On supporting Link Asymmetry in Mobile Ad Hoc Networks

Dongkyun Kim, C.–K. Toh, and Yanghee Choi

Abstract

The existing routing protocols in mobile ad hoc networks assume that all nodes have the same transmission range. In other words, the mobile ad hoc network has only symmetric links. 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. This paper present two protocols that accomodate asymmetric links: link-level and end-to-end Approaches. The link-level approach can be applied to any routing protocols by utilizing GPS(Global Positioning System) location information of nodes at link level. On the other hand, the end-to-end approach does not need GPS devices and employs dual paths between source and destination. Simulation results reveal that these protocols cope well with ad hoc network having asymmetric wireless links under the presence of mobility.

Keywords : *Ad Hoc Network, Asymmetric Links, Routing Protocol, Global Position System, Dual Paths*

I. Introduction

Recently, research effort for mobile ad hoc networks has been made. Moreover, note that most routing protocols proposed for mobile ad hoc networks 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 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 mechanism was introduced [1].

In this paper, we introduce two solutions to address these asymmetric links in mobile ad hoc network: link-level and end-to-end approaches.

In link-level approach, two candidate protocols are presented : *GAHA(GPS-based Hop-by-hop Acknowledgment)* and *GAPA(GPS-based Passive Acknowledgment)* schemes[11]. These schemes are based on hop-by-hop and passive acknowledgment schemes used in DSR for route maintenance as well as link-level acknowledgment of successful reception of data packets. In hop-by-hop acknowledgment scheme in DSR, route is maintained based on the acknowledgment packet from the down-link node. However, in passive acknowledgment scheme in DSR, after sending a packet to the down-link node, the up-link node listens to the down-link node sending the packet further down the path. The absence of a packet forwarded from the down-link node is used to detect a route failure. Therefore, we modified the hop-by-hop and passive acknowledgment schemes to support asymmetric links by using GPS. Since *GAHA* and *GAPA* support the asymmetric links at link level, they can be applied to any routing protocols which need to be revised slightly to get a path accommodating asymmetric links during the route discovery process. That is, *GAHA* and *GAPA* can be used independently from routing protocols.

On the other hand, we also propose a new routing protocol to support asymmetric links in end-to-end manner(called RODA-ROuting protocol with Dual paths to support Asymmetric links)[12]. We use dual paths for route maintenance : forward path(source-to-receiver) and backward path(receiver-to-source). Generally, for the purpose of communicating between the source and receiver, there exists a need to acknowledge the successful end-to-end reception of packets. In addition, the bi-directional channel is preferred because the receiver node may send its packets to the source besides the acknowledgement packets.

Although most existing routing protocols may use a new path to support data or acknowledgement information from receiver to source instead of using a reverse path, they have no mechanism to cope with asymmetric links. Therefore, our protocol takes advantage of the acquired backward path from the receiver to the source to notify the source of route disconnection, and the acquired forward path from the source to the receiver to notify the receiver of route disconnection.

The rest of this paper is organized as follows. Section II discusses the possibility of existing routing protocols to support the asymmetric links. Next, Section III presents proposed link-level approach with the description of *GAHA* and *GAPA*. In section IV, we describe our proposed RODA protocol. In addition, we compare these link-level and end-to-end approaches by presenting simulation results in section V. Finally, the conclusion remarks are given in section VI.

II. Problems Occurred at Routing Protocol

Several on-demand routing protocols such as AODV[8], ABR[5], 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[8], 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[5], 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 desti-

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nation 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 misinterprets node A as a member in its zone. This can cause a serious problem in route decision between the source and destination nodes. An approach for supporting asymmetric links has been proposed in [4]. However, it is only applicable to ZRP and hence not a general solution.

In DSR[1], similar to AODV and ABR, a route request message is flooded into the network to establish a route when the source has data packets to send. The destination node selects the shortest path[1] 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.

III. Link-level Approach

A. Assumption for Routing Protocols

We assume that a routing protocol can provide the end-to-end path from source to destination as follows. Hence, if the path acquired by the routing protocol consists of all symmetric links, the path information can be propagated via reverse path(Figure 1a). 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(Figure 1b), or (b) using another path from the destination to the source(Figure 1c). In Figure 1b, 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 the process of an initial route discovery is able to provide an end-to-end path in the presence of asymmetric links, there can still exist asymmetric links at link level due to mobility and power degradation of nodes.

