PAPER

GAHA and GAPA: Two Link-Level Approaches for Supporting Link Asymmetry in Mobile Ad Hoc Networks*

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SUMMARY Existing routing protocols for mobile ad hoc networks assume that all nodes have the same transmission range. In other words, the mobile ad hoc network has symmetric links, which means that two neighboring nodes A and B are within the transmission range of one another. However, since nodes consume battery power independently according to their computing and communication load, there exist asymmetric links, which means that node A is within node B's transmission range, but not vice versa. In this paper, two approaches are presented to support routing in the existence of asymmetric links: GAHA (GPS-based Hop-by-hop Acknowledgment) and GAPA (GPS-based Passive Acknowledgment) schemes. Both GAHA and GAPA can be applied to any routing protocols by utilizing GPS (Global Positioning System) location information. Simulation results reveal that both GAHA and GAPA protocols cope well in the presence of asymmetric wireless links and nodes' mobility.
key words: *ad hoc network, asymmetric links, routing protocol, global positioning system*

1. Introduction

Recently, research effort was focused on medium access control [10], [11], routing [1]–[7], [12], and transport [8], [9] protocols for mobile ad hoc networks. Unlike traditional mobile networks where base stations and switches are wire-connected together to form the communication infrastructure and mobile nodes can access the network via their corresponding base-stations, nodes in a mobile ad hoc network can move freely and communicate with each other. Intermediate ad hoc nodes relay the packets towards the destination node wirelessly. Due to the characteristics of mobile ad hoc networks, conventional network protocols proposed for fixed networks cannot be used.

Existing routing protocols for mobile ad hoc networks can generally be categorized into two classes: (a) proactive, and (b) reactive. In proactive schemes [2], [12], nodes maintain their routing tables for all possible destinations irrespective of the need of routes. However, in reactive schemes [1], [6], routes are acquired based on-demand manner by the source. Therefore, it does not have to maintain routing tables when there is no desire for routes. In [3], [4], the hybrid approach is presented to take advantages of both reactive and proactive schemes. Additionally, some routing protocols utilize nodes' location information obtained through GPS (Global Positioning System) [5], [7].

Most routing protocols assume that all nodes have the same radio transmission range. This assumption, however, does not reflect real life scenarios since radio transmission ranges of nodes can decrease in different degrees due to battery power consumption. If we are to utilize existing routing protocols in an environment with asymmetric wireless links (If node A is within the radio transmission range of node B, but not vice versa, we can say that there exists an asymmetric link between these nodes.), a route which constitutes only links of the same radio transmission/reception ranges should be selected. In fact, all nodes have to maintain relatively constant power consumption to ensure that their transmission/reception range is not affected. Otherwise, the assumption on symmetric wireless links could be violated over time. In DSR (Dynamic Source Routing Protocol), the existence of asymmetric links was mentioned, but no detailed addressing mechanism was introduced [1].

In this paper, we introduce two approaches to address asymmetric links in mobile ad hoc networks: (a) *GAHA (GPS-based Hop-by-hop Acknowledgment)*, and (b) *GAPA (GPS-based Passive Acknowledgment)* schemes. These *GAHA* and *GAPA* schemes are based on hop-by-hop acknowledgment and passive acknowledgment schemes used in ABR [6] and DSR [1] for route maintenance as well as link-level acknowledgment of successful reception of data packets. In the hop-by-hop acknowledgment scheme, a route is maintained based on receiving the acknowledgment packet from the down-link node. However, in the passive acknowledgment scheme, after sending a packet to the down-link node, the up-link node listens for the echo when the packet is forwarded. In DSR, the absence of a packet forwarded by the down-link node is used to trigger a route failure. Therefore, we modified the hop-by-hop and passive acknowledgment schemes to support asymmetric links by using GPS. Since both *GAHA* and *GAPA* support the asymmetric links at the link level, they can be applied to other routing protocols. This paper is organized as following. Section 2 describes the problems associated with routing over asymmetric wireless links. Section 3 presents the basic hop-by-hop and passive acknowledgment schemes used in DSR for

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route maintenance. Our proposed *GAHA* and *GAPA* protocols are presented in Sect. 4. Section 5 presents the enhancement of IEEE 802.11 CSMA/CA medium access framework to deal with asymmetric links. In Sect. 6, some discussion points are noted to consider the loss of route error message due to the asymmetric links as well as the relationship with the signal strength besides the geographical distance. In addition, the simulation environments and results are given in Sect. 7. Finally, a conclusion is made in Sect. 8.

2. Problem Occurred at Routing Protocol

Several on-demand routing protocols such as AODV [14], ABR [6], ZRP [3] and DSR [1] have been proposed. When a source node has packets to send, it invokes a route discovery process to derive a route. In addition, the source or an intermediate node is supposed to perform the route reconstruction process to acquire a new path when route failure occurs. In AODV [14], each node receiving an RREQ (Route Request) packet rebroadcasts it until it is the destination node or it has a route to the destination. Such a node then replies with an RREP (Route Reply) packet, which is routed back to the source. Therefore, if a node cannot forward the RREP to its next-hop node over the reverse path due to the presence of an asymmetric link, then a failure in route discovery occurs.

In ABR [6], a BQ-REQUEST packet is generated when a source node tries to get an initial path between the source and destination nodes. An intermediate node sends an LQ-REQUEST packet to discover a partial path from itself to the destination node after detecting a route failure. At the destination node, the most stable route is selected and this route information is propagated back to the source via the reverse path. Again, if there exists an asymmetric link during the reply propagation towards the source, the discovered route cannot be established.

