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A Link Heterogeneity-Aware On-demand Routing (LHAOR) Protocol Utilizing Local Update and RSSI Information

Suhua TANG†∗, ***Nonmember***, **Bing ZHANG**†, **Masahiro WATANABE**†, ***and*** **Shinsuke TANAKA**†, ***Members**

SUMMARY Many routing protocols have been proposed for mobile ad hoc networks. Among these protocols, the on-demand routing protocols are very attractive because they have low routing overhead. However, few of the existing on-demand routing protocols have considered the link heterogeneity, such as the different communication rate, different Packet Error Ratio (PER). As a result, the routes tend to have the shortest hop count and contain weak links, which usually provide low performance and are susceptible to breaks in the presence of mobility. In this paper, we analyze the existing on-demand routing protocols and propose a Link Heterogeneity Aware On-demand Routing (LHAOR) protocol, where the link quality and mobility are considered. Specifically, the Local Update (LU) is proposed and the link metric is inversely related with the Received Signal Strength Indicator (RSSI). By using the LU method and RSSI information, the routes adapt to the topology variation and link quality changes, and reach the local optimum quickly, which contains strong links and has a small metric. Simulation and experiment results show that our LHAOR protocol achieves much higher performance than the classical on-demand routing protocols.
key words: *ad hoc networks, link heterogeneity, on-demand, mobility, RSSI*

1. Introduction

Recent years have seen extensive interest in the mobile ad hoc networks [1] for which many routing protocols have been proposed. Based on the route discovery method, they can be mainly classified into proactive and on-demand routing protocols. The proactive routing protocols [2], [3] build a globally optimal route for each destination in the routing table ahead of the communication, and adapt to the topology variations. However, their routing overhead is also high, which causes trouble for the narrow-banded wireless networks. In the on-demand routing protocols [4]–[7], a route is discovered when needed. The routing overhead is low, though the routes can not adapt to the topology variations.

In the mobile ad hoc networks, due to different distances and various propagation paths, the virtual links may have different quality—Signal to Noise Ratio (SNR). Despite the massive research on the routing protocols, most of them adopt hop count as the metric, neglecting the quality differences among the links. In consequence, the route tends to have a short hop count and contain weak links, which provide low communication rate and high PER. Because of the low rate, weak links become the bottleneck of the routes; high PER causes retransmissions, wasting much bandwidth [8]; and the throughput of the whole network is affected [9]. The complex wireless environment often makes things worse. When the line-of-sight (LOS) path does not exist and the RSSI changes greatly due to the multipath fading and mobility, the topology and link quality vary frequently. Thus the on-demand routing protocols have the extra challenge—adapt to the topology variation.

In this paper, we propose the Link Heterogeneity Aware On-demand Routing (LHAOR) protocol. The Route REQuest (RREQ) and Route REPly (RREP) packets determine the initial RSSI; the hello packet is used to detect the link connectivity and collect the RSSI in the communication; the link metric is inversely related with the link RSSI. The initial route is discovered on demand; its information is locally updated during the communication; then the initial route gradually converges to the local optimum, containing strong links and having a small metric. In the same way, the route tracks the variation of link quality and topology. Compared with the existing on-demand routing protocols, LHAOR improves the throughput of the whole network and prolongs the route lifetime. The LU method and relating metric with RSSI can also be applied to other on-demand routing protocols.

Although the signal strength is no longer isotropic due to the different propagation path [10], the links are still nearly symmetric when the same transmitting power is used. With the nearly link symmetry as the only assumption, LHAOR is suitable for the application such as Intelligent Transportation Systems (ITS) where the power is not a concern, but the throughput and the mobility are the main considerations.

The rest of the paper is organized as follows: Section 2 introduces the related work. Section 3 proposes the LHAOR protocol. Section 4 describes the prop-

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†ATR Adaptive Communications Research Laboratories, 2-2-2 Hikaridai "Keihanna Science City" Kyoto 619-0288 Japan
∗E-mail: shtang@atr.jp

erty of LHAOR. Section 5 presents the simulation and experiment results, and gives a performance analysis. Finally Section 6 concludes the paper.

2. Related Work

In the on-demand routing protocols, when the source node tries to communicate with the destination node and there is no route available, a new route is discovered. The route discoveries have different characteristics in different protocols. Johnson et al. proposed DSR in [4] where the source routing is used. Perkins et al. adopted the destination sequence number to avoid loops in AODV [5], and introduced expanding ring search and local repair to control the overhead. Toh reported ABR in [6], where each node calculates the associativity of its neighbors by the periodic beacons. During the route discovery, the destination node waits and collects multiple routes, among which the one with the highest associativity is selected. Dube et al. proposed SSA [7], where the signal stability is used in the route discovery. When a route is being searched, each intermediate node usually forwards a route search packet only when it is fresh and is received over a strong channel. If the route discovery times out, the source node may start a normal route discovery process, where the weak links are also acceptable.