B. Our Proposed Schemes : GAHA and GAPA

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 information is 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.

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

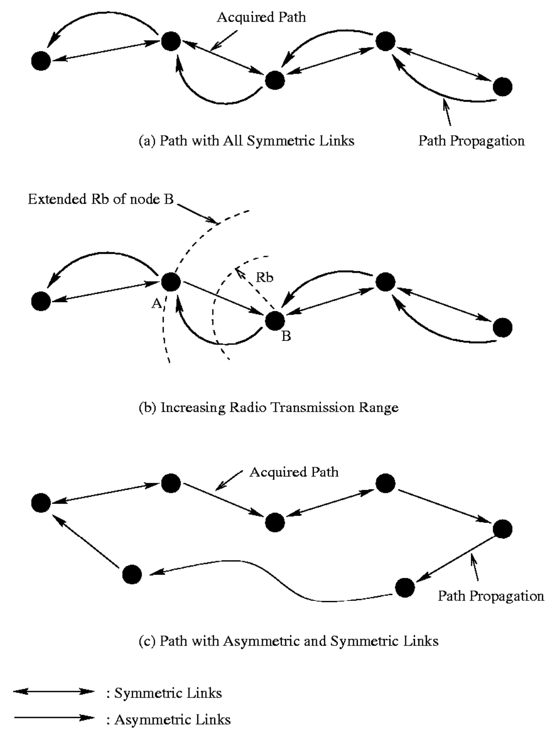

Fig. 1. Acquiring a Path at Routing Protocol.

B.1 <u>G</u>PS-b<u>a</u>sed <u>H</u>op-by-hop <u>A</u>cknowledgment (*GAHA*)

By using the up-link node's location information propagated to the down-link node, the down-link node knows whether 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 corresponding to the geographical distance between the up-link and down-link nodes without loosing connectivity.

Figure 2 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 if 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.

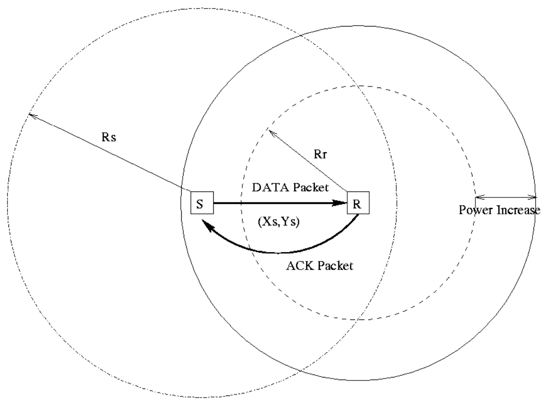

Fig. 2. GAHA

B.2 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 reach the up-link node. However, 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 below 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 be increased only if a node cannot reach its up-link node.

Figure 3 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 Figure 3, 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. This power increase can result in the fewer number of route reconstructions and higher throughput.

IV. End-to-End Approach

A. Proposed RODA Routing Scheme

RODA protocol has two phases: route discovery and route maintenance. When the source has packets to send to the receiver, the source performs the route discovery process in an on-demand manner. Even if the acquired route is used for communication between two end nodes, the route may be broken due to node movements, which results in the need for route reconstruction or extension.

A.1 RODA Route Discovery Phase

Along with using a source-initiated on-demand routing protocol, a route selection scheme is adopted to derive a long-lived route[2]. Unlike the other proposed routing protocols, asymmetric links may be used to route packets using our proposed approach. Although we are able to construct a route by using only symmetric links when deriving a route, asymmetric links can naturally occur over time due to reduction of battery power. Link intermittency and changes can result in many route reconstructions. The forward (source-to-receiver) and backward paths (receiver-to-source) are needed to handle asymmetric links.

