A Reliable and High Throughput Multi-Rate Ad Hoc Routing Protocol: Cross Layer Approach

Cao Trong Hieu
Department of Computer Engineering
Kyung Hee University
Email: hieuct@khu.ac.kr

Choong Seon Hong
Department of Computer Engineering
Kyung Hee University
Email: cshong@khu.ac.kr

***Abstract*—In this paper, a high throughput routing protocol, using the MAC layer information, for Multi-Rate Ad-hoc Networks is proposed. By choosing the route with the minimum value of the proposed *"Route Assessment Index"*, the selected route is ensured to have high throughput with link's reliability. Also, link bottleneck could be avoided in the chosen route. Hence, the packet drop rate is also decreased. The correctness of the proposal is proven and the simulation results show that our new metric provides an accurate and efficient method for evaluating and selecting the high throughput route in Multi-Rate Ad-hoc Networks.**

I. INTRODUCTION

Ad hoc Networks currently have become an ideal topology for establishing an instant communication infrastructure where other kinds of networks have difficulties to be deployed. Each node has the ability to communicate directly with any others in its communication range, while the out-of-range nodes use intermediary hops to communicate with each other. The wireless ad hoc networks (including wireless sensor networks) are applicable to a wide variety of fields as they are operable without any predefined infrastructure.

Nowadays, physical layer enhancements support multiple data rates, which enable wireless nodes to select the appropriate transmission rate depending on the required quality of service, the radio channel conditions, and the relative distance with communicating nodes. For example, the IEEE 802.11g standard [1] with OFDM technology support eight Modulation and Coding Schemes (MCS) and offers eight data rates between 6Mbps to 54Mbps according to the selected MCS.

For transmitting data at a specific rate r_k (i.e., r_k = (6, 9, 12, 18, 24, 36, 48, 54) Mbps), the corresponding receiver sensitivity requirement is needed. Remember that the number of rate levels, as well as the maximum data rate, here follow the IEEE 802.11g standard [1]. Hence, to transmit data at rate r_k, the received signal strength (P_r) must at least equal the receiver sensitivity ($P_{S_{r_k}}$). Using the log-distance path loss model in [2] for radio propagation, we can determine the transmission range R_{r_k} at rate r_k as:

$$R_{r_k} = 10^{\frac{P_t - P_{S_{r_k}} - 20\log_{10}(4\pi f/c)}{10\gamma}} \quad (1)$$

in which, P_t and $P_{S_{r_k}}$ are the transmit signal and required signal sensitivity at rate r_k in dBm, $20\log_{10}\left(\frac{4\pi \bar{d} f}{c}\right)$ is the free space path loss at at unit distance in dBm for signal speed of c and frequency f, and γ is the path loss exponent ($1.8 \leq \gamma \leq 6$) depending on the channel condition between the sender and the receiver.

As shown in the Eq. (1), there are two main factors that affect the transmission rate: the transmission range and the path loss exponent γ. For a predefined network location, the path loss exponent γ is known and can be measured. Hence, with γ is known in advance, only the transmission range can affect the transmission rate, and they have a direct relation: a low rate link can cover a larger distance, while for higher rate link, the communication range is shrunk. The communication rate must be adjusted to the relative distance between two nodes.

To support the selection of data rate r_k, the MAC layer delivers received data packets to the network layer along with the $RSSI$. The $RSSI$ provides the information about receiver power P_r. The received power P_r is used to compare with the referenced sensitivity $P_{S_{r_k}}$. If $P_r \geq P_{S_{r_k}}$, then the highest possible rate r_k is chosen for data transmission. For example, if a node receives a packet with P_r = - 68dBm, then it determines $P_{S_{r_k}}$ = 36Mbps because $P_{S_{r_k}}(36Mbps) < -68dBm < P_{S_{r_k}}$(48Mbps). Hence, the highest supported rate in this case is 36Mbps. The connectivity is broken when the relative distance $> R_{\min(r_k)}$ (the two nodes out of communication range).