In ZRP [3], a node allows nodes within its zone radius to include itself as their member. This is achieved by notifying these neighboring nodes of its identity information. Suppose that node A could notify node B (one of its neighboring nodes) of its identity because node B is within its radio transmission range, but node A is not within the radio transmission range of node B. In this case, node B mistakes node A as a member in its zone. This can cause a serious problem in a decision of route between the source and destination nodes. An approach for supporting asymmetric links has been proposed in [4], but it is only applicable to ZRP and hence not generic.

In DSR [1], similar to AODV and ABR, a route request message is flooded into the network to establish a route when a source has data packets to send. The destination node selects the shortest path[†] and a route reply message containing the path information is routed back to the source node. Thus, in the presence of asymmetric links during the reply propagation, the recorded source route cannot be successfully sent back to the source.

In this paper, we assume that a routing protocol has only to provide the end-to-end path from source to destination. Hence, if the path acquired by the routing protocol consists of all symmetric links, the path information can be propagated via reverse path (Fig. 1(a)). The path consisting of only symmetric links can be acquired at the receiver if the routing protocol allows the flooded route discovery packets to include the location information and radio transmission ranges of intermediate nodes. If there exist both symmetric and asymmetric links on the acquired path, the path information can be propagated toward the source node by: (a) increasing the radio transmission range at an intermediate node (see Fig. 1(b)), or (b) using another path from the destination to the source (see Fig. 1(c)). In Fig. 1(b), the route discovery packet flooded into the network can contain location information of visited nodes. By using this information, the route reply packet allows the intermediate nodes to increase their radio transmission ranges in order for the reply packet to successfully reach the up-link nodes. Note that even if routing protocols are able to provide an end-to-end path in the presence of asymmetric links by using the mechanisms mentioned in Fig. 1, there can still exist asymmetric links at link level over time due to node mobility.

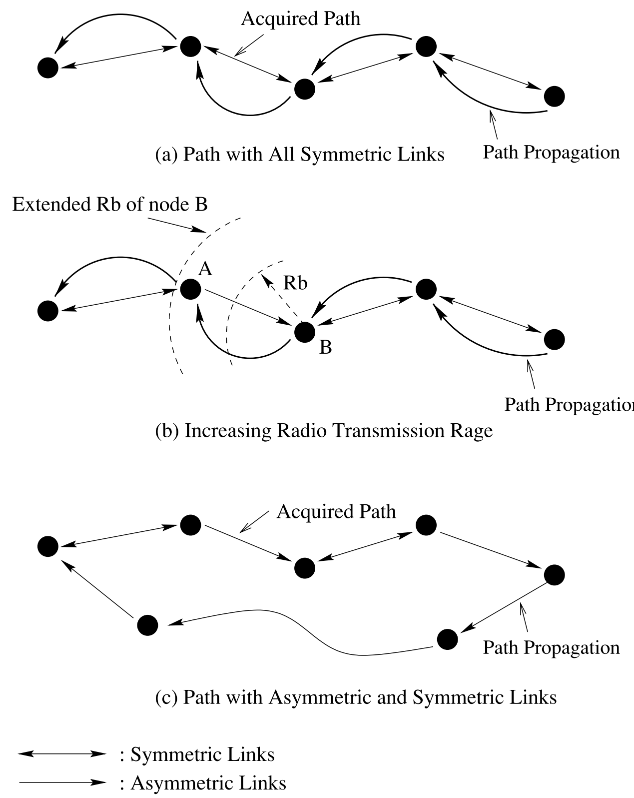


Fig. 1 Acquiring a path at routing protocol.

In this paper, we present two link-level approaches to support asymmetric links independent of the routing protocols at the network layer.

For conventional routing protocols that do not have our

[†]This is different from ABR since the routes so selected are not long-lived.

asymmetric link-level support, there is no guarantee that there will always exist an explicit backward path because most of them should rely on using the explicit backward path to establish a forward route from the source to destination as mentioned before.

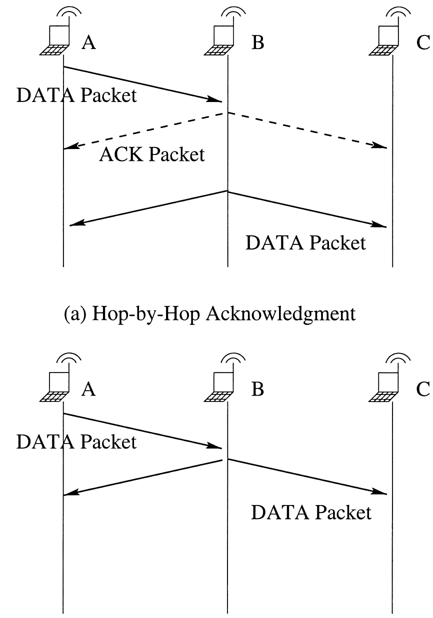
In addition to the difficulty in achieving a route setup, the existence of frequent route reconstruction can result in severe degradation in communication performance. In DSR and a couple of similar protocols during a data session, whenever an upstream node did not receive the expected acknowledgment information (explicit acknowledgment packet or implicit data packet echo) from the downstream node due to the presence of link asymmetry, it concludes that there is a route failure and a ROUTE ERROR message is sent back to the source. This triggers a new route discovery, resulting in interrupting on-going communications. Hence, without the provisions of mechanisms to deal with link asymmetry such as our proposed link-level approaches, most on-demand routing protocols would not perform well.

Therefore, we extend the basic hop-by-hop and passive acknowledgment schemes to efficiently support asymmetric links by exploiting GPS location information. We explain the hop-by-hop and passive acknowledgment schemes in Sect. 3.

