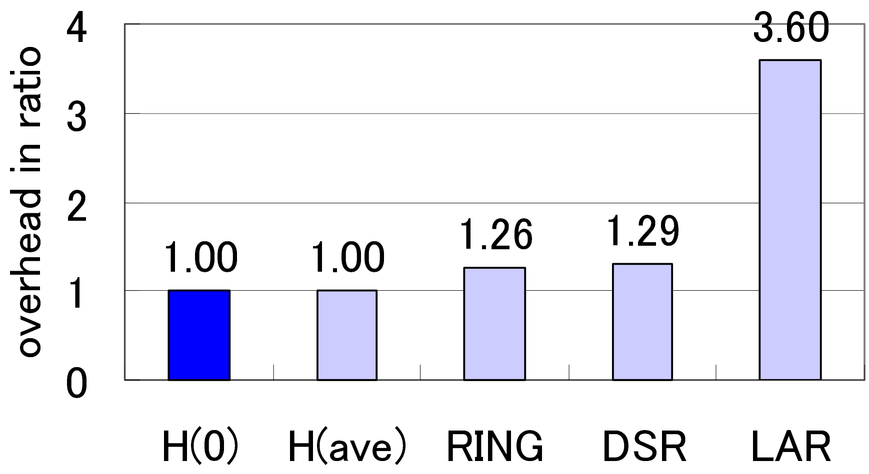

Figure 6.7: Overhead: ND = 1, AH = 10, **LF = 3/100**

This conclusion can be lead from Figures 6.5 and 6.7. In Figure 6.5, efficiency of RING is high since more routes exist when node density is higher. When more routes exist, it is more likely that a route in the cache of intermediate nodes is still valid. And in Figure 6.7, effectiveness of RING is low since when a link failure occurs more frequently, the probability that cache of the intermediate nodes contain a valid route decreases.

The environments in favor of and unfavorable to DSR is same as for RING. However, RING exhibits higher effectiveness than DSR for all four cases.

The effectiveness of HoWL is significantly higher than LAR for all cases.

Without Optimizations:

In Figures 6.8 – 6.11, the efficiency of H(ave) is lower than H(0) when optimizations are eliminated. This result implies that hop count of the previously used route is most important when traffic is constantly sent. In Figure 6.12, overhead comparison is done using the same scenario as Figure 6.11 under discontinuous traffic, where traffic is sent for a minute followed by four minutes interval before sending traffic for a minute again. By making traffic pattern

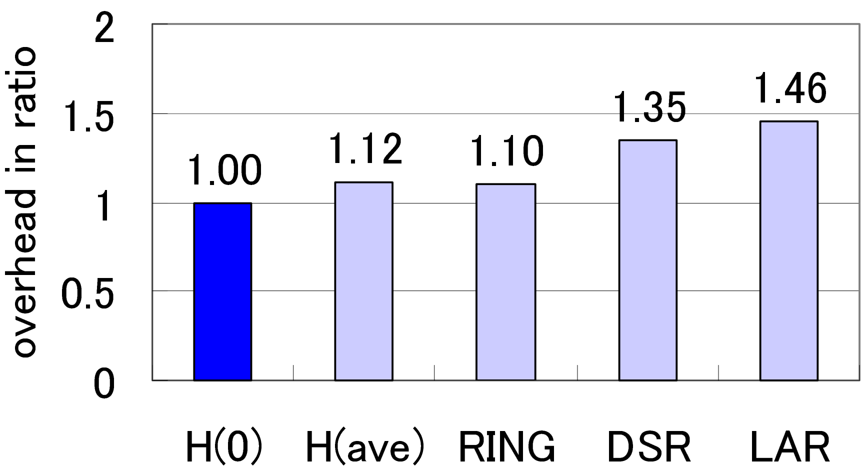

Figure 6.8: Overhead: ND = 1, AH = 10, LF = 1/100 (without optimizations)

