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RAI: A High Throughput Routing Protocol for Multi-hop Multi-rate Ad hoc Networks

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Abstract The advantages of using the multiple rates for wireless communications have been revealed in the recent years. To determine the appropriate rate and to make routing decision more precise, the communication nodes need the information from lower layer. Therefore, in this paper, a high throughput routing protocol using lower layer information for Multi-rate Ad-hoc Networks is proposed. We introduce a new routing metric named *"Route Assessment Index"* (RAI). The route with maximum RAI value is preferred to achieve the high throughput route, and to avoid the link bottleneck for reducing the packet drop rate. The chosen route also has a small number of hops. The routing protocol works in distributed manner, and correctness of the proposal is proven. The simulation results show that our new metric provides an accurate and efficient method for assessing and selecting the best route in Multi-rate Ad-hoc Networks.

Keywords Multi-rate · Ad-hoc routing · Route assessment · Routing protocol

1 Introduction

Ad hoc Networks currently have become an ideal topology for establishing 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 enables wireless nodes to select the appropriate transmission rate depending on the required quality of

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Table 1 Data rate and Rx sensitivity in 802.11 OFDM PHY

Data rate r_k (Mbps)	Modulation type	Coding	Rx sensitivity $P_{S_{r_k}}$ (dBm)
06	BPSK	1/2	−82
09	BPSK	3/4	−81
12	QPSK	1/2	−79
18	QPSK	3/4	−77
24	16-QAM	1/2	−74
36	16-QAM	3/4	−70
48	64-QAM	1/2	−66
54	64-QAM	3/4	−65

service and the radio channel conditions. For example, the IEEE 802.11g standard [7] with OFDM technology support eight Modulation and Coding Schemes (MCS), and offers eight data rates between 6 to 54 Mbps according to the selected MCS as shown in the Table 1. Considering the multi-rate ad hoc networks, up to now, there are still very little papers considering design an effective routing metric that can utilize the benefit of using multi-rate. A well-known existing literature is Medium Time Metric (MTM) in [1]. As discussed in that paper, there is a direct relationship between the rate of communication and the transmission range. Since distance is one of the primary factors that determines the wireless channel quality, there is an inherent trade-off between a high transmission rate and an effective transmission range. A low rate link can cover the distance to the destination in few hops, while a high rate link requires more hops to reach the destination. It means that high rate route must deal with more risk of broken links and route discovery delay, due to the extra hops to the destination.

In this paper, considering both the end-to-end throughput of a route and the rate of each link corresponding to relative distance of two nodes to avoid selecting bottleneck links, we proposed a new routing metric named *"Route Assessment Index"* for multi-rate ad hoc networks. Also, since wireless links are not completely reliable, the routing metric uses the link reliability information (packet delivery rate) from the MAC layer to support choosing the best route. Hence, the new routing metric guarantees a found route has high rate and link reliability. We also prove that the route with maximum RAI value will has the minimum 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 detail will be showed in Sect. 3.2. The conference version of this paper was published in [5], and be selected for this special issue.

The remainder of this paper is organized as follows. In Sect. 2, we analyze related work and some well-known routing metrics. The main part including proposed protocol's model and operation is presented in the Sect. 3. The performance of RAI is given in Sect. 4. Finally, in Sect. 5, we conclude our paper.

2 Related Work

A lot of routing protocols have been proposed for the (mobile) wireless ad hoc networks, which follow one of two major strategies: proactive one such as in DSDV [12] and OLSR [2] and reactive (on-demand) one such as in AODV [11] and DSR [8]. These protocols were originally designed for single-rate networks, thus, have used a shortest path algorithm with 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 rate for data transmission.

The Ad hoc On demand Distance Vector (AODV) protocol [11] is one of the popular reactive routing protocol that discovers the path between the source and destination nodes dynamically. In AODV, when the source node wants to communicate with a destination node, it will broadcast a Route Request (RREQ) packet to the network. The neighboring nodes, which receive the RREQ packet, search for an existing route to the destination in its routing table. If a route already exists, then the intermediate node replies with an unicast Route Reply (RREP) packet to the RREQ sender. Otherwise, the node forwards the RREQ packet to its neighbors. By this way, the RREQ packet traverses hop by hop and reaches the destination. The destination node replies with an RREP to establish a new route by sending the packet traversing the same path in the reverse direction. When the source node receives multiple copies of RREP packets for the same RREQ packet, it selects the path with the minimum number of hops. The Hello and Route Error (RERR) packets is used to manage route failure and reconstruction. The design of the AODV protocol is based on the simple packet radio model without the consideration of data transmission rate. The main problem of AODV is based on hop count, which may avoid to choose the highest data rate route.