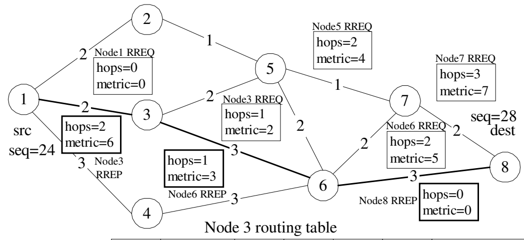
Several schemes have been proposed to control the routing overhead. In OLSR [2], each node chooses from its symmetric immediate neighbors a set of relay nodes, through which the broadcasted packets can reach all its two hop neighbors. The similar idea is reported for the localized minimum energy broadcasting [11] and the power adaptive broadcasting [12], where each node classifies its immediate neighbors as the nearby or far neighbors; the transmitting power is controlled so that the broadcasted packets only arrive at the nearby neighbors, which further forward the packets to the far neighbors. The scheme is generally not suitable for on-demand routing protocols. Expanding ring search is adopted in AODV, where the searching radius is gradually increased in the route discovery. When a link breaks due to mobility, some of the routing protocols, such as ABR and AODV, adopt local repair [13] to maintain the route, where the upstream node of the broken link discovers a new route in a restricted area with a radius nearly equalling the historical hop count. When the broken link is multi hops away from the destination node, the local repair may not be efficient. In the source routing protocols, each node may overhear the source route, and build the link cache [14]. When a node tries to communicate with another node, if the destination is reachable through the cached links, the route discovery can be avoided. Doshi et al. adopted the similar idea in the minimum energy on-demand routing protocol [15], where each node overhears the source route, and notifies the source node in case that a route with less energy consumption is available. However, it requires that each data packet carry the source route, and the MAC firmware needs modification.

A few routing protocols have considered the link heterogeneity, where the good links usually are preferred during routing calculation, by relating the link metric with the link quality. Awerbuch et al. reported the medium time metric (MTM) [16], where all the nodes are supposed to lie in the same interference range and the average transmission time is related with the metric. The links with a high rate usually take a short time to transmit packets and have short metrics. Thus they are preferred. De Couto et al. proposed the expected transmission count (ETX) [17] and the link metric is inversely proportional to the forward link delivery ratio and reverse link delivery ratio. Both of the routing metrics are proposed for the proactive routing protocols and simulated with DSDV [3]. ABR and SSA considered link quality in the route discovery stage. Though the first discovered routes may be stable or contain strong links, they can not avoid the link breaks due to the mobility in the communication.

Compared with ABR where the destination node waits for multiple routes and SSA where two times of discovery may be necessary, which increases the initial delay, in LHAOR, the first arriving RREQ packet determines the route, so the route discovery latency is minimized. By relating the link metric with RSSI and adopting the LU method, the route converges to the local optimum in the static case and tracks link quality and topology variation in the presence of mobility. Local overhead control in LHAOR is partially similar to that in [11], [12], but LHAOR is an on-demand routing protocol and only the active route is locally maintained. Furthermore, MTM and ETX are routing metrics combinable with our LU method. Part of LHAOR makes use of the local optimization idea similar to the minimum energy routing protocol [15], but with two significant differences: LHAOR does not rely on the source routing, and it is compatible with the MAC firmware.

3. Our Proposed Scheme: LHAOR Protocol

In LHAOR protocol, the RREQ, RREP and hello packets are used to collect the RSSI information; and the RSSI is inversely mapped to the link metric. When the initial route is used for forwarding packets (call the forward route FR), the FR information is locally updated by the nodes on the FR. In this way, the immediate neighbors of the FR can build alternative routes (AR), and take part in the route maintenance for the FR. The first arriving RREQ determines the initial route which may contain weak links and has a big metric, by LU, it can gradually converge to the local optimum, which contains strong links and has a small metric. The route also tracks topology variation due to mobility. Thus the route breaks can be reduced.



Node 3 routing table

	dest	dest_seq	next	hops	metric	flag	update_time
Reverse Route (Built by RREQ)	1	24	1	1	2	AR	0
Forward Route (Built by RREP)	8	28	6	2	6	AR	0

Fig. 1 Initial route discovery process.

3.1 Relating the Link Metric with the RSSI

For the purpose of strong links selection, we adopt the discrete metric and use a convenient way to map the link quality to the metric. Usually SNR stands for the link quality. In the case of stationary background noise, the RSSI is proportional to the SNR, so we adopt the RSSI. The RSSI is divided into several non-overlapping ranges, each mapping to one metric with the big RSSI corresponding to a small metric.

At the route discovery stage, the RREQ packet and RREP packet are monitored and the initial RSSI is obtained and mapped to the initial link metric. Later during the communication, the hello packet is sent periodically, which also contains the FR information. On receiving the hello packet, the receiver gets the time-variant RSSI, maps it to the link metric, and also updates the route metric. Moving Average (MA) and other mechanisms are used to make the link RSSI and the link metric relatively stable, as is discussed later.

3.2 Route Discovery

In LHAOR, the hop count and RSSI related metric are different. During the route discovery, both the accumulated hop count and the accumulated link metric are carried in the RREQ and RREP packets. The accumulated link metric is used as the routing metric and the hop count is used for expanding ring search and avoiding loops.

The route discovery process is explained by an example shown in Fig. 1. When node 1 tries to communicate with node 8 and there is no route available, node 1 locally broadcasts the RREQ packet, with the metric and hop count cleared to zero. When an intermediate node—node 3—receives the RREQ and determines it to be fresh, it updates the RREQ packet, adds the link metric 2 (obtained from the link RSSI) to the accumulated metric, increases the hop count by 1, builds the reverse route to node 1, and continues locally broadcasting the RREQ. Node 6 does the same way as node 3. When node 8 receives the RREQ, it adjusts the metric and hop count, builds the route to node 1, with node 6 as the next hop and the metric (8) and hop count (3) taken from the RREQ. Because node 8 is the destination, it also sends an RREP to node 1, with the metric and hop count cleared to zero. The RREP first arrives at node 6. Node 6 adjust the metric to 3 and hop count to 1, builds the forward route to node 8, and sends the RREP to node 3. Node 3 does the same way as node 6. Finally node 1 gets the RREP and builds the forward route to node 8, with node 3 as the next hop and the metric (8) and hop count (3) taken from the RREP. Then the communication starts.