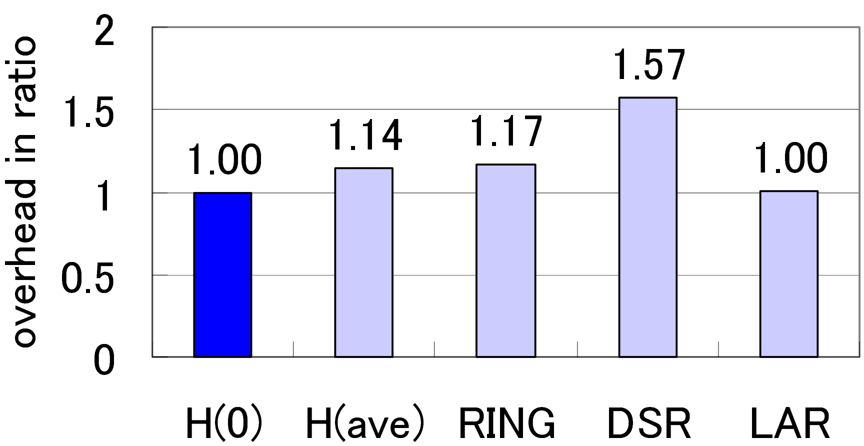

Figure 6.9: Overhead: **ND = 3**, AH = 10, LF = 1/100 (without optimizations)

discontinuous, interval between route requests becomes longer and hop counts vary more. However, utilizing only the hop count of the previous route is still more effective than taking average of the history to predict the current hop count to the destination.

From the fact that the only time RING outperforms HoWL is in Figure 6.10, it can

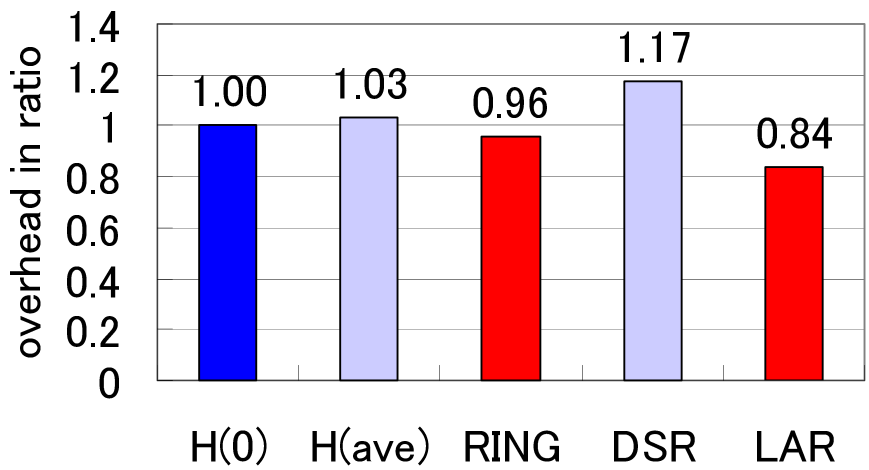

Figure 6.10: Overhead: ND = 1, **AH = 5**, LF = 1/100 (without optimizations)

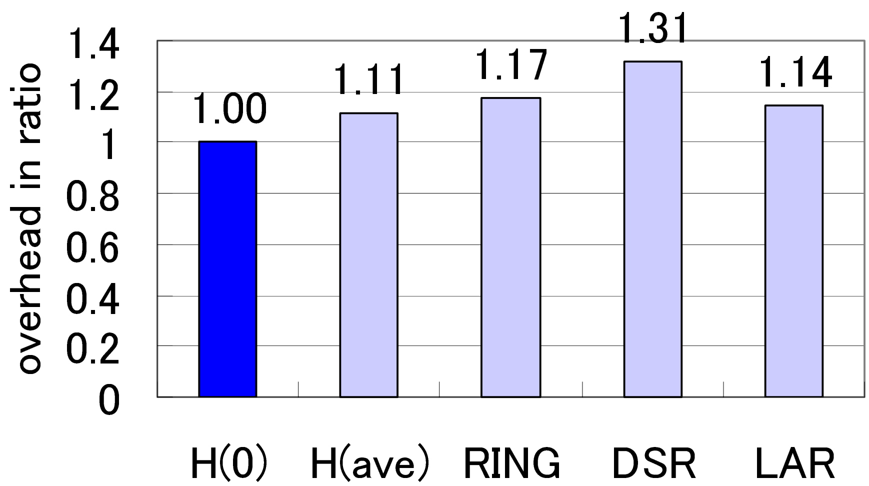

Figure 6.11: Overhead: ND = 1, AH = 10, **LF = 3/100** (without optimizations)

be stated that RING is not suitable for large scale network when cache reply from the intermediate nodes is invalidated. This is because RING conducts up to five limited route requests per each route discovery.