Consider the multi-rate ad hoc networks, up to now, there are still very few works proposing the effective routing metrics that can utilize the benefit of using multi-rates. In this paper, we proposed a new routing metric named *"Route Assessment Index"*, which utilize the benefit of the highest possible rate, under the consideration of link reliability (packet delivery rate), according to the relative distance of two communicating nodes. Selecting the route with minimum RAI value guarantees that a the route has high throughput, and can avoid link's bottleneck. We also prove that the route with the minimum RAI value will have a small number of intermediate nodes among route candidates. Therefore, the end-to-end throughput increases significantly. In this paper, we use the term *link reliability* to refer the ability of a link to successful deliver data packets, and the term *effective link capacity* to refer the combination of link reliability and link rate. The details will be shown in Section III-A.

The remaining parts of this paper are organized, as follows. In Section II, we analyze related work and some well-known routing metrics. The main part including proposed protocol's model and operation with an example is presented in the Section III. The performance of RAI is given in Section IV. Finally, in Section V, we conclude our paper.

II. Related Work

A lot of routing protocols have been proposed for the (mobile) wireless ad hoc networks, which are followed one of two major strategies: proactive such as in DSDV [3] and OLSR [4] and reactive (on-demand) such as in AODV [5] and DSR [6]. These protocols were originally designed for single-rate networks, and have used the shortest path algorithm with the minimum hop count metric to select paths. Min hop is a good metric in single rate networks, where all links are equivalent. However, it does not perform well in the multi-rate wireless network, because it does not utilize the higher link rates for data transmission. Indeed, the transmission range of high data rate is shrunk as discussed in the Section I.

For the multi-rate ad hoc networks, Awerbuch et al. proposed the Medium Time Metric (MTM) in [7] with the consideration of multiple data rates. The authors claim that MTM can select optimal throughput paths, and tends to avoid long unreliable links. MTM assigns a weight to each link in the path, which is proportional to the packet transmission time on that link, and then adds all the weights for the path. The proactive routing protocol DSDV[3] is modified by using MTM as metric instead of hop count. The simulation results show that the throughput gains of up to 100% to 200% can be achieved over the traditional route selection. However, the weak points of MTM is it was designed for proactive routing protocol, so that each node must maintain the whole network information of others. Without an effective route discovery strategy, the needed time to find a good route is considerable. Also, MTM was not designed to avoid selecting some particular lower rate links, hence, they will cause high packet drop rate at those bottleneck links. Consequently, the throughput will be downgraded. Our proposed routing protocol will solve those weaknesses.

The author in [8] introduced an approach for multi rate MANETs to improve the traditional AODV routing protocol. The proposal based on the link cost which is simply provided by delay time for transfer a packet from the MAC layer which is inherited from [7]. Nicolaos et al. in [9] proposed a routing metric for communication network using the connection probability approach. The authors also introduced the concept of link cost. However, they did not specify how to calculate the link cost for their routing metric. Also, the complexity of their proposal is very high because each node has to maintain the information of all other nodes in the network to calculate the routing metric based on the proposed probability models.

III. Proposed Routing Protocol

In this section, we propose the new routing metric working for the reactive protocols. Along with the routing metric, the route discovery phase also plays an important role in a routing protocol, by helping source find as good as possible route to destination within a negligible time. Therefore, in this section, we introduce an effective strategy for the route discovery process with an example as the demonstration. Finally, we explain the operation of our routing protocol.

A. Proposed Routing Metric

Consider a multi-rate ad hoc network, in which, any two neighboring nodes (direct communication) use the highest possible rate to communicate corresponding to their relative distance as described in Section I. In the wireless environment, due to the impacts of many factors, such as interferences and collisions, wireless links are not completely reliable. Hence, a packet may need to be transmitted more than one times, in order to be successfully received. Let d_f and d_r denote the packet delivery ratio in the forward and reverse directions, respectively. Let $\delta_{ab}^{(r_k)}$ is the *link reliability* when node a and node b communicates at rate r_k. So that the *link reliability* $\delta_{ab}^{(r_k)}$ is the fraction of the packets which are successfully received, and can be defined as $0 < \delta_{ab}^{(r_k)} = d_f \times d_r \leq 1$.