3.3 LU in LHAOR

The route update procedure is similar to that in DSDV, but with a significant difference: in LHAOR protocol, the route update is made local, only around the FR, by distinguishing FR from AR. An FR contains the flag RT_FORWARD while an AR's RT_FORWARD flag is cleared. The initial route is discovered on demand and built as an AR. When the AR is used to forward the data packet, its RT_FORWARD flag is set; it becomes an FR. Then the nodes on the FR start to send the hello packet periodically. The format of hello packet is shown in Fig.3. It consists of two parts: the first part is the same hello message as in AODV, and the second part contains route update entries taken from the routing table shown in Fig. 1. Each route update entry contains all the necessary information, especially the route flags. The neighboring nodes may join the route maintenance on receiving the route update message.

The route update entry processing procedure is shown in Fig. 2 for a single route entry. When a node receives a route update entry from the sender, it constructs a new temporary route entry with destination dest, destination sequence number dest_seq, next hop nnext, hop count nhcnt and metric nmetric, and follows the procedures:

(1) If there is no route in the table for the destination, and the RT_FORWARD in the flags is set, the receiver adds the newly constructed route to the table as an AR, whose RT_FORWARD flag is cleared. It then starts to broadcast the hello packet periodically with its route entries appended. Its neighbors on the FR may update their route entry while its other neighbors that are two hops away from the FR will not build AR in the table, and will not take part in the route maintenance. In this way, the route update is made local in the space, just around the FR.

(2) If the route for the destination already exists and the new route has the same next hop, the route is updated.

(3) If the new route has a different next hop, and its destination sequence number is fresher, or its metric is smaller than that of the current route, it becomes the new FR.

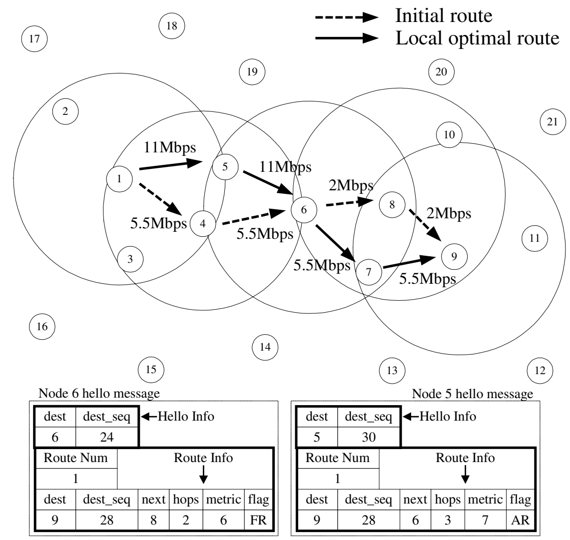
Each route entry has a state update_time to de-

```
for each route entry appended in the hello packet, perform the
following operation:
get route information: dest, dest_seq, next, metric, hcnt, flags
get link_metric for the link to the sender of the hello packet
nnext = sender of the hello packet; //new next hop
nmetric = metric + link_metric; //new metric;
nhcnt = hcnt + 1; // new hop count
rt = route entry for the dest in the routing table
if (! rt) {
   if (flags & RT_FORWARD) {
      flags &= ~ RT_FORWARD;
      build AR with dest, dest_seq, nnext, nmetric, nhcnt, flags
      AR->update_time = CURRENT TIME;
   }
}
else if (rt->next == nnext) {
   if (rt->flags & RT_FORWARD)   //FR
      flags |= RT_FORWARD;
   else { //AR
      if (flags & RT_FORWARD)
         rt->update_time = CURRENT TIME;
      flags &= ~ RT_FORWARD;
   }
   update rt with dest, dest_seq, nnext, nmetric, nhcnt, flags
}
else if (nhcnt < rt->hcnt+2 && (dest_seq>rt->dest_seq
   || dest_seq==rt->dest_seq && nmetric<rt->metric)) {
   if (rt->flags & RT_FORWARD)   //FR
      flags |= RT_FORWARD;
   else { //AR
      if (flags & RT_FORWARD)
         rt->update_time = CURRENT TIME;
      flags &= ~ RT_FORWARD;
   }
   update rt with dest, dest_seq, nnext, nmetric, nhcnt, flags
}
```

Fig. 2 route update procedure.

termine the freshness of the route during the LU. Each time a packet is forwarded, the FR's update_time is updated. Each time the FR information is received, the corresponding AR's update_time gets updated. When the hello packet is sent, only the valid route entries with the fresh update_time are appended. When the communication finishes and the active route times out, or the link breaks and the route becomes invalid, the RT_FORWARD flag is cleared, the nodes on the FR stop updating the FR information; and the corresponding ARs in the neighboring nodes time out quickly. So the route update is local not only in the space but also in the time domain.

Figure 3 shows the concept of LU, where the initial AR consists of nodes 1, 4, 6, 8 and 9. When the AR is used to forward packets, it becomes an FR and the update_time is refreshed. Then the node on the FR, for example, node 6, appends the FR information in the hello packet and starts LU. Its neighbor—node 5—builds an AR and joins the LU on hearing the FR information. Then the node on the FR—node 1—hears the update entry from node 5 and updates its route entry with node 5 as the new next hop node; but node 19 does not build any route entry because the route update entry from node 5 is an AR. Thus only the nodes (1, 4, 6, 8, 9) on the FR and their immediate neighbors (2, 3, 5, 7, 10, 11) take part in the route maintenance for the FR. Because 1-5-6-7-9 has a smaller metric, it becomes the new FR. The local update area changes correspondingly.



dest	dest_seq
6	24

Route Num
1

dest	dest_seq	next	hops	metric	flag
9	28	8	2	6	FR

dest	dest_seq
5	30

Route Num
1

dest	dest_seq	next	hops	metric	flag
9	28	6	3	7	AR

Fig. 3 Concept of local update.