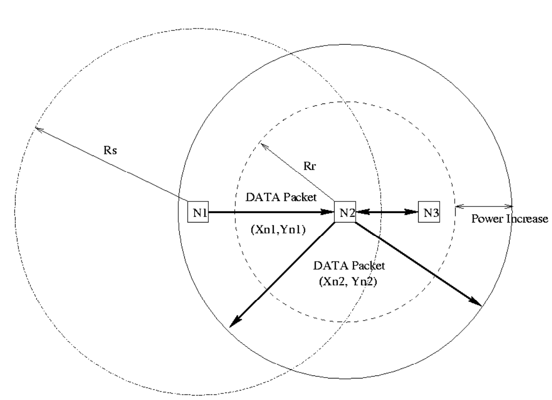

Fig. 3. GAPA

In this section, we describe briefly the process of acquiring the two paths in the presence of asymmetric links. When a source wants to send packets to the receiver, it floods a route discovery packet which will include information of nodes visited as the packet propagates towards the destination. At the receiver node, among the collected candidate paths (which include asymmetric links), the best route is selected. To derive the best route, GPS (Global Positioning System)[6] or association stability information [5] can be used. This selected path will be used as the forward path from the source to receiver. Next, the information of forward path is embedded into the route discovery packet which is flooded into network by the receiver to derive a backward path to the source.

Consequently, at the source, the information on forward path can be extracted from the route discovery packet which is propagated to derive the backward path. A packet (Forward_Packet) is generated by the source to make nodes along the forward path function as forwarding nodes and it also contains information on the backward path selected by the source. Each intermediate node receiving the Forward_Packet keeps track of the up-link and down-link nodes for forwarding the data packets. Finally, on receiving the Forward_Packet, the receiver generates a Backward_Packet which is sent to make nodes along the acquired backward path forward data packets over the reverse path.

A.2 RODA Route Maintenance Phase

In RODA protcol, packets are able to reach the receiver only if the down-link node is within the transmission range of the up-link node. As beacon signals are generated periodically at nodes along the acquired path, a down-link node is able to detect route disconnection if it cannot hear any beacon signal from the up-link node for a given time duration(a system parameter).

Let's consider a forward path from the source to the receiver (Figure 4). When a down-link node (node D) detects a link breakage due to the absence of beacon signals from its up-link node (node C) during a time duration, node D generates an

[2] the best route which is highly likely to be used for the longest time without a route disconnection

RDN(Route Disconnection Notification) message towards the receiver (node E) along the partial path from itself to the receiver node. After being notified of the link breakage, the receiver node also propagates this information towards the source along the backward path (E-F-G-H-I-A). On receiving the RDN message, the source recognizes the breakage of the forward path and tries to acquire a new forward path. A route discovery packet is generated by the source, and it is flooded towards the receiver. The best route can be selected by the receiver among the candidate paths. The information on the newly acquired forward path is made known to the source along the existing backward path. As mentioned above, a Forward_Packet is also generated by the source at this time. State information of each node for maintaining the corresponding route (information on up-link node, down-link node, and beacon signal generation) needs to be refreshed as each intermediate node(which has to play a role in forwarding data packets) receives the route discovery or extension packet.

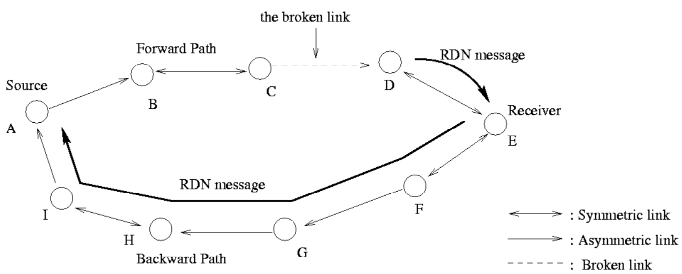

Fig. 4. An Illustration of Route Recovery Process for Acquiring a New Forward Path

Even if an up-link node at some broken link of a forward path is able to acquire an extended partial path to the receiver after receiving the RDN message propagated by the source (as in the ABR protocol), it is possible that the RDN message generated by a down-link node cannot reach the up-link node of the broken link as follows. As shown in Figure 5, when the other link (B-C) is also broken before the RDN message reaches the up-link node (node D). The RDN message cannot reach the corresponding up-link node (node D) because node C is unable to receive the RDN message. Therefore, node D cannot initiate the route discovery procedure, which results in a deadlock for acquiring a new path.