The author in [4] introduced an approach for multi-rate MANETs to improve traditional AODV routing protocol. The proposal based on the link cost which is simply provided by delay time for transferring a packet from the MAC layer which is inherited from the conference version (published in the year 2004) of [1]. Nicolaos et al. in [10] proposed a routing protocol for communication network using the new metric with connection probability approach. Karayiannis and Kaliyur [10] also introduces the concept of link cost. However, the authors 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.

Traditionally, the Automatic Rate Fallback (ARF) protocol originally developed in [9], has been widely-adopted by the industries to determine the initial transmission rate. In ARF, the node first transmits packet to a particular destination at the highest data rate and it switches to the next available lower data rate when it does not receive two consecutive ACK frames and starts a timer after the switch. When the node receives 10 consecutive ACK frames successfully or the timer expires, it switches to the next higher data rate again and packets are always transmitted at the highest possible rate. In another paper, the Receiver Based Auto Rate (RBAR) protocol [6] allows the receiving node to select the rate. This is accomplished by using the SNR of the RTS packet to choose the most appropriate rate. The CTS packet is used to ACK that rate to the sender. The Opportunistic Auto Rate (OAR) protocol presented in [14] operates using the same receiver-based approach. It allows high-rate multi-packet bursts to take advantage of the coherence times of good channel conditions. OAR uses the IEEE 802.11 mandated fragmentation field to hold the channel for an extended number of packet transmissions. In IEEE 802.11, each node has equal opportunity to send the same number of packets, so that the node transmitting at a high rate actually does not gain high throughput if it shares the channel with some nodes at a lower transmission rate. However in OAR, each node accesses the medium for the same amount of time, so the overall throughput will increase with the higher link rates. Therefore, both RBAR and OAR require modifications to the 802.11 standard but can increase the overall throughput.

For multi-rate wireless ad hoc networks, *Medium Time Metric* is one of the well-known routing metrics. In this section, we briefly present and analyze this metric for further comparison with our metric.

Medium Time Metric (MTM):

Awerbuch et al. in [1] showed the efficiency of the medium time metric (MTM) in selecting high throughput route. MTM uses the total medium time of a packet in a given path, where the medium time is defined as the time needed to transmit a packet on a given link with a particular data rate including the MAC delays and control overheads.

The simulation results in [1] showed the relationship between the throughput across the path and the length of the path:

(1) At certain distances, low rate links can achieve higher throughput than high rate links, because high rate path may take more hops.
(2) Due to spatial reuse, as the path becomes longer, multiple transmissions can take place along the path at the same time.
(3) High rate links can achieve high throughput after this distance though more hops needed.

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. When applying MTM to on-demand routing protocols such as DSR, it will result in the path lasting longer. The proactive routing protocol DSDV [12] is modified by using MTM as metric instead of hop count. It also uses OAR as the lower layer to provide multi-rate access and the current communication rate. The strong point of MTM is simplicity. It only needs the link rates provided by OAR instead of link utilization which is difficult to detect. The simulation results show that by combining MTM and OAR, throughput gains of up to 100–200% can be achieved over traditional route selection. However, the weak point of MTM is a longer path normally caused by the MTM metric, which will increase contention for the medium, finally decrease performance. 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.

3 Proposed Routing Protocol

In this section, we will discuss about the relation between transmission range and communication rate based on the received *Received Signal Strength Indicator (RSSI)*. Then, we propose the new routing metric and explain the operations of our routing protocol.

3.1 Relation Between Transmission Range and Communication Rate

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 [7]. Table 1 shows the data rate and Rx Sensitivity in IEEE 802.11 OFDM PHY.