3.4 Processing Link Breaks

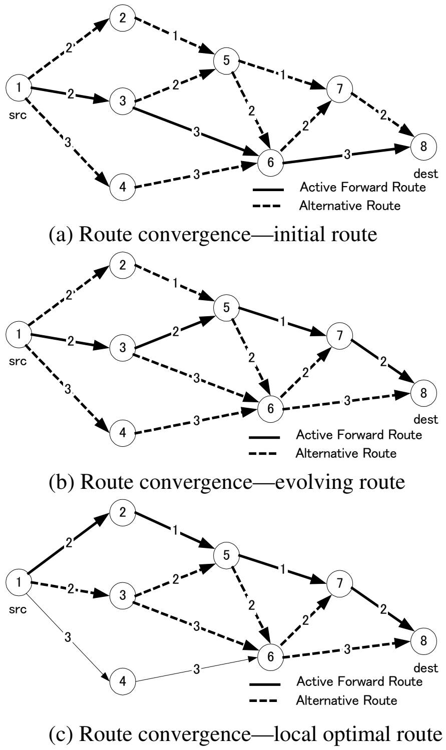
As will be shown later, by LU and preferring the route with a short metric, most of the link breaks, due to the slow speed mobility, can be avoided. However, some link breaks can not be avoided because of low node density or high mobility. In this case, the route is repaired if the node is near to the destination; otherwise a Route ERRor (RERR) packet is sent towards the source node, just like that in AODV. In the worst case, the network is partitioned. Shortly after the route breaks, LU is stopped because there is no active route any more. After several backoffs due to route discovery failure, LHAOR stops route discovery like that in other on-demand routing protocols.

4. Analysis of LHAOR

In the above, we presented LHAOR protocol. Next we describe some of its properties.

4.1 Strong Links Selection and Route Convergence

In LHAOR protocol, the initial route may contain weak links and have a big metric. Later by LU and preferring the route with a short metric, the route gradually converges to the local optimum, having the short metric and containing strong links. The process is shown in Fig. 4. The initial route is 1-3-6-8, with the hop count 3 and metric 8. The FR information is locally updated. The neighboring nodes of the FR may build the ARs and take part in the route maintenance. Node 3 finds that the partial route 3-5-7-8 has a shorter metric than the current route 3-6-8, so it adopts the new route 3-5-7-8 and the partial route 3-6-8 will time out. Finally the route converges to the local optimum: 1-2-5-7-8.

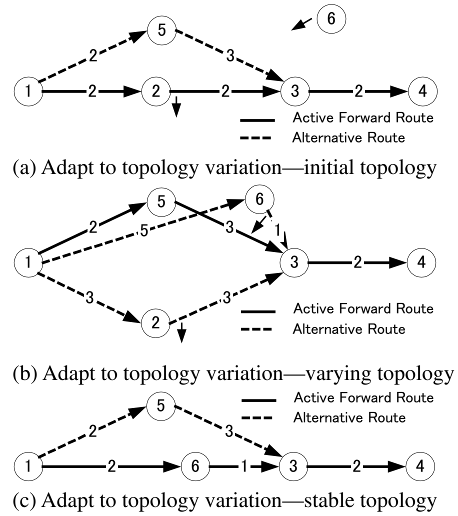


(a) Route convergence—initial route

(b) Route convergence—evolving route

(c) Route convergence—local optimal route

Fig. 4 Route convergence process.



(a) Adapt to topology variation—initial topology

(b) Adapt to topology variation—varying topology

(c) Adapt to topology variation—stable topology

Fig. 5 Adapt to topology variations.

4.2 Adapting to Topology Variations

In the case of low mobility, when an intermediate node on the FR moves away slowly, the link RSSI decreases gradually and the route metric becomes bigger. By LU, the upstream node of the link may detect the changes of the route metric. If it receives the route update information from other downstream nodes and build a new route before the current route breaks, the route break can be avoided and the routing overhead can be reduced. Later, other nodes may move near to the route and provide a better route. So by LU and preferring routes with a short metric, the route can adapt to the topology variations.

In Fig. 5, the initial route is 1-2-3-4. Then node 2 begins to move away and node 6 starts to move near to node 1. As node 2 moves away, both the link 1-2 and the link 2-3 become weak. Node 1 finds the AR 1-5-3-4 is better than the route 1-2-3-4, so it sends data packet along the new route 1-5-3-4. Later node 6 moves to the middle of node 1 and 3, and provides a better partial AR. So node 1 sends packets along the new route 1-6-3-4. In this way, the route breaks can be reduced.

4.3 Route Stability

Several factors may affect the route stability. The most important is the RSSI variation. In the real wireless environment, the RSSI may vary frequently and greatly. The non-smooth change of the RSSI may cause the link metric and route metric to change frequently. Sometimes the occasional route update may cause a route to temporarily have a short metric and be selected as the new FR. However the route may break soon, and the communication is affected; when the route changes, it may cause out of order packets. So it is necessary not only to make the route consist of the strong links, but also to make the route metric and the route itself relatively stable.