3. Hop-by-Hop and Passive Acknowledgment Schemes

In this section, two link level approaches for route maintenance are described as shown in Fig. 2. In the hop-by-hop acknowledgment scheme (Fig. 2(a)), node A sends a data packet to node B. Node B executes the link-layer functions (such as error checking) and acknowledges the successful reception of the data packet by transmitting an explicit ACK packet back to node A. This ACK packet is then used for two purposes. One is to notify the sender of an error-free reception by the receiver node B. The other is that the link between node A and node B is still alive. Therefore, a final destination node should also send an ACK packet to its up-link node for the above purposes. The absence of the ACK packet from node B (for a given timeout) enables node A to detect the presence of link failure. If an asymmetric link exists between nodes A and B, the ACK packet will not reach node A, resulting in node A generating a Route Error Message toward the source. This causes the source to restart a new route search even if data communication between node A and node B can continue.

In the passive acknowledgment scheme shown in Fig. 2(b), when node B receives the data packet from node A, node B forwards the received data packet to its down-link node (node C) over the acquired path instead of sending an explicit ACK packet. The transmission from node B to node C can be overheard† by node A. If node A can overhear the forwarded data packet sent by node B, this means that node B has received the data packet successfully and there is no link breakage between nodes A and B. Although there exists no down-link node at the final destination, it should still broadcast the received data packet in order to notify its up-link node of the successful reception of the data packet, as well as indicating there is no link failure.



(a) Hop-by-Hop Acknowledgment

(b) Passive Acknowledgment

Fig. 2 Two link level approaches for route maintenance and flow control.

Similar to the hop-by-hop acknowledgment sch-eme, the asymmetric link between nodes A and B can prevent node A from hearing the data forwarded by node B. This causes node A to generate a Route Error Message back to the source unnecessarily.

4. Our Proposed Schemes: GAHA and GAPA

4.1 Basic Assumptions

As mentioned before, we assume that the routing protocol at network layer provides an end-to-end path between the source and destination nodes. Each node in the route path is allowed to increase its radio transmission range to reach its up-link node. Data packets will contain location information of nodes, which are obtained by GPS. These informations are used for calculating the geographical distance between two nodes. In addition, it is assumed that GPS has a high degree of accuracy. Although current GPSs have slight inaccuracy in providing location information, the error range usually falls below 5 meters. Finally, we assume that nodes are capable of dynamically adjusting their transmission power.

4.2 GPS-Based Hop-by-Hop Acknowledgment (*GAHA*)

By using the up-link node's location information propagated to the down-link node, the down-link node knows whether

†We assume the presence of omni-directional antennas.

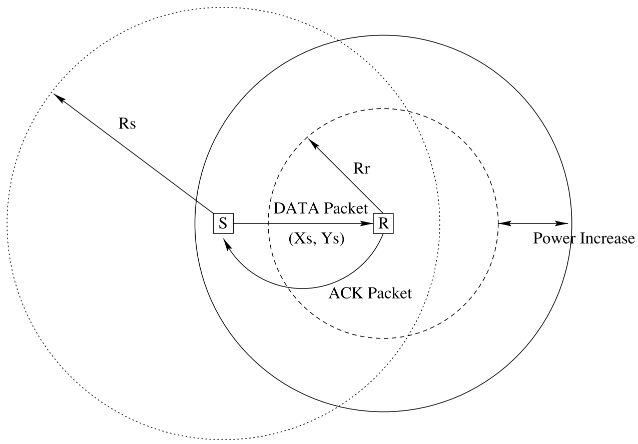


Fig. 3 GAHA protocol.

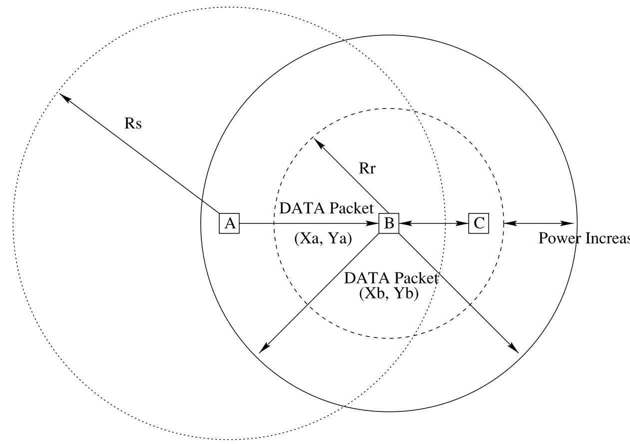


Fig. 4 GAPA protocol.

the transmission range of its own ACK packets is able to reach the up-link node. This is achieved by comparing the radio transmission range of the node with the Euclidean distance, i.e., $\sqrt{(X_U - X_D)^2 + (Y_U - Y_D)^2}$ between the up-link (node U) and down-link (node D) nodes. If the radio transmission range of the down-link node is not sufficient to reach the up-link node, the down-link node will increase its radio transmission range to allow the ACK packet to be received by the up-link node. The extra transmission power needed is determined by the distance between two nodes. Otherwise, even if the current radio transmission range of a node is able to reach its up-link node sufficiently, the power consumption can be reduced by lowering the power up to the corresponding geographical distance between the up-link and down-link nodes without losing connectivity.

Figure 3 illustrates the mechanism of *GAHA* protocol. Node S forwards the data packet received from its up-link node to node R. The data packet contains the GPS location information of node S such as (X_s, Y_s). When node R receives the data packet, it calculates the distance between node S and itself by extracting the location information of node S. Since the radio transmission range of node R cannot reach node S, node R increases its radio power momentarily to acknowledge the successful reception of the data packet. Hence, node S will accept that there is no route failure from itself to node R.