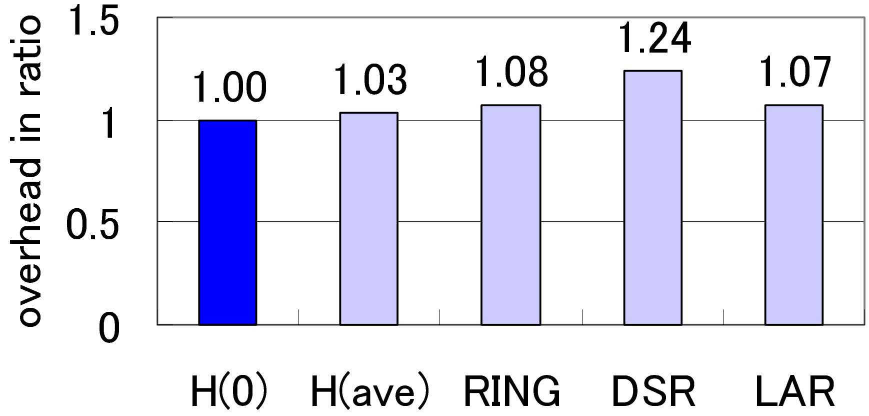

Figure 6.12: Overhead: ND = 1, AH = 10, **LF = 3/100** (without optimizations)
Under Discontinuous Traffic

Similar to comparison with optimizations implemented, RING exhibits higher performance than DSR for all four cases.

Although comparison is done under same conditions, HoWL generally outperforms LAR. The results show that HoWL is more scalable than LAR.

6.3.2 Latency

Figures 6.13 – 6.16 present the ratio of the latency of each protocol when the latency of H(0) is regarded as 1, and in Figures 6.17 – 6.20, the results for the protocols without optimizations are shown.

With Optimizations:

In Figures 6.13 – 6.16, H(0) and H(ave) are about the same. This accords with the result from overhead comparison.

When cache reply from the intermediate nodes succeeds, delay is short. Thus, for the same reason described in Subsection 6.3.1, RING increases its efficiency when node density