Hence, to transmit data at rate r_k, the received signal strength must at least equal the receiver sensitivity $P_{S_{r_k}}$. Using the log-distance path loss model in [13] for radio propagation, the received signal strength at receiver R with distance d far away from the transmitter T is calculated as:

$$P_r = P_t - 20\log_{10}\left(\frac{4\pi\overline{d}f}{c}\right) - 10\gamma\log_{10}\left(\frac{R_{r_k}}{\overline{d}}\right)\ \text{(dBm)} \tag{1}$$

in which, P_r and P_t are the receive and transmit signal power in dBm, $20\log_{10}\left(\frac{4\pi\overline{d}f}{c}\right)$ is the free space path loss at a reference distance $\overline{d}$ (normally, 1 m) in dBm for signal rate of c and frequency f, and γ is the path loss exponent ($2 \leq \gamma \leq 6$) depending on the channel condition between T and R. From Eq. (1), let $P_r = P_{S_{r_k}}$ and $\overline{d} = 1$, we can determine the transmission range R_{r_k} at rate r_k as:

$$R_{r_k} = 10^{\frac{P_t - P_{S_{r_k}} - 20\log_{10}(4\pi f/c)}{10\gamma}} \tag{2}$$

As showed in the Eq. (2), there is a direct relation between communication rate and transmission range. The communication rate must be adjusted to the relative distance of a link between two nodes. To support the selection of data rate r_k, MAC layer delivers received data packets to the network layer along with the $RSSI$ for the packet. The RSSI provides information about receiver sensitivity $P_{S_{r_k}}$. The received sensitivity P_r is used to compare with the referenced sensitivity $P_{S_{r_k}}$ as showed in Table 1. If $P_r \geq P_{S_{r_k}}$, the highest possible rate r_k is chosen for data transmission. For example, if a node receives a packet with $P_r = -68$ dBm, then it determines $P_{S_{r_k}} = 36$ Mbps because $P_{S_{r_k}}$ (36 Mbps) < -68 dBm $< P_{S_{r_k}}$ (48 Mbps). Hence, the highest supported rate in this case is 36 Mbps. The connectivity is broken when the relative distance is greater than $R_{\min(r_k)}$ (the two nodes out of communication range).

3.2 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. In wireless environment, due to the impacts of many factors such as interference and collision, wireless links are not completely reliable. Hence, a packet may need to be transmitted more than one attempt 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 $\delta_{ab}^{(r_k)}$ be 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 packets which are successfully received and can be defined as $0 < \delta_{ab}^{(r_k)} = d_f \times d_r \leq 1$.

Next, let consider node ith 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 ith position is the sum of the link weight between the node that occupies the ith position and the nodes occupying the previous and next positions in the route. Therefore, the weight associated with the ith position can be defined as:

$$W_i = \delta_{i-1}^{(r_k)} r_k + \delta_{i+1}^{(r_l)} r_l \tag{3}$$

in which r_k and r_l are the maximum possible rates that the node occupying the ith position and the nodes occupying the previous and next positions can use to communicate respectively. As mentioned in the Sect. 1, $\delta_{i-1}^{(r_k)}$ and $\delta_{i+1}^{(r_l)}$ denote the link reliability with the previous and next hop of node (i)th at rate r_k and r_l respectively. And $\delta^{(r_k)} \times r_k$ is effective link capacity at rate r_k.

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

$$C_i = \frac{\delta_{i-1}^{(r_k)} r_k + \delta_{i+1}^{(r_l)} r_l}{\ln\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|} = \frac{W_i}{\ln\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|} \tag{4}$$

The denominator in Eq. (4) 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 $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right| = 0$. In this paper, we use natural logarithm (base $e = 2.718$) for calculation, although using any other logarithm base is acceptable.

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

$$\alpha_i = \frac{C_i}{\sum_{i=1}^{N_i} C_i} \tag{5}$$

in which, $\sum_{i=1}^{N_i} \alpha_i = 1$. Note that α_i always greater than 0 because for a valid route, there exists at least one link in that route (in case $N_i = 0$ 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 source/destination pairs

$$\text{RAI} = \begin{cases} -\frac{1}{N_i}\sum\limits_{i=1}^{N_i} \alpha_i \ln\alpha_i + \ln\frac{\sum_{i=1}^{N_i} C_i}{N_i} & \text{if } N_i > 0, \\ \ln C_0 & \text{if } N_i = 0. \end{cases} \tag{6}$$

where $C_0 = \delta_{sd}^{(r_k)} r_k$ (source and destination direct communicates at link rate r_k).