Next, we consider node i-th belonging to a route from source to destination, and define a weight for that position in the route. For a route, the weight associated with the i-th position is the sum of the link weight between the node that occupies the i-th position and the nodes occupying the previous and next positions in the route. Therefore, the weight associated with the i-th position can be defined as:

$$W_i = \frac{\delta_{i-1}^{(r_k)} r_k + \delta_{i+1}^{(r_l)} r_l}{\ln\left(r_{\max} - \min(\delta_{i-1}^{(r_k)} r_k, \delta_{i+1}^{(r_l)} r_l) + e\right)} \tag{2}$$

where r_k and r_l are the maximum possible rates that the node occupying the i-th position, and the nodes occupying the previous and next positions can use to communicate respectively. Here, $\delta_{i-1}^{(r_k)}$ and $\delta_{i+1}^{(r_l)}$ denote the *link reliability* with the previous and the next hop of node i-th at rate r_k and r_l, respectively. A node with a low link rate will have the lower weight as defined in the denominator. And, $(\delta^{(r_k)} \times r_k)$ can be defined as the *effective link capacity* at rate r_k. In this equation, r_{max} is the maximum data rate that a specific standard supports (in this case $r_{max} = 54Mbps$). We use natural logarithm (base $e = 2.718$) for calculation in this paper. Using any other logarithm base is straightforward.

If the value of r_k is much different to r_l, for example $r_k \ll r_l$, then the route will have a link bottleneck between $(i-1)$-th and i-th positions. To avoid choosing that node, we define the cost of node i-th as

$$C_i = \frac{W_i}{\ln\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|} \tag{3}$$

The denominator in the Eq. (3) is $\ln\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|$ to ensure that the value of C_i is finite when $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|$ = 0.

Let N_i is the number of intermediate nodes in the route, the coefficient α_i of position i-th is defined as

$$\alpha_i = \frac{C_i}{\sum\limits_{i=1}^{N_i} C_i} \tag{4}$$

in which, $\sum\limits_{i=1}^{N_i} \alpha_i = 1$. Note that α_i always greater than 0, because for a valid route, there exists at least one link in that route (in the case of $N_i = 0$ as source and destination are neighbors), and $\alpha_0 = 1$ in this special case.

Finally, the *Route Assessment Index* (RAI) is defined to choose the best route between the source and destination

$$RAI = \begin{cases} \frac{1}{N_i}\sum\limits_{i=1}^{N_i} \alpha_i \ln \alpha_i - \ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{max}} & \text{if } N_i > 1, \\ -\frac{\ln e}{e} - \ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}} & \text{if } N_i = 0, 1 \end{cases} \tag{5}$$

The metric is obtained as following: The first part ($\frac{1}{N_i}\sum\limits_{i=1}^{N_i} \alpha_i \ln \alpha_i \leq 0$) is formulated by applying the entropy properties[1]in [10] as an indication of the link's homogeneity and the path length: route with the minimum difference on capacities among links, and small number of hops, is preferred to choose. The second part ($\ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}}$) is the reference to choose the high data rate of individual links in a route: route with high capacity in each node is preferred to choose. Hence, the route with the smaller value of RAI will be proved to be a high throughput route without bottleneck links, and has small the number of hops.

We will discuss the effect of each parameter in Eq. (5) on choosing the better route by the following properties.

Lemma 1: The value of RAI satisfies the following condition:

$$-\frac{\ln N_i}{N_i} - \ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}} \leq RAI \leq -\ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}}$$

Proof: First, in Eq. (4), we have $0 < \alpha_i \leq 1$. Hence, $\ln \alpha_i \leq 0$ and max $\sum\limits_{i=1}^{N_i} \alpha_i \ln \alpha_i = 0$, leads to $RAI \leq -\ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}}$.

Next, for a sequence of non-negative number $\{\alpha_i\}$, using *Jensen's inequality* [10] we have

$$\frac{1}{N_i}\sum_{i=0}^{N_i} \alpha_i \ln \alpha_i \geq \frac{1}{N_i} \ln \sum_{N_i} \sum_{N_i} \alpha_i \geq -\frac{\ln N_i}{N_i}$$

Hence, $min(\frac{1}{N_i}\sum\limits_{i=1}^{N_i} \alpha_i \ln \alpha_i) = -\frac{\ln N_i}{N_i}$, and the lemma is proven. ■

[1]The entropy's properties for some sets $\{\alpha_i\}$ satisfied $\sum \alpha_i = 1$ can be expressed as following: - ***Maximality***: among observing sets which contain the same number of elements in each set, the set with more resemble elements will have the higher entropy outcome. Especially, a set of homogeneous elements will have the maximum entropy outcome. - ***Uniform distribution***: for sets with the different number of homogeneous elements, the higher number of elements a set has, the lower entropy outcome that set gets.