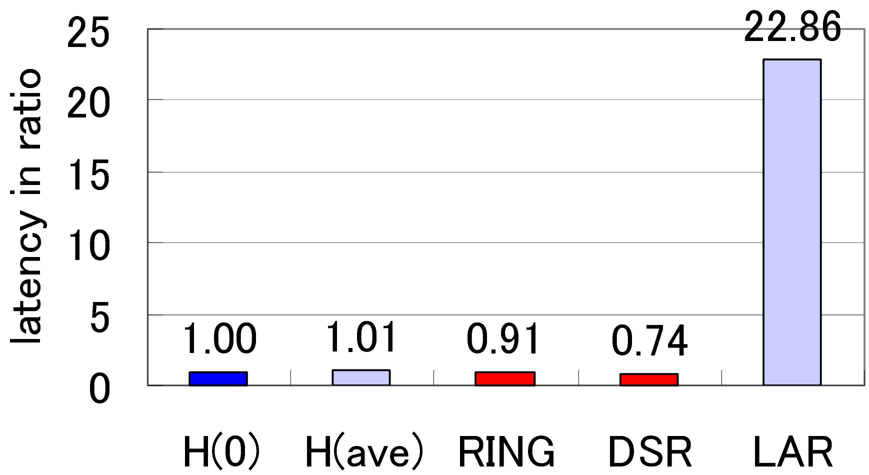

Figure 6.13: Latency: ND = 1, AH = 10, LF = 1/100

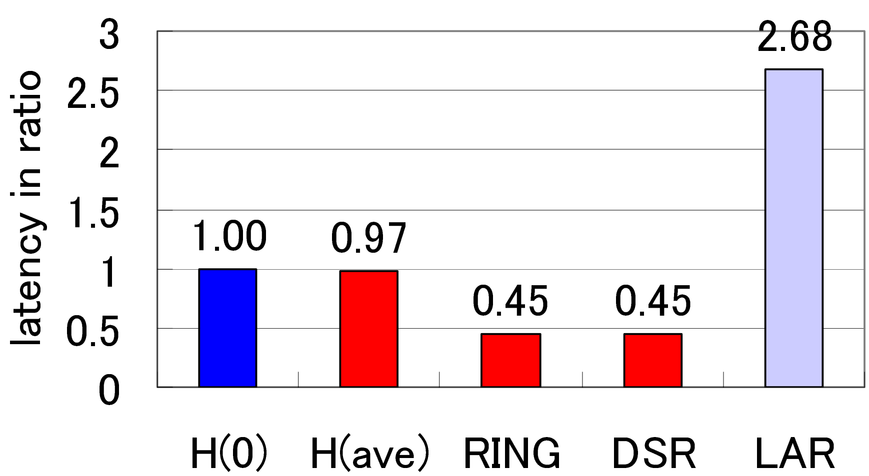

Figure 6.14: Latency: **ND = 3**, AH = 10, LF = 1/100

is high, and decreases its efficiency when link failure rate is high.

Unlike overhead comparison, DSR may exhibit higher performance than RING since latency cumulates when limited route search fails.

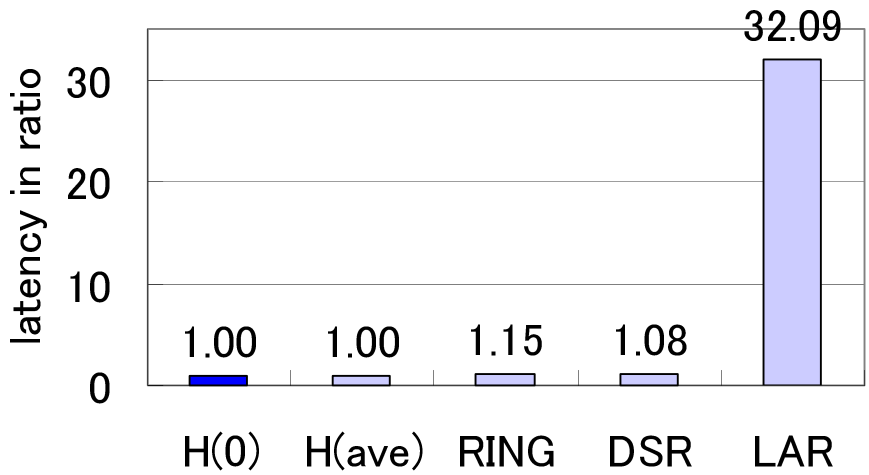

Figure 6.15: Latency: ND = 1, **AH = 5**, LF = 1/100

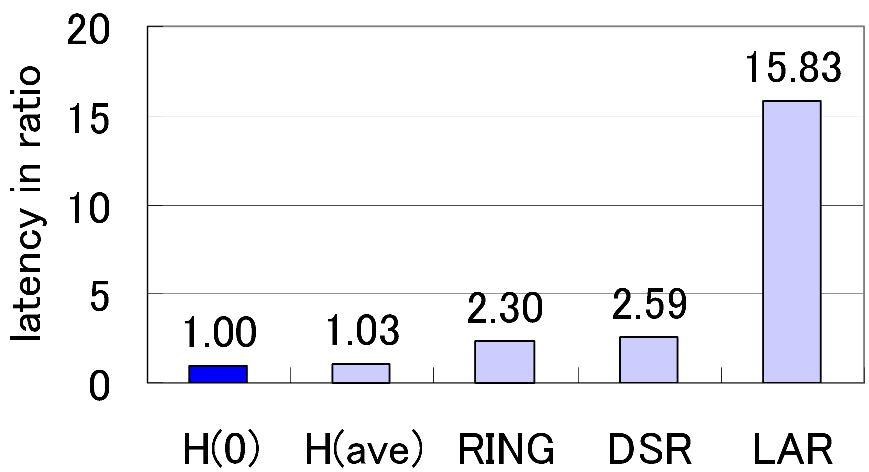

Figure 6.16: Latency: ND = 1, AH = 10, **LF = 3/100**

Latency for LAR is significantly high for all four cases of up to 32 times longer latency than HoWL. The explanation for this result is that LAR uses constant two seconds backoff interval between route requests, whereas DSR gradually increases backoff interval from 0.03