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

$$\ln\frac{\sum_{i=1}^{N_i} C_i}{N_i} \le RAI \le \frac{\ln N_i}{N_i} + \ln\frac{\sum_{i=1}^{N_i} C_i}{N_i}$$

Proof First, in Eq. (5) we have $0 < \alpha_i \le 1$, so that $\log\alpha_i \le 0$ and $\min\sum_{i=1}^{N_i} \alpha_i \ln\alpha_i = 0$, leads to $\text{RAI} \ge \ln\frac{\sum_{i=1}^{N_i} C_i}{N_i}$. Next, for a sequence of non-negative number $\{\alpha_i\}$, using *Log sum inequality* [3] we have

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

Hence, the lemma is proven. □

The problem of selecting the best route becomes the problem of choosing a route with maximum cost C_i in each intermediate node and maximum RAI value of the route. In fact, the former and the latter conditions happen together, because they have the relation shown in Eqs. (5) and (6). The proposed metric considers both the balance of effective link capacity of every node in the route and the capacity of each node. The former is represented by the first part in the Eq. (6): route with minimum difference among effective link capacity is preferred. The latter is represented by the second part in the Eq. (6): route with high capacity in each node is preferred. Hence, the following properties of a route are achieved when those maximize problems are satisfied:

Theorem 1 *The route with maximum RAI value defined by Eq. (6) prefers to minimize number of hops between source and destination.*

Proof From Lemma 1, $\text{RAI}_{\max} = \frac{\ln N_i}{N_i} + \ln\frac{\sum_{i=1}^{N_i} C_i}{N_i}$. Therefore, 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, $\text{RAI}^{(1)} < \text{RAI}^{(2)}$. Hence, the value of RAI will be decreased as the number of intermediate nodes increases. Moreover, RAI is maximized when α_i is maximized. From Eq. (5), 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 increased. Hence, the theorem is proven. □

Theorem 2 *The route with maximum cost C_i defined by Eq.* (4) *and RAI value defined by Eq.* (6) *can avoid link's bottleneck.*

Proof From Lemma 1, the equality holds ($\text{RAI}_{\max} = \frac{\ln N_i}{N_i} + \ln \frac{\sum_{i=1}^{N_i} C_i}{N_i}$). This implies that α_i of any node in the route must have the equal value. Also, maximize the cost C_i in Eq. (4) becomes maximize the weight W_i and minimize $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|$. It means that intermediate nodes with high data rates in all two links and a small difference between two effective link capacities $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|$ are preferred. Hence, the best case is $\delta_{i-1}^{(r_k)} r_k = \delta_{i+1}^{(r_l)} r_l$ (node ith communicates with the previous and next nodes at the same effective link capacity). Contrarily, if there exist some links that have data rate much lower than other links in the route, the RAI value will be reduced and that route will not be chosen. The example given below will make it more clear.

Suppose we have two candidate routes with 4 intermediate nodes ($N_i = 4$) in each route. The first route has all links at cost $C_i = 2.5$. The second route has 3 links at cost 3 and the remain link at cost 1. Hence, the average link cost of two routes are $0.25(2.5 + 2.5 + 2.5 + 2.5) = 2.5$ and $0.25(3 + 3 + 3 + 1) = 2.5$ respectively (two routes have equal average link cost). Also, we can calculate the value $\{\alpha_i\}$ of the former as {0.25, 0.25, 0.25, 0.25} and the latter as {0.3, 0.3, 0.3, 0.1}, respectively. Finally, using Eq. (6) we can calculate the RAI value of the former $\text{RAI}^{(1)} \simeq 1.2629$ that is greater than the RAI value of the later $\text{RAI}^{(2)} \simeq 1.2447$. Therefore, the later will not be used for delivering data because it contains a bottleneck link ($\alpha_4^{(2)} = 0.1$). □

Theorem 3 *The route with maximum cost C_i defined by Eq.* (4) *has the highest throughput among route candidates.*

Proof As showed in Eq. (4), maximize C_i leads to maximize the value of W_i, and the value $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l + e\right|$ is minimized, as shown in the proof of Theorem 2. There is an alternative way to prove this theorem: Suppose we have two candidate nodes with two weights ${W_i}^{(1)}, {W_i}^{(2)}$ and two differences in effective link capacities $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|^{(1)}, \left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|^{(2)}$, respectively.