The problem of selecting the best route becomes the problem of choosing a route with the minimum RAI value, as equivalent to choose the maximum cost C_i in each intermediate node. Hence, the following properties of a route are achieved when it has small/minimum RAI value:

Theorem 1: The route with minimum RAI value, defined by Eq. (5), is the route with the small number of hops between source and destination.

Proof: From *Lemma* 1, $RAI_{\min} = -\frac{\ln N_i}{N_i} - \ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}}$. So when the number of intermediate nodes increase, we have

$$\lim_{N_i \to \infty} \frac{\ln N_i}{N_i} = 0$$

This means for route 1 with $N_i^{(1)} < N_i^{(2)}$ of route 2, $RAI^{(1)} < RAI^{(2)}$. So that the value of RAI will be increased as the number of intermediate nodes increases. Moreover, RAI is minimized when $\{\alpha_i\}$ have maximum values. From Eq. (4), α_i has higher value when N_i is small and $max(\alpha_i) = 1$ when $N_i = 0$ (no intermediate node) or $N_i = 1$. Therefore, with N_i small, the value of RAI will be decreased. Hence, the theorem is proven. ■

Theorem 2: The route with the minimum RAI value, defined by Eq. (5), (consequently, has maximum cost C_i defined by Eq. (3)), can avoid link's bottleneck.

Proof: From *Lemma* 1, the equality holds ($RAI_{\min} = -\frac{\ln N_i}{N_i} - \ln \frac{\min(\delta_i^{(r_k)} r_k)}{r_{\max}}$) as the *Maximality* of the entropy properties holds. This implies that α_i (or C_i) of any node in the route must have the equal value. Also, maximize the cost C_i in Eq. (3) becomes maximize the weight W_i and minimize the $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|$ value. That means the intermediate nodes with high data rates in all two links (minimize $r_{\max} - \min(\delta_{i-1}^{(r_k)} r_k, \delta_{i+1}^{(r_l)} r_l)$ value), and small difference between two effective links capacity (minimize the $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|$) are preferred. Hence, the best case is when $\delta_{i-1}^{(r_k)} r_k = \delta_{i+1}^{(r_l)} r_l$ (node i-th communicates with the previous and next nodes at the same highest effective link capacity). Contrarily, if there exist some links that have data rates more lower than other links in the route, then the RAI value will be increased, and that route will not be chosen. ■

Theorem 3: The route with the minimum RAI value, defined by Eq. (5), has the highest throughput among route candidates.

Proof: As shown in the Theorem 2, to get the minimum RAI value is equivalent to get the maximum C_i. To get the maximum C_i, the value of W_i in the Eq. (2) needs to be maximized along with minimize the difference between two effective link capacities. The value W_i is maximize when $(\delta_{i-1}^{(r_k)} r_k + \delta_{i+1}^{(r_l)} r_l)$ is maximized and $[r_{\max} - \min(\delta_{i-1}^{(r_k)} r_k, \delta_{i+1}^{(r_l)} r_l)]$ is minimized. Hence, an intermediate node will choose the next hop which has the highest effective link capacity with that intermediate node to communicate. The process is the same for all links in the route. Also, the length of routes is taken into account as discussed above. Therefore, the selected route will have the highest throughput among route candidates. ■

B. Route Discovery Strategy

It is conceivable that any routing metric based on the weight/cost of node/link should only be ensured to find the best path if and only if each node knows the entire network topology. Hence, it is straightforward for those metrics to be used in the proactive routing protocols. However, for the reactive routing protocols, since the traditional method is to keep track on only the 1-hop neighbor information, the first received RREQ at the destination apparently can not guarantee that the found route is either the best or the better route compare with others. Certainly, if the network information is unknown, for example, in the case of using MTM for the reactive routing, then every intermediate node in the network needs to forward any copies of the received RREQ to help the source node calculate all possible combinations of metric values. Also, the destination must wait for an unknown time to receive those copies of a RREQ to find the best route. However, the authors in [7] did not mention about any specific mechanism for the efficient route discovery to solve that problem.