seconds to 16 seconds as described in Section 6.2. Thus, DSR starts with shorter backoff interval and ends up limiting more route requests than LAR. This technique is especially more effective than using constant value for backoff interval when hop count to the destination is small or when a route to the destination does not exist. For example, this tendency is especially strong in Figure 6.15 since shorter backoff interval is more effective under small scale networks.

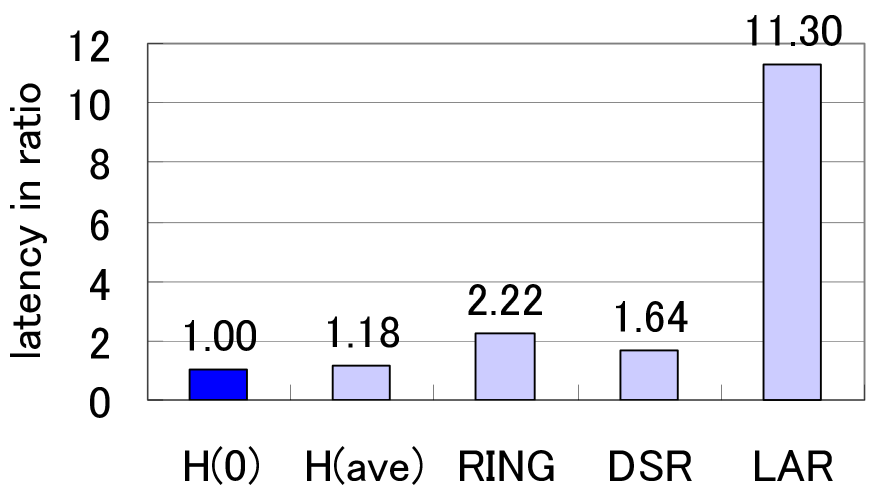

Figure 6.17: Latency: ND = 1, AH = 10, LF = 1/100 (without optimizations)

Without Optimizations:

In Figures 6.17 – 6.20, the efficiency of H(ave) is lower than H(0) when optimizations are eliminated. This result corresponds with the analysis in overhead aspect, and implies that hop count of the previously used route is most important for predicting the current hop count to the destination.

For RING, the performance in aspect of latency degrades significantly when optimizations are eliminated. This result supports our conclusion that this scheme depends on the route cache of the intermediate nodes.

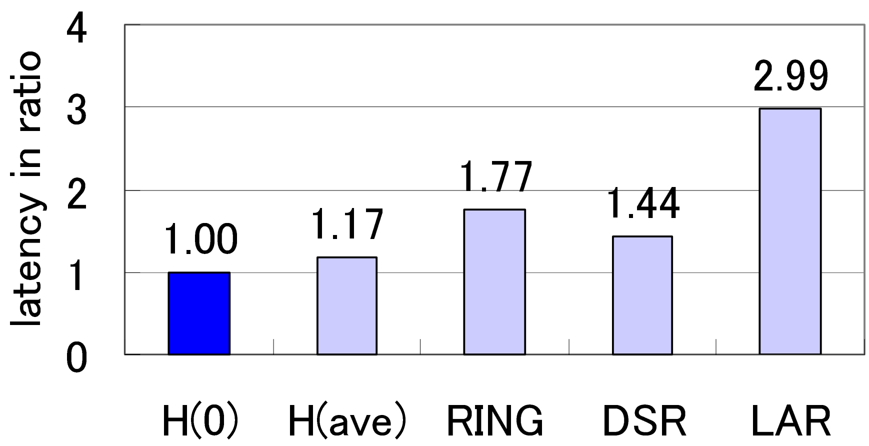

Figure 6.18: Latency: **ND = 3**, AH = 10, LF = 1/100 (without optimizations)