In the office environment, when the nodes do not move very quickly, the MA RSSI can be used to get a relatively stable RSSI. Because the RSSI is divided into several ranges, each mapping to a metric, when the MA RSSI is changing within a certain range, the link metric keeps unchanged. However, when the MA RSSI varies over the range border, even a small change can lead to a link metric variation. The threshold, RSSI_TH is introduced. Only when the new MA RSSI is different from the recent MA RSSI by at least RSSI_TH will it trigger the calculation of the new link metric. Otherwise the link metric is kept unchanged. RSSI_TH usually depends on the standard deviation of all the RSSI within the specific range. For simplicity, it can be set as half of the RSSI range length.

In the testbed system, the hello packet is used to determine the link connectivity. When several continuous hello packets are missing, the link is regarded as broken. One problem is how a node can be regarded as a neighbor when a hello packet is received. In LHAOR, only when the RSSI of a sender of the hello packet is big enough, a hello packet was heard from the sender recently, and the metric of the new 1-hop route is smaller than that of the existing multi hop route can the sender be regarded as a new neighbor. Otherwise the previous multi hop route is kept.

In the case of route update entry processing, only when the hello packet comes from a stable neighbor will the appended route update entries be processed. For the newly constructed route with a different next hop, only when its metric is smaller than that of the existing route by at least METRIC_TH can it trigger the route update. Otherwise, the existing route is kept unchanged.

4.4 Avoiding Loops

In LHAOR, the destination sequence number is adopted to avoid loops, just like in AODV. The route update is only local and periodical so as to reduce the overhead. When only the metric is used, it is possible that loops may be formed. So in the update message, the next hop and the hop count are contained. In the LU, only the immediate neighbors of the FR can hear the FR information. By ignoring the entries whose next hop equals its own address, the receiver can avoid most of the loops.

Sometimes the hello packet loss and the RSSI variation make the multi hop loop possible. When a route with a better metric is available, restricting the hop count increase may remove the loop. In this way, the route is loop free.

5. Performance Evaluation

In this section we evaluate LHAOR protocol. It is implemented on the basis of AODV-UU [18], which is suitable for both simulation and testbed evaluation. Because the simulator does not support adaptive rate and multipath fading, in the simulation we mainly compare the performance among LHAOR, AODV, SSA and ABR under different mobility. In the testbed experiments we dwell on the effect of the link heterogeneity and verify the benefits of preferring strong links.

5.1 Simulation Environment

The simulation was implemented under the network simulator ns-2 [19], which can simulate a layered network protocol stack and wireless channel. IEEE 802.11 [20] distributed coordination function (DCF) is used as the medium access control protocol. The mapping from the RSSI to the metric is shown in Tab. 1 and the simulation condition is shown in Tab. 2. Constant bit rate (CBR) traffic is used to simulate UDP performance and there are 10 traffic instances. The results of 30 different scenarios are averaged.

5.2 Simulation Results and Analysis

Figures 6 - 11 show the UDP simulation result, comparing the overhead, route break number, route lifetime, hop count, end-to-end delay and packet delivery ratio among LHAOR, AODV, SSA and ABR with respect to mobility.

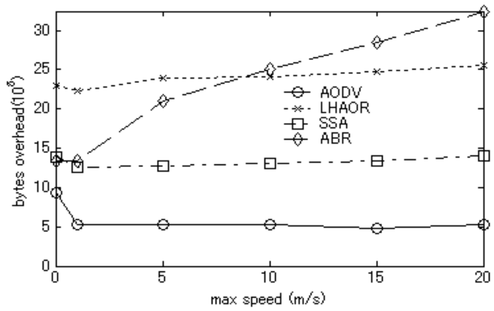


Fig. 6 Byte overhead.

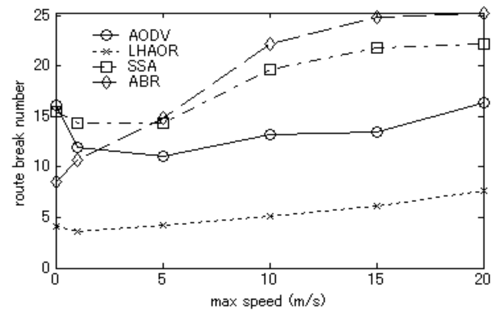


Fig. 7 Average route break number.

Routing overhead. Figure 6 shows the routing overhead. In AODV, the hello message is transmitted only during the communication; thus its routing overhead is low. Both ABR and SSA contain periodic beacons, and LHAOR has LU overhead, thus their overhead is higher. ABR performs an aggressive route discovery, so its overhead increases very obviously as the mobility gets higher. The overhead of AODV becomes smaller in the presence of mobility than in the static case, and almost keeps unchanged as the mobility increases. This is because of the frequent route breaks and the backoff

Table 1 Map the RSSI to the link metric.

SNR Range (dB)	Transmission range (m)	metric
∞ - 20.92	0 - 100	1
20.92 - 13.88	100 - 150	2
13.88 - 8.88	150 - 200	3
8.88 - 5.0	200 - 250	5

Table 2 Simulation condition.

Network size	2000m x 300m
Number of nodes	50
Transmission range	250m
Simulation time	500s
Traffic type	CBR (size=512byte, interval=0.2s)
MAC protocol	IEEE 802.11b DCF
Link bandwidth	2Mb/s
Link break detection	Hello packets (interval=1s)
Propagation model	Two ray
Mobility pattern	Random walk
Max speed	0, 1, 5, 10, 15, 20 m/s

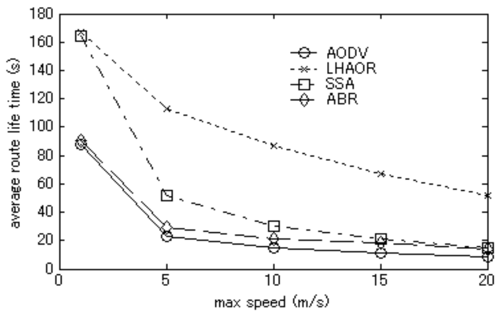


Fig. 8 Average route lifetime.