Similar to the MTM or any other weight/cost based metrics, the RAI metric must allow duplicated RREQs to be retransmitted to find a better route within an acceptable time in the route discovery phase. In this section, a simple but effective technique is used to find a high throughput route. From the fact that the prior knowledge about neighbors information can support to find the better route (in the case of partial knowledge of network topology), or the best one (in the case of full network topology information), we propose to use the 2-hop neighbor information for the effective route discovery phase. The advantages of using 2-hop information will be show in the example below.

In order to keep track of the topology of the 2-hop neighbor, a node should include a list of its 1-hop neighbors in the Hello messages that it periodically broadcasts, together with the link weight towards each of the neighbors. By receiving Hello messages from every neighbor, a node is able not only to have a complete view of the 1-hop neighbor topology, but also to know its 2-hop neighbors and their connectivity with the 1-hop neighborhoods. It means that a node should know the links among the 2-hop neighbors to have a complete 2-hop topology information. Figure 1 shows how route discovery works with the assistance of 2-hop topology information. To make it simple for understanding, we only consider link rate without link reliability in this example. Suppose the first arrived RREQ on the destination will go through route $\{S, I_2, I_6, D\}$. Apparently, AODV based on the minimum hop count will select that route for the communication. However, that route is not a high throughput one and contains a link bottleneck (I_2, I_6). Therefore, in the case of RAI protocol, when node I_6 receives a RREQ message from node I_2, it calculates RAI values of all possible routes from source node up to node I_6 itself, using the link weights that it knows from 2-hop topology. By this

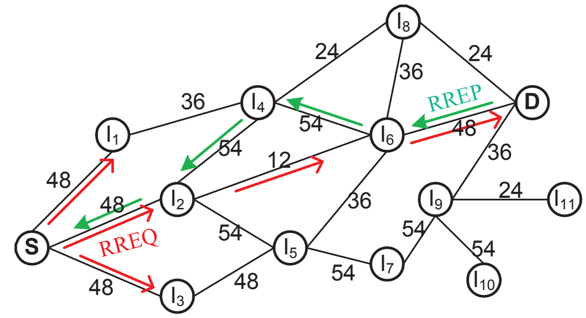


Fig. 1: An Example of Route Discovery

way, even though node I_6 still does not receive a copy of that RREQ from other neighbors (except from node I_2), it knows that the best route (within 2-hop topology knowledge) from source up to current node I_6 must go through node I_4 as $\{S, I_2, I_4, I_6, ...\}$. Hence, node I_6 will continue forward that RREQ to its neighbors with the list of nodes which forms the most high throughput route from the source. In this example, node I_6 will send the list $\{S, I_2, I_4, I_6\}$ instead of the list $\{S, I_2, I_6\}$ as traditional protocols will do. Every node has already included in the list (i.e. node I_4) will simply discard all latter arriving duplicated RREQs to avoid addition overhead of message flooding. Therefore, the route discovery using 2-hop information is enough effective, also, can balance the tradeoff between the overhead of maintaining the network information and the time consuming for finding a good route. We also observed that, by using 2-hop information, the first arrived RREQ packet in almost cases provides the information of the best route. The reason is the latter arrived RREQ packets usually go through routes with the considerable number of addition nodes, that make the RAI value increase.

C. Protocol Operation

Similar to other on-demand routing protocols, the processes of the route discovery and maintenance based on the Route Request (RREQ), Route Reply (RREP) and Route Error (RERR) exchange are used in our protocol. The operation is the same as the traditional AODV protocol[5] with some modifications presented below. The source address and sequence number fields in the RREQ jointly identify a unique RREQ instance in the network. Instead of the hop count, we use the *"Route Assessment Index"* as the routing metric. The proposed protocol enables a node to choose and control the data rate for a packet. The network layer sends a packet to the MAC layer with the desired data rate for transmission. The MAC cooperates the network layer by delivering the delivery ratio (link reliability) and the received signal strength ($RSSI$) along with a received packet. From those parameters, the network layer can calculate the link cost and select the appropriate data rate to adjust with the corresponding distance.