Consider that node R is not within the radio transmission range of node S. Node R will never respond to the data packet because it has not received any data packet. Meanwhile, since node S has not received any ACK information, it tries to retransmit the data packet several times. Because node S has received no ACK packets from its down-link node, node R, for a given timeout duration, node S confirms that there is a link breakage. Therefore, node S generates a Route Error Message toward the source node, which then activates a new route discovery process on receiving the Route Error Message.

4.3 GPS-Based Passive Acknowledgment (*GAPA*)

As mentioned earlier, the passive acknowledgment scheme uses the data packet forwarding of the down-link node as the implicit acknowledgment instead of utilizing an explicit ACK packet. To support asymmetric links, the down-link node should increase its radio transmission power to increase its radio transmission range to reach the up-link node. However, even if the current radio transmission range is large enough to cover the up-link node, the transmission power should not be reduced to a level of the geographical distance between the up-link and down-link nodes. This is because the packet forwarding is only used to implicitly acknowledge the up-link node and the radio transmission should concurrently reach the next hop node. Therefore, the radio transmission power should increase only if a node cannot reach its up-link node.

Figure 4 illustrates the *GAPA* mechanism. Node A sends the data packet which contains the location information of itself, (X_a, Y_a) to node B. When node B receives the data packet, node B also forwards this received packet to node C. During the process, node A will listen for node B's relay of this packet. As mentioned before, there could be retransmission of the data packet if the up-link node did not overhear the relay broadcast. If node A has not heard node B's packet relay for a given timeout duration, it concludes that the out-going link is broken and generates a Route Error Message towards the source. In Fig. 4, the radio transmission range of node B cannot reach node A, hence node B should increase its power. The amount of increase is determined by the distance between nodes A and B, $\sqrt{(X_a - X_b)^2 + (Y_a - Y_b)^2}$. This power increase can result in the fewer number of route reconstructions and higher throughput.

5. A Mechanism within the IEEE 802.11 CSMA/CA Framework

In this section, we will present a practical implementation of

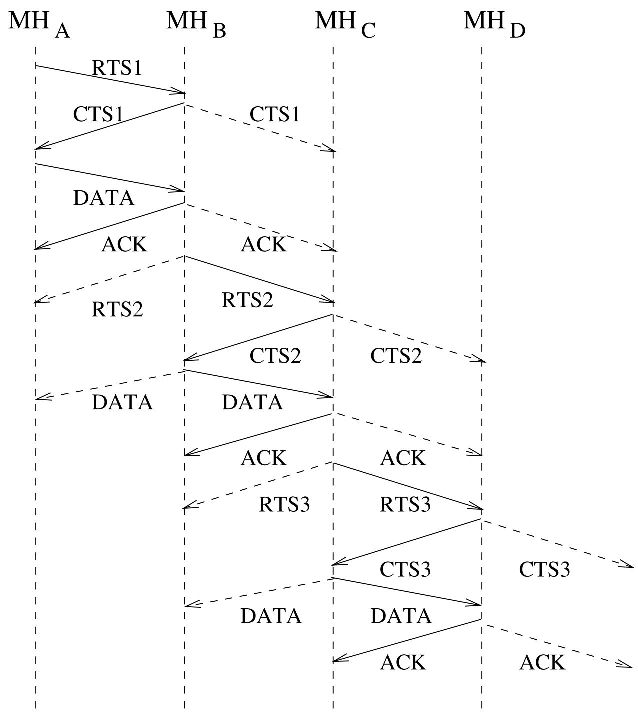


Fig. 5 The RTS-CTS handshake in IEEE 802.11 DFWMAC.

the proposed models within the framework of IEEE 802.11 CSMA/CA MAC paradigm. Our proposed protocol can be implemented with the help of the existing MAC protocol which may be modified for including the GPS information in the data frame transmitted. In general, most Wireless LANs today have a 802.11 compliant wireless adapter card. This card implements the 802.11 DFWMAC (Distributed Foundation Wireless MAC) [17] protocol, which essentially uses the similar concept of RTS/CTS handshaking. However, it adds an ACK message to enhance the reliability of data transmission, which is not present in the basic DCF (Distributed Coordination Function) using a simple RTS-CTS-DATA handshaking. Therefore, DFWMAC is an enhancement of the DCF protocol. The DFWMAC protocol performs a four-way exchange, i.e., RTS-CTS-DATA-ACK, in order to transmit data to a down-link node, as shown in Fig. 5. A mobile node needs to sense the channel to decide if the channel is indeed idle for a DIFS (Distributed Inter-Frame Space) interval before attempting to send an RTS. It also needs to sense for an SIFS (Short Inter-Frame Space) interval before sending ACK and CTS packets. Figure 5 illustrates how a source node, MH_A, can transmit data to the destination node, via MH_B, MH_C, etc. Note that DIFS and SIFS intervals are not shown in the figure. In order to forward a data packet, MH_B needs to deal with two control packets, i.e., a CTS_1 packet destined for MH_A and an RTS_2 packet destined for MH_C. On receiving the CTS_1 packet, MH_A can transmit data to MH_B. Having received the data, MH_B transmits an ACK message back to MH_A. If the ACK was not received by an estimated RTT (Round Trip Time), the data is assumed to be lost and needs to be retransmitted. Similarly, in order to forward the received data to MH_C, MH_B should perform the same handshaking process. This means that an RTS/CTS handshake cannot be avoided for every hop in an ad hoc wireless route. Specially, in an asymmetric link, for example, the route error message at the network level can be propagated towards the source with the help of MAC protocol because the node having sent an RTS message cannot receive the corresponding CTS message within a given time even after several trials. However, the problem caused by a formation of an asymmetric link can be addressed by including the GPS information of the node sending an RTS message in the RTS frame header. The receiving node can send its CTS message to the sender by adjusting the transmission power to reach the sender of the RTS message. Afterwards, the ACK message can also arrive at the up-link node by including the GPS information of the up-link node in the DATA frame header in the same way and allowing the down-link node to adjust its transmission range for the ACK message to reach the up-link node.