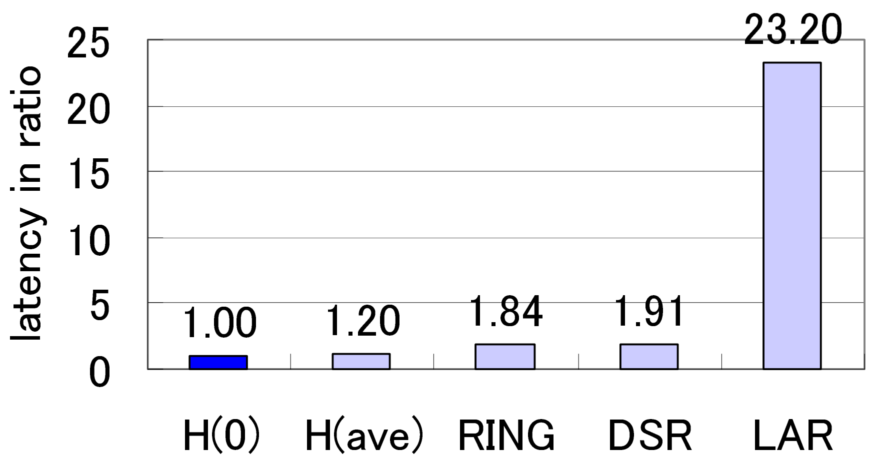

Figure 6.19: Latency: ND = 1, **AH = 5**, LF = 1/100 (without optimizations)

DSR generally shows shorter latency than RING when cache reply can not be utilized.

Although compared under same conditions, latency for LAR is still significantly high for all four cases. From this result, it can be concluded that backoff interval between route requests must be gradually increased when a route request fails.

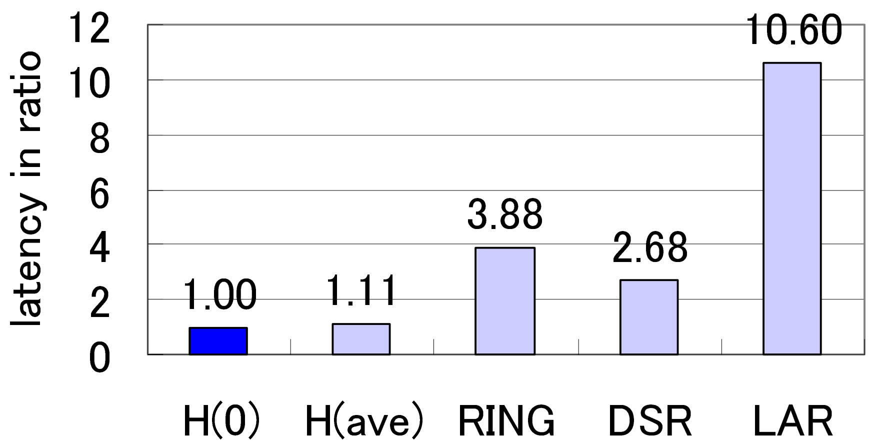

Figure 6.20: Latency: ND = 1, AH = 10, **LF = 3/100** (without optimizations)

6.3.3 Discussion

The conclusions derived from quantitative evaluations are listed below.

- Performance of a limited route search is significantly improved when cache reply from intermediate nodes is implemented.
- HoWL deals well with high mobility compared to related work.
- Significance of calculating weighted average of hop history for predicting the current hop count to the destination depends on the traffic pattern.
- RING depends on route validity of the cache of the intermediate nodes.
- RING exhibits high performance under high density and low mobility environments.
- Overall, DSR should implement RING.
- HoWL is more scalable than LAR.
- LAR can improve its performance by implementing similar optimizations done to DSR. However, results from performance comparison without optimizations imply that

HoWL will still outperform LAR.

- Backoff interval between route requests should be increased when a route request fails.