Each node uses a routing table (or cache) for multi-hop communications. The table maintains the route entries in the following format:

$$\{destination,\ next\ hop,\ \{C_i\},\ N_i\};$$

where, N_i is the cumulative value of the number of intermediate nodes up to that node. Here, $\{C_i\}$ are the costs of node i between link of the previous node and other links connecting to node i. For example, in Fig. 1, node I_2 will calculate its costs formed by $\{S, I_2, I_4\}$, $\{S, I_2, I_6\}$, $\{S, I_2, I_5\}$. A node updates entries in the table if there is any change of those parameters.

When a node receives a RREQ, it locally calculates RAI values as described in the Section III-B, and chooses the best one within 2-hop information knowledge. Then, the RREQ is forwarded with the list of nodes which forms the best route and their costs if it receives the request for the first time. Unlike AODV which will discard the duplicated RREQ, in our protocol, when a RREQ with the same ID to the previous RREQ arrives a node, that node checks the list of nodes constructed from the source node. If the list is different, then it calculates and checks the value of new RAI. If the new value of RAI is lower than the previous value, then it will update that value and forward that RREQ copy. Otherwise, it will discard that RREQ. The process is repeated until a specific RREQ reaches destination. The destination then calculates the value of α_i and RAI based on information of received RREQ. The first received request at the destination is immediately replied with an unicast RREP packet, that contains the RAI value of the route. That route is always the best route within 2-hop neighbor information. By this way, the destination does not have to wait for an amount of time to get the better route. If destination receives another RREQ through a better route (lower RAI value) later, then it overrides the previous route by sending a new RREP. Otherwise, it will discard that duplicated RREQs, because the route with higher RAI value will not be chosen. Each time the source node receives an update RREP with the lower RAI value, it will use the updated route for delivering data.

IV. Performance Analysis

We evaluate the performance of the proposed multi-rate routing metric named RAI to compare with the traditional AODV metric[5] and Medium Time Metric (MTM)[7] which also utilized the MAC layer information and the advantage of multi-rate. We use the developed module in *Ns-2*[11] of the Monarch project [12] to completely support the simulation of the multi-hop wireless networks with the physical, data link and MAC layer models. The network with the number of nodes varying from 50 to 250 are randomly distributed over a 500m x 500m area. Each node can send/receive data packets at any of the IEEE 802.11g supported data rates (i.e., 6, 9, 12, 18, 24, 36, 48 or 54 Mbps), and uses IEEE 802.11 DCF for channel access. We pick up some source-destination pairs randomly. UDP flows with the Constant Bit Rate (CBR) traffic are applied in the source nodes, and the packet size is set to 1024 bytes. Each simulation run has been executed 20 times, and the average results are plotted in the graphs.

We observe the average route discovery time of the mentioned metrics above. The Fig. 2 shows that in all cases, the discovery time increases sharply when the number of hops

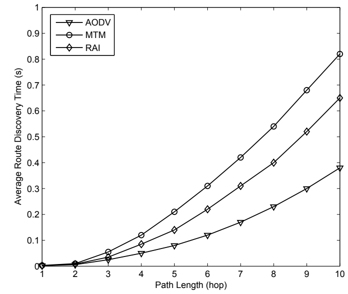


Fig. 2: The Average Route Discovery Time

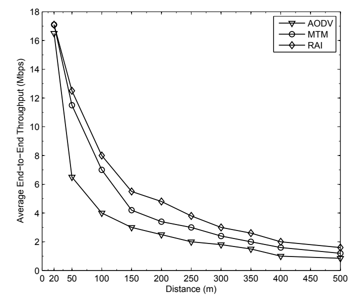
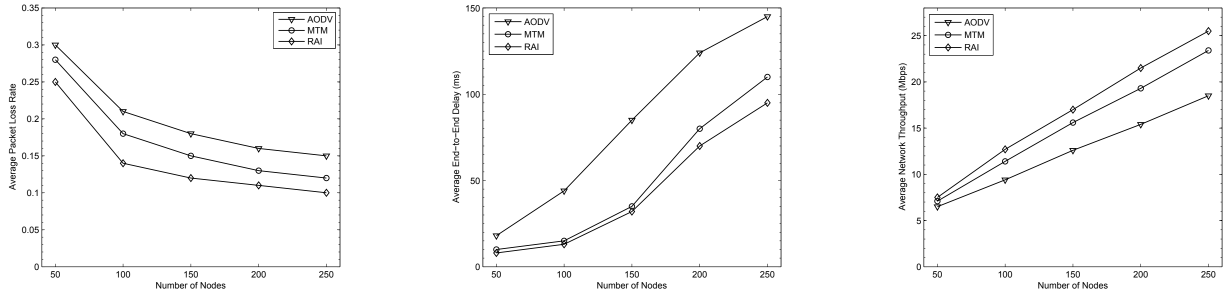