6. Discussions

In this section, we would like to discuss two issues considerable. One is how to handle the loss of route error message due to the existence of asymmetric links towards the source node. The other is how to extend our basic protocol for considering the degradation of signal strength.

6.1 Loss of Route Error Message

First, to recover from a route failure, the source should be notified of the link failure and it will try to acquire a new route again. For example, as shown in Fig. 6, node D detects a link breakage because node E has moved out of the proximity of node D. However, a Route Error Message generated by node D cannot reach node B because of the presence of an asymmetric link between nodes B and C. In this case, the source node is not notified of the route failure and hence cannot perform any route recovery.

To address this kind of issue of asymmetric links, two possible approaches are described in this paper. The first approach requires every node in the acquired path to keep track of location information of its up-link node. The second approach is that the next arriving data packet enables the node having failed to transmit the Route Error Message to retransmit a new Route Error Message to its up-link node but with a higher transmission power. We shall elaborate there approaches as follows.

6.1.1 Keeping Track of Up-Link Node's Location Information

When a node receives a data packet from its up-link node, the down-link node records the location information of the up-link node in its *LT (Location Table)*. The entries in LT are deleted if there has been no data transmission from the up-link node for a given timeout interval. Furthermore, the

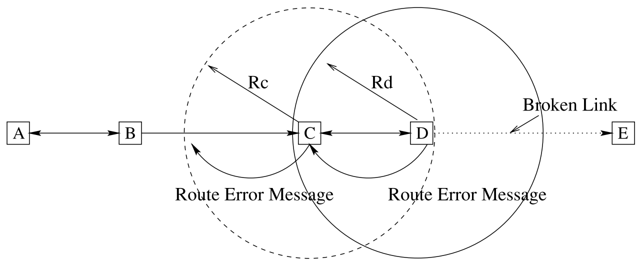


Fig. 6 The case where Route Error Message cannot be propagated to the source node.

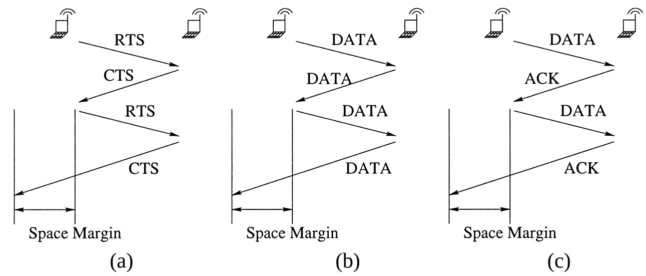


Fig. 7 Some relationship with signal strength: (a) IEEE 802.11 based, (b) passive acknowledgment and (c) DSR-specific acknowledgment.

timeout values are updated whenever a new data packet from its corresponding up-link node arrives at the node. With these information, the asymmetric link between nodes B and C as shown in Fig. 6 can be overcome if node C increases its transmission power to reach node B.

Consider that the down-link node happens to be within the radio transmission range of the up-link node, but not vice versa due to the mobility of the up-link or down-link node despite using location tables, the up-link node cannot receive any Route Error Message as mentioned before. Even if this scenario is rare, to address this problem, the down-link node should increase its transmission power enough to reach the up-link node.

6.1.2 Retransmitting a New Route Error Message

When a Route Error Message could not reach the source node due to the presence of asymmetric links, the source node will continue to transmit data packets downstream. The new data packets will eventually arrive at node C as shown in Fig. 6. This new packet also contains the location information of node B. Therefore, node C becomes aware that node B couldn't receive the Route Error Message and tries to resend the Route Error Message enough to reach node B by adjusting its transmission range for the Route Error Message. This process is repeated until the source node is notified of the route failure. However, this can take a long time before the source is notified of the link breakage since an intermediate node can only resend the Route Error Message after it has received a new data packet.

6.2 Some Relationship with Signal Strength

We developed two link-level approaches to support link asymmetry: *GAHA* and *GAPA*. We extended the basic hop-by-hop and passive acknowledgment schemes used in DSR to address asymmetric links with additional location information. However, even if the transmission range increases to reach up-link node, it is possible that the up-link node cannot receive the corresponding packet due to bad signal strength. In addition to the distance between two nodes, the signal strength should be also considered. However, since the signal strength varies according to environmental factors, the packet loss due to the degradation of signal strength can be resolved by the retransmission scheme with the increased space margin as follows.

6.2.1 IEEE 802.11 Based Scheme

IEEE 802.11 performs data transmission via the exchange of RTS and CTS messages. Therefore, when sending RTS message, we can piggyback the location information with the message. When sending CTS message with transmission range adjusted according to the distance information, the sender receiving the CTS message can measure the current signal strength. If the signal strength is insufficient to receive the ACK packet, the retransmitted RTS requires the receiver to increase its transmission range with more space margin (see Fig. 7(a)).

6.2.2 Promiscuous Mode Passive Acknowledgment Scheme

Nodes may enable promiscuous receive mode on their wireless network interface hardware, causing the hardware to deliver every received packet to the network driver software without filtering based on the link layer destination address as it is common in current LAN hardware for broadcast media [1]. Therefore, in Passive Acknowledgment scheme, a sending node overhears the DATA packet forwarded to next hop node. When the signal strength is too low to interpret the overheard DATA, or the sender cannot have received any transmission for a timeout period, the sender retransmits the DATA packet, which also requires the receiver to increase the transmission range with more space margin. If the successful reception of the overheard DATA packet fails even after n times trials (n is a system parameter), the source node becomes notified of link breakage and tries to acquire a new stable path (see Fig. 7(b)).