- If ${W_i}^{(1)} = {W_i}^{(2)}$ and $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|^{(1)} < \left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|^{(2)}$, then ${C_i}^{(1)} > {C_i}^{(2)}$.
- Alternatively, if ${W_i}^{(1)} > {W_i}^{(2)}$ and $\left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|^{(1)} = \left|\delta_{i-1}^{(r_k)} r_k - \delta_{i+1}^{(r_l)} r_l\right|^{(2)}$, then ${C_i}^{(1)} > {C_i}^{(2)}$.

Hence, an intermediate node will choose the highest combination of rate and the link reliability when using that rate to communicate with the next hop in the route. Also, the links with small difference in effective link capacities are preferred. The process is the same for all links in the route. Therefore, the selected route will have the highest throughput among route candidates.

3.3 Protocol Operation

Like other on-demand routing protocols, the process for route discovery and maintenance are based on the Route Request (RREQ), Route Reply (RREP) and Route Error (RERR) exchange the same as traditional AODV protocol briefly discussed in Sect. 2 with some modifications presented below. The source address and sequence number fields in the RREQ jointly identify a unique and instant RREQ in the network. Instead of hop count, we use *"Route Assessment Index"* as the routing metric. The proposed protocol enables a node to choose and to control the data rate for a packet. The network layer sends a packet to the MAC layer with the desired data rate for a transmission. The MAC cooperates the network layer by delivering the delivery ratio (link reliability) and the received signal strength (or, the RSSI) along with a received packet. From those parameters, the network layer can calculate the link cost and selects 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:

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

where, $\{C_i\}$ are the costs of the intermediate nodes from the source toward the current node, and N_i is the cumulative value of the number of intermediate nodes up to that node.

When a node receives a RREQ, it locally calculates cost C_i using Eq. (4). Then the RREQ is forwarded to the next hop with the list of $\{C_i\}$ values of the previous nodes belonging the route. Unlike AODV which will discard the duplicated RREQ, in our protocol, when a RREQ with the same ID with previous RREQ arrives a node, that node calculates and checks the value of new C_i. If the new value of C_i is higher than the previous value, then it will update that value and forward that RREQ copy. Otherwise, it will discard that RREQ. By that way, the low throughput route can be eliminated at intermediate nodes during the route discovery process. Also, this strategy helps to reduce the overhead of forwarding any copy of RREQ at a node to its neighbors.

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 replied with an unicast RREP packet that contains the RAI value of the route. If destination receives another RREQ through a better route later (higher RAI value), it overrides the previous route by sending a new RREP. Otherwise, it will discard that duplicated RREQ to avoid route discovery overhead because the route with lower RAI will not be chosen. Each time the source node receives an update RREP with higher RAI value, it will use the updated route for delivering data.

Discussion: As because the RAI value is calculated locally and only when needed if a node receives a RREQ, the route discovery phase and the computation overhead are negligible. Indeed, for the route discovery phase, the duplicated RREQs are allowed, but only when the higher value of RAI needs to be updated. Also, RREQs through lower throughput routes toward a destination are excluded at intermediate nodes as discussed above. Therefore, the time delay for the route discovery is noticeable reduced. The details will be shown and discussed more in Sect. 4.

For the computation overhead, the calculation of $\{C_i\}$ is distributed among intermediate nodes up to destination. Hence, the protocol is distributed orientation. Furthermore, each node keeps track of the necessary information by passive hearing the hello messages periodically broadcasted from its neighbors. The costs $\{C_i\}$ are inserted in the packet header, and the forward nodes just need to add their own costs to this field. Therefore, the message exchanges of this routing protocol are similar to those of the traditional AODV protocol. In fact, the necessary information is only needed to be attached in the periodically broadcasted hello messages, and the RSSI information can be directly measured from those received hello packets to decide the communication rate. The computation complexity is trivial and identical for every intermediate node. Because each node only needs to calculate its own C_i value, and forwards the $\{C_i\}$ values of previous nodes from the source up to that node. Hence, the proposed routing protocol is implementable without the concern of computational complexity.