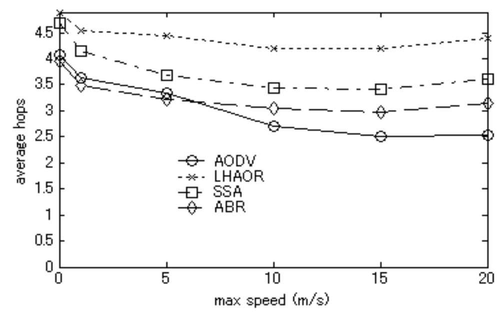


Fig. 9 Average hop count.

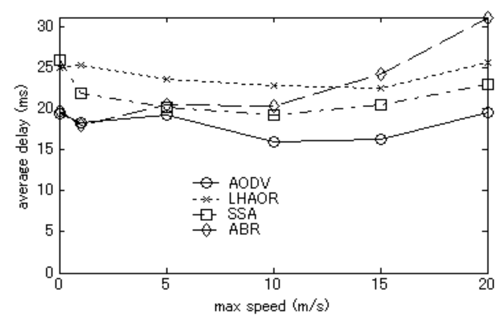


Fig. 10 Average end-to-end delay.

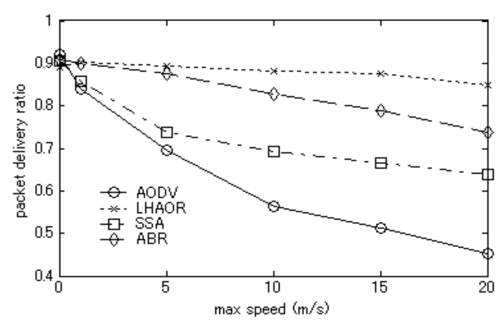


Fig. 11 Packet delivery ratio.

in the case of route discovery failure. When there is no active route, each node stops sending hello packets. Though the overhead is low, many packets are dropped due to the lack of valid routes in AODV, as is shown in Fig. 11.

Route break number and route lifetime. Figure 7 shows that the routes in AODV, SSA and ABR are easier to break, and the breaks usually are more than two times of that in LHAOR. As the mobility increases, the break number in LHAOR becomes bigger, but it is always much smaller than that in AODV, SSA and ABR. Figure 8 shows the average route lifetime, where the route lifetime is the duration between the time a route is discovered and the time the route times out; in the duration the route may be repaired in the case of link break. As the mobility increases, the average route lifetime decreases for all the protocols. When the mobility is low (1m/s), LHAOR and SSA have longer route lifetime. The superiority of LHAOR over other protocols is very obvious at higher mobility.

Hop count and end to end delay. Figure 9 shows that the routes in LHAOR usually have the biggest hops and that in AODV and ABR have the least hop count with that of SSA in the middle because in LHAOR and SSA the strong links are preferred and the route may contain more links to avoid the weak links. As a result, the end-to-end delay in Fig. 10 for LHAOR and SSA is bigger than that in AODV due to more forwarding delay. As the mobility increases, the delay in ABR becomes the biggest due to its highest overhead.

Packet delivery ratio. Figure 11 shows the packet delivery ratio. In the static case, AODV and ABR have a little higher packet delivery ratio than LHAOR and SSA because in the simulation bit error is not considered. In the presence of mobility, LHAOR, ABR and SSA all have a higher packet delivery ratio than AODV. Under the low mobility, ABR and LHAOR almost have the same performance; as the mobility increases, the superiority of LHAOR over AODV, ABR and SSA becomes very obvious.

5.3 Experiment Environment

The experiment topology is shown in Fig. 13. Altogether there are 5 IBM R40 (1, 3, 4, 5, 6), and 3 Panasonic CF-R2 (7, 8, 9). The OS of all the nodes is Redhat 9 with Linux kernel 2.4.20-8. Node 1 is the source and node 9 is the destination. Other nodes act as the relay nodes. Each node has the same type of 802.11b card made by BUFFALO. In the experiment channel 14 with the frequency 2.484GHz is always used.

The mapping of RSSI to metric is determined by the experiments. The MA time is 2s except especially pointed out. The hello period is 1s.

Three kinds of experiments are performed to test and compare AODV and LHAOR. Ping is used to test PER (actually PER means the packet loss ratio in the evaluation) and end-to-end delay; the ICMP echo packet size is 520Bytes and is sent every one second. Netperf is used to test UDP/TCP throughput respectively; their duration is 30s. Between each test, the network is kept idle for 30s so that the old route times

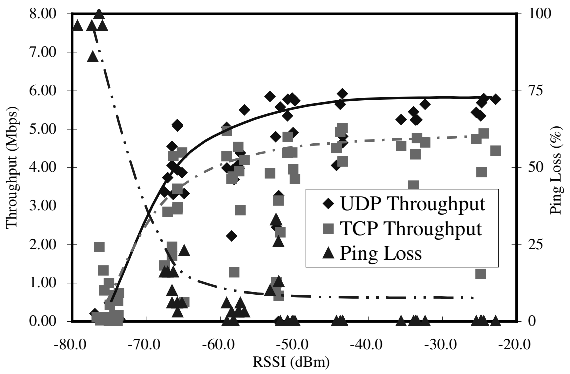


Fig. 12 The effect of RSSI on the one-hop performance.