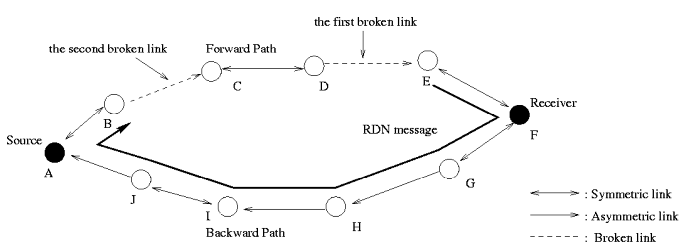

Fig. 5. Source node initiates route reconstruction to avoid the deadlock where RDN messages cannot reach the up-link node due to multiple link-breakage

To address this problem, we adopt a scheme in which the source derives a new forward path. As for a link breakage on the backward path, the resolution procedure is similar with exception that the receiver node tries to obtain a new backward path.

Route reconstructions for forward and backward paths are performed by the source and receiver nodes, respectively. However, when two consecutive route failures occur over both forward and backward paths as shown in Figure 6, as both the source and receiver nodes cannot receive their corresponding RDN messages, route re-construction process will fail to operate.

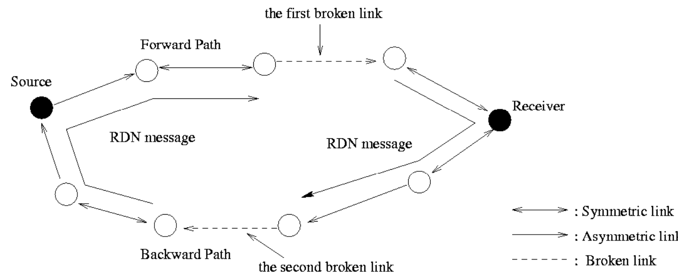

Fig. 6. An Illustration on the Necessity for RDN_Timer Mechanism

To avoid the possibility of a deadlock situation where there exist no routes between the source and the receiver, after the source receives an RDN message requiring the source to execute the route reconstruction process for the backward path, it sets RDN_Timer. If the RDN message has succeeded in reaching the receiver, a route discovery packet for a new backward path will reach the source before the RDN_Timer expires. Otherwise, in the absence of any route discovery packet during the RDN_Timer, the source will think that a situation like Figure 6 has occurred and will try to flood the route discovery packet to derive the new complete dual paths(forward and backward paths).

If the receiver also tries to let the source acquire a new forward path based on RDN_Timer, the following problem can occur. As shown in Figure 6, the receiver node also receives the RDN message which notifies the receiver node of the link breakage over the forward path. Therefore, if the receiver node activates its RDN_Timer for the forward path, the RDN_Timer's expiration results in sending a route reconstruction packet for the forward path.

Consequently, the source and receiver nodes perform the route-reconstruction for each unidirectional path independently. After getting a backward path (a forward path), the path information should be flooded to the receiver (the source) in case that there is no route to the receiver (the source). Alternatively, the source (the receiver) should wait for the completion of route establishment for the forward path (the backward path). This results in too much overhead for maintaining the routes. Therefore, in our proposed protocol, the source node only maintains RDN_Timer for acquiring two paths. In summary, when an RDN message cannot be propagated properly due to multiple link failures, the source will derive new complete dual routes according to the RDN_Timer's timeout mechanism.

V. Comparison of Link-level and End-to-end Approaches

A. 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, a source-initiated on-demand routing protocol is implemented with relying on the source receiving the Route Error Message. We use the random waypoint model[1] 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 m x 5000 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 70 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.

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 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[9].

The power consumption model assumes that power is depleted proportionally to d^2, where d is the distance between the sender and receiver nodes[7]. According to [10], 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 each protocol consumes 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.