4 Performance Analysis

We evaluate the performance of proposed multi-rate routing metric named RAI using *NS-2* [15] to compare with the traditional AODV metric [11] and Medium Time Metric (MTM) [1]. The network with the number of nodes varying from 50 to 250 are randomly distributed over a 500 m $\times$ 500 m 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 1,024 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. 1 shows that in all cases, the discovery time increases sharply when the number of hops (path length) between source and destination increases. This is because the more intermediate nodes in the path, the more medium access contentions will occur that 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 case of MTM, theoretically, the

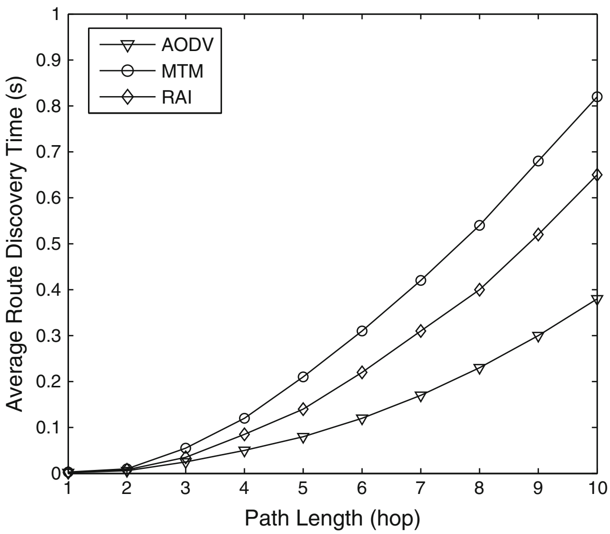

Fig. 1 Average route discovery time

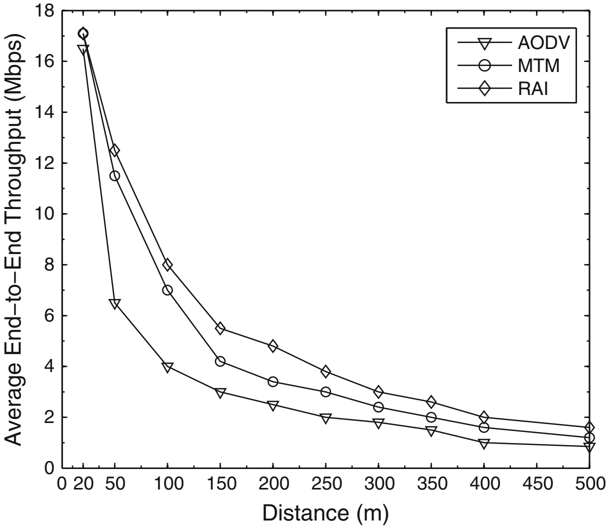

Fig. 2 Average end-to-end throughput with varying distances

metric is efficient in selecting the optimal route. However, only forwarding the first RREQ, which is used in the original AODV, does not guarantee that the RREQ for the optimum path will be forwarded. The destination can select the optimum route only when it receives all possible combinations. 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. Therefore, the time delay is still smaller than 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 various distances from 20 to 500 m. At any distance, RAI performs better than AODV and MTM with the improvement is about 5–88% depending on specific distances as showed in the Fig. 2. When the distance is far, even though the throughput is downgraded rapidly, RAI throughput deduction is less severe than 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, for the longer distance with more hops between end nodes, MTM may not consider the route with small value of $|r_k - r_l|$ at all intermediate nodes like RAI does. Hence, the drop rate will be high at bottleneck links, and it will downgrade the throughput.

We also consider the following performance metrics:

(1) *Packet loss rate*: the ratio of the packets that are lost in the route to the number of packets generated by the sources,
(2) *End-to-end delay*: the average delay experienced by all successfully delivered packets, and
(3) *Network throughput*: the sum of the size of the total data packets received by the destinations per unit time.

The results 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 with small value of $|r_k - r_l|$, so