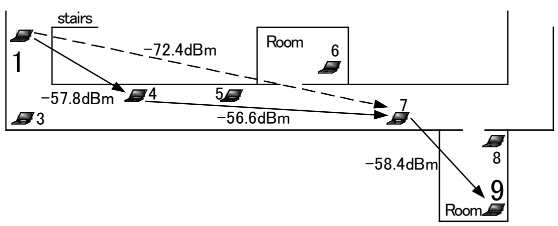


Fig. 13 Average RSSI in the topology.

out and a new route is discovered for the next test. In this way, both the route discovery capability and the route maintenance capability are evaluated.

5.4 Experiment Results and Analysis

Determination of the RSSI threshold. Figure 12 shows the effect of the RSSI on the UDP/TCP throughput and ping loss. The communication is between two nodes within the same subnet and no routing protocol is used. Changing the distance, the RSSI correspondingly varies and the performance is affected. It is obvious that when the RSSI is big enough ($RSSI > -60dBm$), its effect on the performance is little; as the RSSI decreases, the performance degrades; when the RSSI decreases to -80dBm, almost no packet can be delivered. Thus the mapping of the RSSI to the link metric is determined and shown in Tab. 3. The RSSI_TH is 2.5dBm, half of the RSSI range length. And the METRIC_TH is 3.

RSSI, metric and hop count. The average RSSIs of some links are shown in Fig. 13. The average RSSI of 1→7 is -72.4dBm, while the average RSSI of 1→4 is -57.8dBm and that of 4→7 is -56.6dBm. The link 1→7 is regarded as a weak link while 1→4 and 4→7 are regarded as the strong links. The hello packet can be received over the weak link 1→7 at a low rate and conforms the connectivity while the data packet

Table 3 Map the link RSSI to the link metric.

RSSI (dBm)	-60	-65	-70	-75	
Metric	1	2	4	8	16

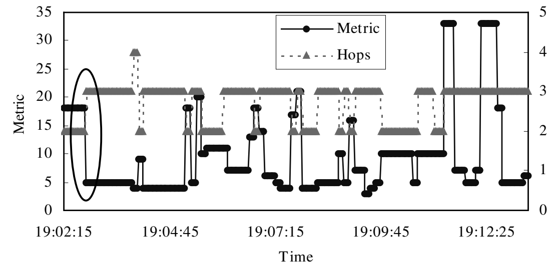


Fig. 14 Route hop count and metric in LHAOR.

transmitted at a high rate has a high PER. In LHAOR, the partial route 1→ 4 →7 is preferred to the short one 1→7 because the former route has a shorter metric. As a result, the route in LHAOR has a bigger hop count. For the forwarding route, in LHAOR, 20.1% routes are two hops, 72.5% routes are three hops, and 7.2% routes are four hops, and the average hop count is 2.87; while in AODV, 98.9% routes are two hops, and the average hop count is 1.99.

Figure 14 shows the route metric and route hop count in LHAOR. Due to the variation of the link RSSI and by LU, the route metric and hop count are also time-variant. A hop count increase and metric decrease near the time 19:02:30 is marked out. This reflects the LU effect. A route with more links is selected as the new FR, the hop count increases while the route metric decreases because the links have strong RSSI and small link metrics. The benefit is an improvement in both the packet delivery ratio and throughput.

PER and throughput. By preferring the strong links with the big RSSI, LHAOR has an average PER of 58%, much smaller than that of the original AODV, 90%. Though the routes in LHAOR have a bigger hop count, they have smaller average Round Trip Time (RTT) (19ms in LHAOR and 93.8ms in AODV). This is due to the fact that in AODV, the route often breaks and the packets are buffered. The delay of packets in the queue increases the RTT.

In the following we regard the normally finished netperf test as the successful access. Table 4 shows that in LHAOR the access success ratio is usually greater than 95% while that of AODV is as low as 15%. The achieved improvement is over 5 times. As for the average throughput of the successful access, LHAOR has an average throughput of 1.70Mbps for UDP, 2.36 times of 0.72Mbps, the one of AODV; and LHAOR has an average throughput of 1.23Mbps for TCP, 3.32 times of 0.37Mbps, the one of AODV.

Figure 15 - 16 show the distribution of the through-

Table 4 Access success ratio and throughput.

	Access Success Ratio		Average throughput	
Protocol	AODV	LHAOR	AODV	LHAOR
UDP	15.3%	95.1%	0.72Mb/s	1.70Mb/s
TCP	10.6%	95.3%	0.37Mb/s	1.23Mb/s

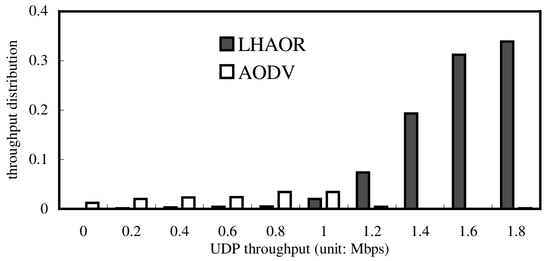


Fig. 15 Distribution of UDP throughput.