Fig. 3: The Average End-to-End Throughput with Varying Distances

(path length) between source and destination increases. The reason is that the more intermediate nodes the path has, the more medium access contentions will occur, which cause more time consumption. AODV allows only one RREQ per node to find the minimum hop route. Each node is expected to forward the RREQ only once (totally *O(n)* broadcasts with n number of nodes). Hence, apparently, its discovery time is shortest. In the case of MTM, theoretically, the metric is efficient in selecting the optimal route. However, forwarding the first RREQ only, which is used in the original AODV, does not guarantee that the RREQ for the optimal path will be forwarded. The destination can select the optimal route only when it receives all possible routes as the combinations of available links. Therefore, all intermediate hops in the network need to forward every copy of the received RREQ (requires $O(n^2)$ RREQ broadcasts). For RAI, duplicated RREQs are allowed, but only when the higher value of RAI needs to be updated. Also, RREQs through lower routes toward destination are excluded at intermediate nodes by using the above route discovery strategy. Therefore, the time delay is still smaller than that of the MTM, which needs to get all possible combinations of its value before selecting a route.

Next, we evaluate the average end-to-end throughput for different path lengths. We randomly generate 10 simultaneous flows with the various distances from 20m to 500m. In the Fig. 3, at any distance, RAI performs better than AODV and MTM with the improvement is about 5% to 88% depending on the specific distance. When the path length becomes longer, although the throughput is downgraded rapidly, the



(a) The Average Packet Loss Rate

(b) The Average End-to-End Delay

(c) The Average Network Throughput

Fig. 4: Impacts of Node Density

RAI throughput deduction is less severe than that of the remain observing metrics. The main reason is for MTM, it uses path with the shortest deliver time, so that, it is better than AODV. However, without an efficient route discovery strategy, the selected route for the data delivery in the case of MTM metric, in almost cases, is not the best one. Also, for a longer distance with more hops between end nodes, MTM does not consider the route with small value of $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|$ at all intermediate nodes like RAI does. Hence, the drop rate will be high at bottleneck links, causing the throughput reduction.

We also consider the impact of node density on the following performance metrics: *Packet loss rate*, *End-to-end delay*, and *Network throughput*. The results in the Figure 4 show that RAI outperforms AODV and MTM for all performance metrics. For the packet loss rate, it is reduced when the number of nodes increases, because the network connectivity is high. As mentioned above, RAI selects route without link's bottleneck, which can reduce packet loss rate due to buffer overflows. As shown in the Fig. 4a, RAI limits the loss rate better than the others. For the end-to-end delay, in the Fig. 4b, RAI can deduct from 35% to 55% delay time compare to MTM and AODV. The reason is that RAI chooses the high throughput route and less number of intermediate nodes. Also, the link reliability is included so that the actual capacity of a link is considered. Hence, the end-to-end delay is the smallest among the observing metrics. For the average network throughput, it is also increased when the network density is high. In fact, when the number of nodes and their loads increase, there are more chances for routing protocols to find the better path. In the Fig. 4c, RAI performs better than AODV and MTM with the improvement is about 15% to 38% depending on the network density. RAI, by using appropriate data rate under the effects of network conditions, can improve the overall network throughput. Also, the RAI metric itself considers the link reliability when calculating its value. Hence, the RAI metric get the better performance of both end-to-end throughput and network throughput by choosing the high throughput route under the real network conditions.

V. Concluding Remarks

In this paper, we proposed a routing protocol with a new routing metric that supports reliable and high throughput route selection for multi-rate ad hoc networks. The route with no bottleneck link, small relay hops and high throughput is preferred by choosing the route with minimum *Route Assessment Index* value. The simulation results have shown that the proposed metric outperforms the existing routing metrics, and can be applied for multi-rate ad hoc networks as an effective route selection method.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by MEST (No. 2009-0083838). Dr. CS Hong is the corresponding author.

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