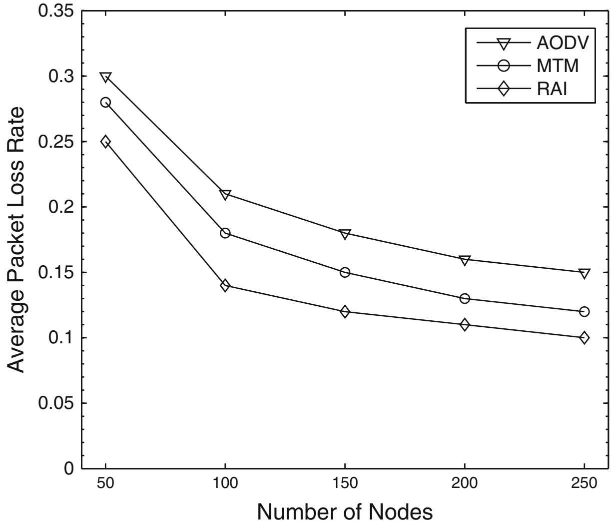

Fig. 3 Average packet loss rate

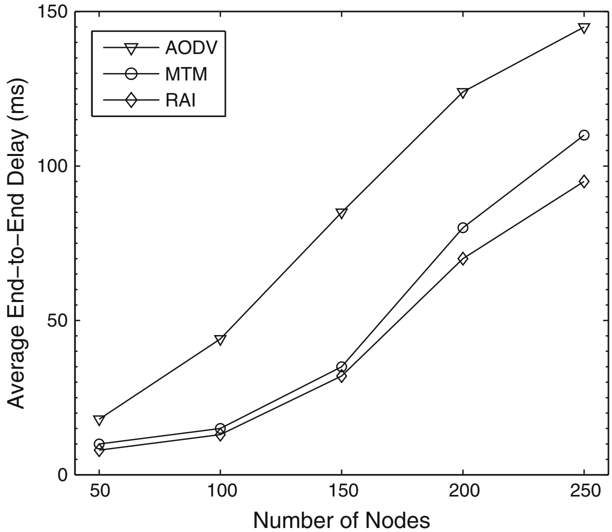

Fig. 4 Average end-to-end delay

that it will limit the link bottleneck and packet loss rate due to buffer overflows. As showed in the Fig. 3, RAI limits the loss rate better than the others. For the end-to-end delay, in the Fig. 4, RAI can reduce from 35 to 55% delay time compare to MTM and AODV. The reason is that RAI chooses the route with high throughput and less number of intermediate nodes. Also, the link reliability is included, hence, the actual capacity of a link is considered. Therefore, the end-to-end delay is smallest among those observing metrics. For the average network throughput, it also increases when the network density is high, because when the number of nodes and their loads increase, there are more chances for routing protocol to find

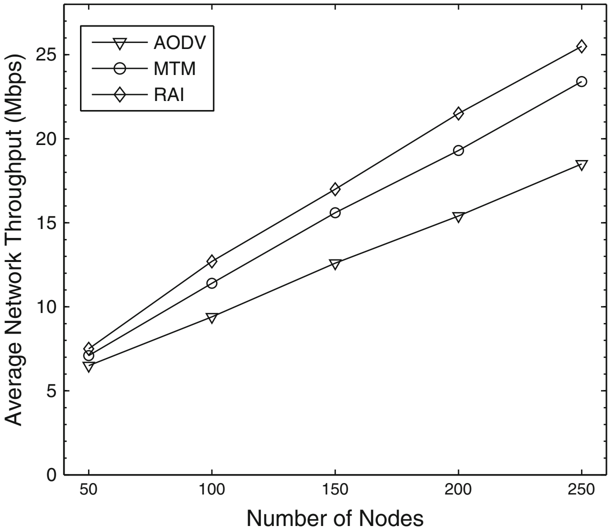

Fig. 5 Average network throughput

a better route. In the Fig. 5, RAI performs better than AODV and MTM with the improvement is about 15–38% depending on the network density. RAI, by using appropriate data rate under the effects of network conditions, can improve the network throughput. Indeed, the received RSSI reflects network conditions, such as the path loss exponent γ, inter-flow interference (the interference suffered among concurrent flows), and intra-flow interference (occurs when nodes in a single path attempt to transmit packets of the same flow and interfere with each other), through its value. Also, RAI metric itself considers the link reliability when calculating its value. Hence, the RAI metric effectively chooses the best route under the real network conditions to get better performance of both end-to-end throughput and network throughput.

5 Concluding Remarks

As showed in many existing literatures, routing protocols with the supported information from lower layer can perform better, because they take into account the actual conditions of the networks. In this paper, we proposed a new routing protocol based on the RSSI and link reliability, which reflect actual network conditions and decide the communication rate of a links, for each node. The proposed routing metric supports a reliable and high throughput route selection for multi-rate ad hoc networks. The route without link bottleneck and small relay hops is also preferred by maximizing the value of *Route Assessment Index*. The corresponding proofs and simulation results have showed that the proposed metric outperforms the existing routing metrics, and it can be efficiently applied for multi-rate ad hoc networks.

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