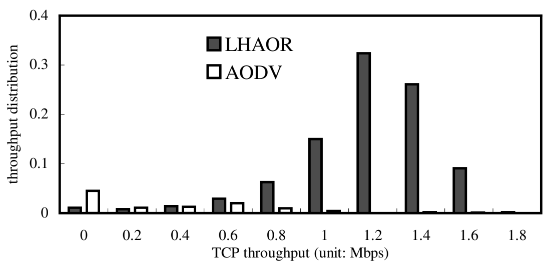


Fig. 16 Distribution of TCP throughput.

put of UDP and TCP respectively. Many netperf tests for AODV can not finish normally due to the lack of the route stability. As a result, in both figures AODV has a much smaller percentage than that of LHAOR. The throughput of LHAOR usually lies in the high rate range while that of AODV usually lies in the low rate range. From Fig. 15 - 16 and Tab. 4, it is obvious that LHAOR achieves a much higher performance than AODV.

Tradeoff between stability and throughput. MA RSSI is used in LHAOR to make the route metric relatively stable. As is shown in Tab. 5, MA duration affects PER, throughput and access success ratio. When MA duration is 2s, UDP throughput reaches 1.70Mbps and TCP throughput reaches 1.23Mbps; UDP access success ratio is 95.1% and TCP access success ratio is 95.3%; PER is as high as 58%, and most of the packet loss is due to the lack of route stability. When MA duration gets bigger, the route becomes more stable, the throughput gets low; the access success ratio increases and PER decreases. When MA duration is 5s, UDP throughput drops to 1.33Mbps and TCP throughput drops to 0.73Mbps; UDP access success ratio increases to 99.3% and TCP access success ratio increases to 99.9%; PER is as low as 6%. The above result is due to the following fact: in the experiment, netperf (UDP/TCP test) can take advantage of the route diversity and transmit many packets at the instantaneous high MAC rate. An ICMP echo packet (ping test) is transmitted every second; when the route changes and causes it dropped by the intermediate node, the packet is not retransmitted by the source node. So when the route adapts to fast link quality variation, the throughput is improved, but at the cost of route stability. In the real system, there must be a tradeoff between the route stability and throughput.

6. Conclusion

We have proposed an efficient on-demand routing protocol LHAOR to improve the network performance. The link metric is related with the link RSSI. In addition, the nodes on the FR and their immediate neighbors take part in the route maintenance. LHAOR has two main properties:

(1) Maintaining the FR by LU allows the routes to adapt to the topology and link quality variations, makes them robust against mobility, and enables them to reach local optimum. Correspondingly, LHAOR improves the throughput, reduces route breaks, and prolongs route lifetime.

(2) Only the FR is maintained and the route update message is only broadcasted locally to 1-hop neighbors. Therefore, the update is local both in the space and time domain, and the routing overhead is low compared with proactive routing protocols such as DSDV.

The simulation and experiment results show that LHAOR achieves a great improvement in the packet delivery ratio, throughput and route lifetime compared with AODV. Also, LHAOR exhibits great superiority over AODV, SSA and ABR as the route gets longer and the mobility becomes higher.

Currently in LHAOR protocol, the route is only locally optimal. If there are multiple routes between the source node and the destination node and these routes lie within disjoint areas, the LU is restricted within only one area. The route change may cause some packets out-of-order. Utilizing the method proposed in Section 4.3 to make the route stable, this problem is partially solved.

We are planning to further optimize both the route discovery and the route maintenance, and make the route adapt to fast topology variation while keeping the route stability. We will simulate the routing protocols with the adaptive rate control in the MAC layer.

Acknowledgments

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Table 5 Effect of moving average duration in LHAOR.

MA Duration (second)	2	3	5
Ping PER	58%	43%	6%
UDP throughput (Mb/s)	1.70	1.51	1.33
TCP throughput (Mb/s)	1.23	1.16	0.73
UDP access success ratio	95.1%	98.8%	99.3%
TCP access success ratio	95.3%	99.5%	99.9%

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Suhua Tang received his B.S. degree in 1998, Ph.D. degree in 2003, all in Electronic Engineering and Information Science from University of Science and Technology of China. Since 2003, he is a researcher in ATR Adaptive Communications Research Laboratories. His research interests include wireless signal processing, wireless media access control, mobile ad hoc networks and ITS communications.

Bing Zhang received her B.S. degree in 1983 from Peking Aeronautics and Astronautics University, China, and M.S. in 1987 and Ph.D. degrees in 1990 from Hiroshima University, Japan. From 1991, she has been working at the Communications Research Laboratory of Japan Ministry of Posts and Telecommunications (presently, Communications Research Laboratory, Independent Administration Institution), as a senior researcher. She stayed in the University of Tennessee as a postdotoral research associate in 1995-1996. From 2000 to 2004, she was with ATR Adaptive Communications Research Laboratories as a senior researcher. Her research interests include information processing, adaptive QoS management, mobile networking. She is a member of the IEICE.

Masahiro Watanabe received his B.S. degree in electronic engineering from Kyoto Institute of Technology in 1982. He joined Mitsubishi Electric Corporation in 1982 and was engaged in research and development of Radar system and Inter vehicle communication system as a senior researcher of Advanced Technology R&D Center. Since 2002, he has been working at ATR Adaptive Communications Research Laboratories as a senior researcher. His research interests include wireless media access control and mobile ad hoc networks. He is a member of IEICE.

Shinsuke Tanaka received his B.E. degree and M.E. degree in material engineering from Kyoto University in 1978 and 1980, respectively. After he joined KDD in 1980, he has researched magneto-optical recording medium and semiconductor optical devices for optical fiber communications, and received D.E. degree from Kyoto University in 1988. In 2002, he was appointed to the manager of the First Research Department of Adaptive Communications Research Laboratories in ATR. His research interests are wireless ad hoc networks and communication quality. He is a member of IEICE.