B. Observed Results

We compared delivery ratio(defined as the ratio of the successfully received UDP packets to the number of UDP packets transmitted by the source node) for four protocols: DSR-asymmetric, RODA, GAHA and GAPA(Figure 7). For the pupose of comparison of delivery ratio, the modified version of the DSR protocol is also simulated for supporting asymmetric links, called DSR-asymmetric protocol which can notify the source node of the path information acquired at the receiver node by either using an explicit backward path from receiver to source or the reverse path of the acquired route. When using the reverse path, radio transmission should increase in order to reach up-link node in case of the existence of asymmetric links over the obtained path. In DSR-asymmetric protocol, when an up-link node of a link over the path cannot receive the acknowledgement information whether it is implicit or explicit, it generates an ROUTE ERROR message to the source node which triggers a process of route reconstruction on receiving the ROUTE ERROR message.

As mentioned above, GAPA outperforms GAHA because GAPA may larger radio transmission ranges of nodes for the data transmission than GAHA due to node mobility. It results in reduction of the number of route failures. However, RODA makes use of two paths, in other words, forward and backward paths. It increases the probability of route failures over the path, resulting in lower delivery ratio than GAHA and GAPA. Instead, DSR-asymmetric protocol makes the source perform a new route reconstruction although the up-link node of an asymmetric link is capable of forwarding the received data toward the destination, resulting in breakages of data transmission until a new path is acquired, namely, the worst reduction of delivery ratio among four protocols.

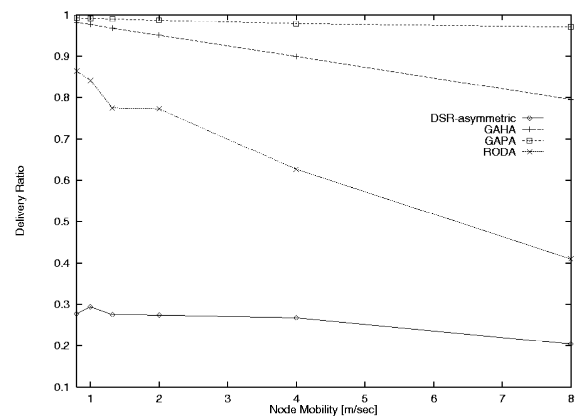

Fig. 7. Throughput Comparison.

From Figure 8, we can see that DSR-asymmetric protocol experiences the largest number of route failures among four protocols. The reason why DSR-asymmetric protocol shows several thousands of route reconstructions while the others show several tens of route reconstructions is that whenever an acquired path contains some asymmetric links, the source tries to get a new path which may contain asymmetric links, resulting in the successive processes of route reconstructions. Note that at high movement rate of nodes, RODA shows more reduced frequency of route failure than GAHA. RODA makes link breakage on forward and backward paths occurred frequently at high movement rate, depending on the timeout mechanism of RDN_Timer. It spends most of time in waiting for the event of RDN_Timer expiration , when the source tries to acquire two paths, resulting in less number of route reconstructions and lower delivery ratio than GAHA.

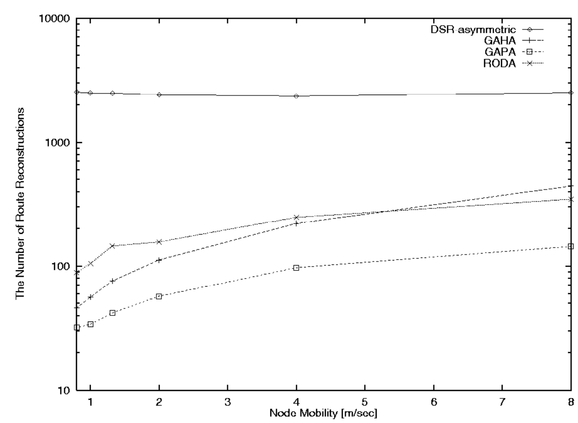

Fig. 8. Comparing Frequency of Route Reconstructions.

We also measured the end-to-end delay in the pair of source and destination nodes without queueing delay at source and intermediate nodes for three protocols. 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 is able to connect in less number of hops than those with small transmission ranges. This means smaller delay for GAPA than GAHA and RODA, as shown in Figure 9.

However, RODA shows better performance than GAHA in terms of end-to-end delay. Since RODA experiences more route reconstructions than GAHA, the source node acquires a new path with the smallest number of hops at every route recovery, resulting in smaller end-to-end delay.