6.4 Qualitative Evaluation

This section shows some of the results from the qualitative performance comparison between HoWL and the related work listed in Section 6.2.

For the performance comparison between HoWL and its related work, we use the following three metrics to verify that the goals of HoWL stated in Section 3.1 are accomplished. Qualitative comparison is summarized in Table 6.2.

Table 6.2: Qualitative comparison

Protocol	HoWL(α)	HoWL(ave)	RING	DSR	LAR
Cost	○	○	○	○	×
Simplicity	○	○	○	○	×
Generality	○	○	○	△	×

- Cost

  Cost of LAR is high since LAR needs GPS which is not readily available.

- Simplicity

  LAR sacrifices simplicity by requiring information about average moving speed of other nodes which can not be acquired locally.

- Generality

  From results exhibited in Section 6.3, the advantageous environments for HoWL and RING differ. RING exhibits high effectiveness when node density is high and mobility is low. In contrast, HoWL copes with high mobility and low density better than RING and LAR.

DSR generally shows lower performance compared to RING.

And lastly, HoWL is generally considerably more effective than LAR even without optimizations implemented.

6.5 Summary

In this chapter, we have evaluated the quantitative performance of HoWL over its related work, LAR and RING, through simulations on the network simulator GloMoSim, and we have also exhibited the qualitative evaluation.

The results from quantitative and qualitative comparisons have shown that the environments in favor of HoWL and expanding ring search differ. Namely, HoWL has the highest effectiveness when mobility is high, and under high density and low mobility environments, expanding ring search exhibits higher efficiency.

LAR can improve its performance by implementing similar optimizations done to DSR, though based on simulation results, HoWL will still be more effective both in quantitative and qualitative aspects.

Chapter 7

Conclusion and Future Work

We conclude this thesis by summarizing our contributions and stating future directions for our work.

7.1 Summary

In this thesis, we have proposed an efficient route discovery scheme for mobile ad hoc networks called HoWL. HoWL executes an efficient route discovery by predicting current location of destination utilizing hop count of previously used routes.

Furthermore, we have introduced CEI that characterizes uniform real world environments for networks of mobile nodes. Namely, by node density, average hop count of utilized routes, and frequency of link failure. Then, we have verified that CEI is also applicable to simulation environments.

We have implemented HoWL as an extension to DSR on network simulator GloMoSim to conduct quantitative evaluation. From the results derived from quantitative and qualitative comparisons between HoWL and its related work, the environments in favor of HoWL and expanding ring search differ. Specifically, HoWL shows high effectiveness when mobility is high, and under high density and low mobility environments, expanding ring search exhibits high performance. LAR can improve its performance by implementing similar optimizations done to DSR, though based on simulation results, HoWL will still be more effective both in quantitative and qualitative aspects.

7.2 Future Work

Some of our future work include performance comparison with a table-driven protocol which uses network-wide broadcasts as a means to discover a route, such as OLSR.

In addition, we intend to find algorithm that acquires the optimized value for the hop count of limited search area. The algorithms taken into consideration are as follows. Firstly, to utilize estimated relative speed of a source-destination pair, calculated by dividing the hop variance by the elapsed time between time of a link failure and the time of next route discovery. Secondly, continually compare the calculated hop count of limited search area with the actual hop count of the found routes to refine the algorithm dynamically.

We also plan to investigate further optimization where link level broadcasts are avoided. For example, introduce hierarchical structure where only selected nodes within a limited search area receive route request messages in order to abandon link level broadcast altogether, and consider advantage in performance against disadvantage in computational cost.

Furthermore, additional performance evaluation under different traffic patterns and different mobility models is needed.

Further analysis of CEI is also future work.

Moreover, we aim to list possible applications for HoWL. For example, HoWL can be applied to car networks when information from only nearby cars are needed, or when information aggregation is done within localized area in sensor networks.

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Mika Minematsu

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Published Papers Related to this Thesis

- Mika Minematsu, Masato Saito, Hiroto Aida, Yoshito Tobe, and Hideyuki Tokuda
  "HoWL: An Efficient Route Discovery Scheme Using Routing History in Ad Hoc Networks, "
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