6.2.3 Explicit Hop-by-Hop Acknowledgment Scheme

If neither of the confirmation of IEEE 802.11 and Passive Acknowledgment mechanisms is available, the node transmitting the packet may set a bit in the packet's header to request that a DSR-specific software acknowledgment packet be returned by the next-hop node. This mechanism requires the procedure of hop-by-hop acknowledgment to be carried out. A sending node receives the explicit ACK (In Passive Acknowledgment mechanism, the overheard DATA is used as an implicit ACK). When the signal strength is too low to interpret the ACK packet, or the sender cannot have received any transmission for a timeout period, the sender retransmits the DATA packet, which also requires the receiver to increase the transmission range with more space margin to transmit the ACK packet with sufficient signal strength. If the successful reception of the explicit ACK packet fails even after *n* times trials (*n* is a system parameter), the source node becomes notified of link breakage and tries to acquire a new stable path (see Fig. 7(c)).

7. Simulation Environment and Results

Since conventional routing protocols cannot function properly without the presence of asymmetric link support, we therefore focus our simulation on evaluating the performance of our proposed *GAHA* and *GAPA* schemes. As mentioned earlier, our proposals can be applied to existing routing protocols since they are link-level solutions.

7.1 Simulation Environment

We developed an event-driven simulator where the physical and MAC protocols are not implemented. Instead, radios with omnidirectional antennas and an ad hoc MAC protocol based on CSMA/CA are assumed. In our simulation, the DSR routing protocol is implemented since it relies on the source receiving the Route Error Message. We implement both *GAHA* and *GAPA*, as mentioned in Sect. 4. We use the random waypoint model [1], [6] for mobility. Two parameters: the maximum speed and the pause time are used here. All nodes in the network are mobile within the area of $5000\,\mathrm{m} \times 5000\,\mathrm{m}$, with a pause time of 0 second and a maximum speed of 15 m/s. Additionally, the priorities are given to the direction of movement. For example, we place higher priority for left movement over right movement, up movement over down movement, etc. We randomly placed 60 nodes within the given area. Furthermore, nodes are strongly connected, meaning there exists at least one route between any two nodes in the network. This also implies that nodes' mobility does not result in partitioning of the network.

When it comes to asymmetric links, each node has its own radio transmission range uniformly distributed from 70 to 150 meters. Each intermediate node considers that there is a link failure if there is no ACK packet nor data packet received over 1 second period.

UDP (User Datagram Protocol) traffic is injected into the network between the source and receiver at constant bit rate. Basically, a packet is generated every 5 ms. In our simulations, we use a data packet size of 640 bytes and the link bandwidth of 1 Mbps [15].

To compare the amount of power consumption of *GAHA* and *GAPA*, the power consumption model assumes that the amount of power consumption is depleted proportionally to d^2, where d is the distance between the sender and receiver nodes [13]. According to [16], sending a bit of information through free space from node A to node B incurs an energy cost E_t, which is a function of the distance d between the nodes. More precisely, $E_t = \beta \times d^\gamma$, with $\gamma > 1$ as the path-loss exponent. β is a proportionality constant describing the overhead per bit. Therefore, instead of observing how much *GAPA* and *GAHA* protocols consume the quantitative energy power, respectively, we measure the relative ratio of power consumption. Furthermore, for simplicity, the ratio of power consumption of an ACK packet and a data packet is assumed to be 1:30, which means that we use an ACK packet of 60 bytes (including 40 byte-sized header) and a data packet of 640 bytes (including 40 byte-sized header) during our simulation.

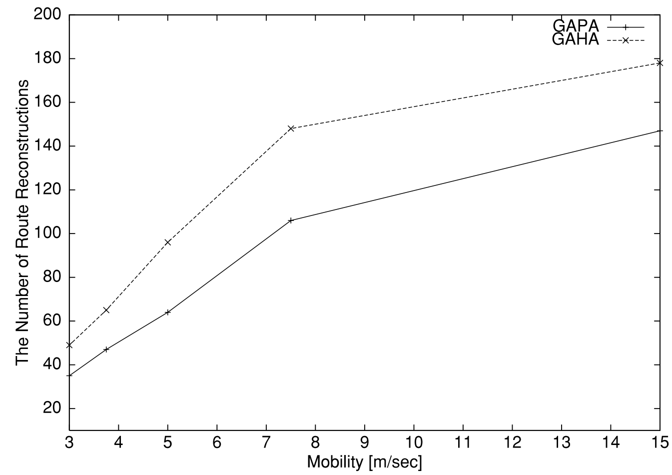


Fig. 8 Frequency of Route Reconstructions: GAHA and GAPA.

7.2 Observed Results

7.2.1 Comparing Frequency of Route Reconstructions

In the first simulation, we measure the impact of nodes' mobility on the frequency of route reconstructions for *GAHA* and *GAPA*. As shown in Fig. 8, as the rate of nodes' mobility increases, more route reconstructions are invoked for both *GAHA* and *GAPA* schemes.

In *GAHA*, the radio transmission ranges of data packets are fixed, while those of ACK packets are variable. However, in *GAPA*, since the radio transmission ranges of data packets are variable and extensible to reach the up-link node in case that the up-link and down-link nodes are more and more far away, the increase of radio transmission range of data packets results in fewer route failures because the partial path from the down-link node towards the destination is more stable. This explains why *GAPA* outperforms *GAHA*.