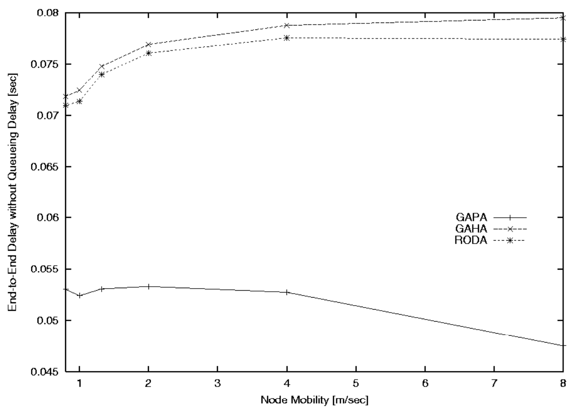

Fig. 9. End-to-End Delay without Queueing Delay.

Finally, we also compared three protocols in terms of power consumption(Figure 10). In our simulation, we measure the ratio of the power consumption of GAHA and GAPA as well as RODA and GAPA (i.e., $\frac{Power\_Consumption\_of\_GAHA}{Power\_Consumption\_of\_GAPA}$ and $\frac{Power\_Consumption\_of\_RODA}{Power\_Consumption\_of\_GAPA}$, which are less than 1). Moreover, when node mobility increases, GAPA consumes more power than GAHA and RODA, as shown in Figure 10 (we also see that the ratio decreases as node mobility increases.). RODA outperforms GAHA because GAHA increases the radio transmission range of nodes in order for ACK packet to reach the up-link node. We can easily infer that a heavy traffic requires more adjustments of radio transmission range.

However, RODA always utilizes the static radio transmission range, resulting in reduction of power consumption even if the reduced power consumption might be achieved due to the small amount of transferred data packets between the source and destination. Although RODA makes use of beacon signals for detecting route failure, as the beacon signals are generated periodically, for example, every second, and furthermore, the packet size of beacon signal is very small, the total amount of power consumption are not influenced very much.

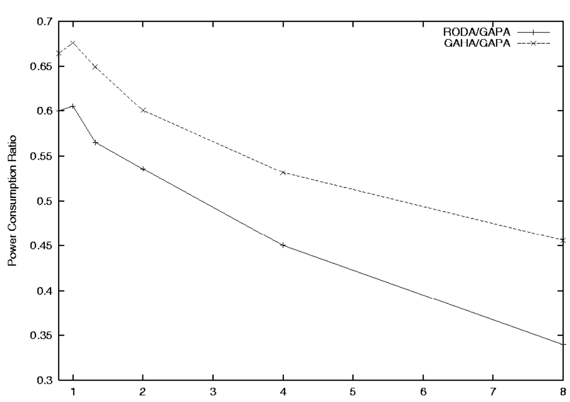

Fig. 10. Comparison of the Amount of Power Consumption.

VI. Conclusions

In this paper, we introduced two approaches to support the occurrences of asymmetric links in mobile ad hoc network: link-level and end-to-end approaches. For the purpose of supporting the asymmetric links, both *GAHA(GPS-based Hop-by-hop Acknowledgement)* and *GAPA(GPS-based Passive Acknowledgement)*, which are link-level approaches, are the modified protocols of the basic hop-by-hop and passive acknowledgment schemes used in DSR(Dynamic Source Routing) protocol. *GAHA* and *GAPA* utilize the GPS(Global Positioning System) location information of nodes. Unlike link-level approach, in end-to-end approach called RODA, two independent paths for forward and backward data transmission are maintained. Unidirectional link breakage on forward or backward path are recovered by invoking route reconstruction procedure at the source or receiver, respectively. Furthermore, a timer-based route reconstruction method at the source is introduced to address scenarios with simultaneous and consecutive broken links on both the forward and backward paths.

Link-level protocols outperforms the end-to-end protocol in terms of the frequency of route failures and throughput. However, the former consumes more power than the latter since the link-level protocols change radio transmission ranges of nodes, while the end-to-end approach utilizes static ranges. In wireless network with limited battery power, the end-to-end protocol is more likely to be used even if there is some expense for performance. Otherwise, we can take advantage of link-level protocol for performance improvement.

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