7.2.2 Throughput Comparison

We investigate the impact of nodes' mobility on throughput. Throughput is defined as the ratio of the successfully received UDP packets to the number of UDP packets transmitted by the source node. For both *GAHA* and *GAPA*,

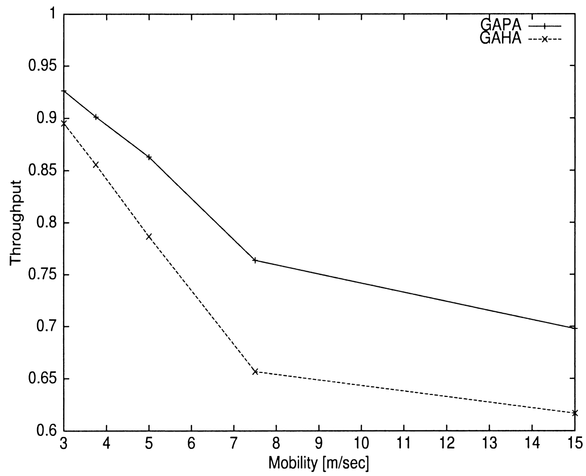


Fig. 9 Throughput: GAHA and GAPA.

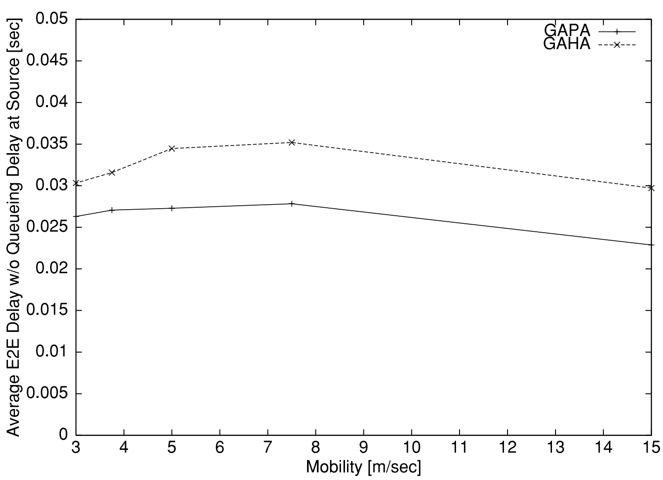


Fig. 10 Average end-to-end delay without queueing delay: GAHA and GAPA.

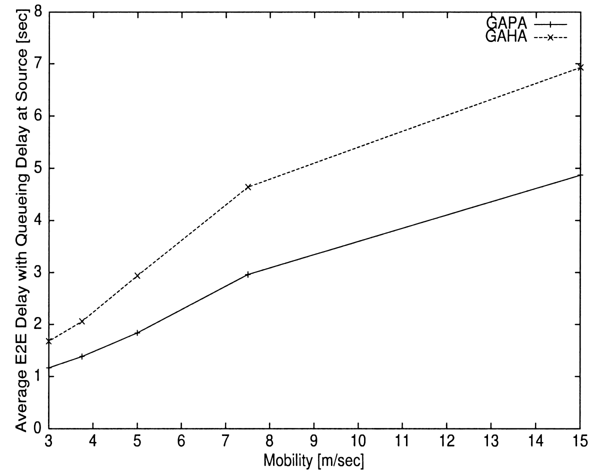


Fig. 11 Average end-to-end delay including queueing delay at source node: GAHA and GAPA.

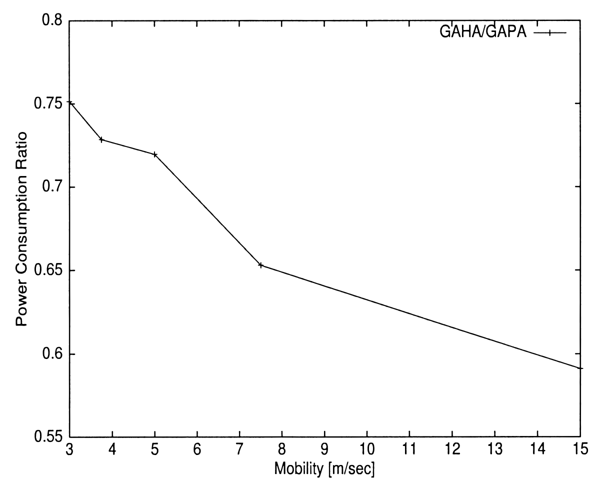


Fig. 12 Power consumption ratio: GAHA/GAPA.

throughput decreases as the rate of nodes' mobility increases because the source node stops sending the data packets more often due to route failures. Figure 9 shows that *GAPA* has better performance than *GAHA* since *GAPA* uses a shorter acquired path due to the previously increased transmission ranges of intermediate nodes when performing a route recovery and the fewer number of required route reconstructions as well.

7.2.3 Comparison of Packet Delays: End-to-End Delay without and with Queueing Delay at Source Node

We performed two simulations to observe the average end-to-end delay taken to send the data packet from the source to destination. First, we measure the average delay taken for a packet to arrive at the destination node from the departure of the source node's queue. In *GAPA*, since nodes can increase their radio transmission ranges to reach their up-link nodes according to node mobility, the nodes with large transmission ranges can have much more neighboring nodes than ones with small transmission ranges. In other words, nodes with large transmission ranges are able to connect in less hops than those with small transmission ranges. This means smaller delay for *GAPA* than *GAHA*, as shown in Fig. 10. Since Fig. 10 also shows that nodes' mobility has little influence on the average delay of packet propagation, the average delay depends mainly on the traffic condition on each intermediate node in the path as well as the path length.

In the second case, we include queueing delay at the source node before transmission into consideration (i.e., we measure the average time spent by a packet from the instant it is enqueued until it arrives at the destination.). Similar to the reasoning mentioned before, *GAPA* shows better performance than *GAHA* (see Fig. 11). However, unlike Fig. 10, the mobility of nodes has the serious impact on the average delay factor because the packets requested to be sent to the destination are pending for the transmission at the source's queue until the new path is acquired after the route failure. In other words, frequent route disconnections result in a longer packet queueing delay at the source node.

7.2.4 Comparison of Power Consumption

Although *GAPA* has outperformed *GAHA* in terms of route reconstructions, throughput, and end-to-end delay performance, we should also measure the amount of power consumption. This is a crucial factor since mobile nodes have limited battery life time. As shown in Fig. 12, in *GAPA*, since nodes can increase their radio transmission ranges for data packets when needed to overcome problems of asymmetric wireless links, and furthermore, continue using the increased transmission ranges for the successively arriving data packets, *GAPA* consumes more power than *GAHA*. Note that *GAHA* requires nodes to increase their radio transmission ranges for the ACK packets momentarily. In our simulation, we measure the ratio of the power consumption of *GAHA* and *GAPA* (i.e., $\frac{Power\_Consumption\_of\_GAHA}{Power\_Consumption\_of\_GAPA}$, which is less than 1). Moreover, when rate of nodes' mobility increases, *GAPA* consumes even more power than *GAHA* as shown in Fig. 12 (we can see that the ratio decreases according to nodes' mobility).

8. Conclusions

In this paper, we introduced two approaches to cope with the presence of asymmetric links in mobile ad hoc networks, namely: (a) GAHA (GPS-based Hop-by-hop Acknowledgment), and (b) GAPA (GPS-based Passive Acknowledgment) schemes. Both *GAHA* and *GAPA* were applicable to the basic hop-by-hop and passive acknowledgment schemes used in several source-initiated on-demand routing protocols. *GAHA* and *GAPA* utilize GPS (Global Positioning System) location information of nodes. Simulation results show that *GAPA* outperforms *GAHA* in terms of frequency of route failures, throughput, and end-to-end delay. However, when it comes to power consumption, *GAPA* consumes more power than *GAHA* due to the large radio transmission range for data transmission. Hence, for networks where battery power is very constrained, *GAHA* protocol is more suitable. *GAPA* yields better communication performance at the expense of power. Furthermore, our schemes can be applied to existing on-demand routing protocols to overcome asymmetric link problems.

References

[1] J. Broch, D.B. Johnson, and D.A. Maltz, "The dynamic source routing protocol for mobile ad hoc networks (Internet draft)," Dec. 1998.
[2] C. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector (DSDV) routing for mobile computers," ACM SIGCOMM, Sept. 1994.
[3] Z. Haas and M. Pearlman, "The zone routing protocol (ZRP) for ad hoc networks," draft-ietf-manet-zone-zrp-02.txt, June 1999.
[4] D.K. Kim, S.J. Ha, and Y.H. Choi, "Cluster-based dynamic source routing protocol in wireless ad hoc network with variable-sized cluster and variable transmission ranges," IEEE VTC, 1999.
[5] Y.B. Ko and N.H. Vaidya, "Location-aided routing (LAR) in mobile ad hoc network," MOBICOM'98, 1998.
[6] C.-K. Toh, "Associativity based routing for ad hoc mobile networks," Wireless Personal Communications Journal, Special Issue on Mobile Networking & Computing Systems, vol.4, no.2, pp.103–139, March 1997.
[7] D.K. Kim, C.-K. Toh, and Y. Choi, "Location-aware long-lived route selection in wireless ad hoc networks," IEEE VTC Fall, Boston, USA, 2000.
[8] K. Chandran, S. Raghunathan, S. Venkatesan, and R. Prakash, "A feedback based scheme for improving TCP performance in ad hoc wireless networks," ICDCS, 1998.
[9] D.K. Kim, C.-K. Toh, and Y. Choi, "TCP-BuS: Improving TCP performance in wireless ad hoc networks," J. Communications and Networks, vol.3, no.2, pp.175–186, 2001.
[10] F. Talucci and M. Gerla, "MACA-BI (MACA By Invitation) A wireless MAC protocol for high speed ad hoc networking," ICUPC, 1997.
[11] Z. Haas and J. Deng, "Dual Busy Tone Multiple Access (DBTMA): Performance evaluation," IEEE VTC, 1998.
[12] P. Krishna, M. Chatterjee, N.H. Vaidya, and D.K. Pradhan, "A cluster-based approach for routing in ad-hoc networks," Second USENIX Symposium on Mobile and Location-Independent Computing, 1995.
[13] T.S. Rappaport, Wireless Communications: Principles & Practice, Prentice-Hall PRT, Upper Saddle River, New Jersey, 1996.
[14] C.E. Perkins, E. Royer, and S.R. Das, "Ad hoc on demand distance vector (AODV) routing," Internet Draft, http://www.ietf.org/internet-drafts/draft-ietf-manet-aodv-05.txt, March 2000.
[15] S. Desilva and S.R. Das, "Experimental evaluation of a wireless ad hoc network," Proc. International Conference on Computer Communications and Networks (ICCCN), Las Vegas, USA, 2000.
[16] J.M. Rabaey, M.J. Ammer, J.L. da Silva, Jr., D. Patel, and S. Roundy, "Picoradio supports ad hoc ultra-low power wireless networking," IEEE Comput., vol.33, no.7, pp.42–48, July 2000.
[17] IEEE Computer Society LAN/MAN Standards Committee, ed., IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Std 802.11, 1997.

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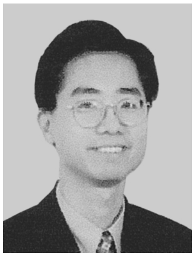

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