A New Routing Protocol with High Throughput Route Metric for Multi-Rate Mobile Ad-hoc Networks

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Abstract—**In this paper, we propose a new routing protocol to support the selection of stable and high speed route in Multi-Rate Mobile Ad-hoc Networks (MANET). We introduce another approach for modeling the mobility aspect under the relation with the variation of communication rate. Maximize the proposed *"Route Selection Indicator"* (RSI) ensures that the the selected route is the most stable, has highest speed among route candidates. The correctness of proposal is proved and the simulation results show that our proposed approach provides an accurate and efficient method for evaluating and selecting the best route in mobile environments.**

I. Introduction

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

Consider the multi-rate ad hoc networks, there is a direct relationship between the rate of communication and the transmission range [1]. Since distance is one of the primary factors that determines wireless channel quality, there is an inherent trade-off between high transmission rate and effective transmission range. Low speed link can cover the distance to the destination in few hops, while high speed link requires more hops to reach the destination. It means that high speed route must deal with more risk of broken links and route discovery delay due to node mobility and the extra hops to the destination. In this paper, to avoid selecting an unstable route, we choose the links which have least relative distance change (that causes data rate fluctuation) for communication. Hence, by choosing those stable links for communication route, we can reduce the probability of link breakage and route repair. Moreover, our proposal also ensures that route with the highest speed and minimum hops is selected among stable route candidates.

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 [2] and OLSR [3] and reactive (on-demand) such as in AODV [4] and DSR [5]. These protocols were originally designed for single-rate networks, and thus have used a shortest path algorithm with minimum hop count metric to select paths. Min hop is an excellent criteria 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 speed for data transmission.

The Ad hoc On demand Distance Vector (AODV) protocol [4] 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 there is a route already exist, the intermediate node replies with an unicast Route Reply (RREP) packet to the RREQ sender. Otherwise, it 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 traverses 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 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 can avoid to choose the highest data rate route.

Recently, physical layer enhancements support multiple data rates, which enables wireless nodes to select the appropriate transmission rate depending on the required quality of service and the radio channel conditions. For example, the IEEE

802.11g standard [6] with OFDM technology support eight modulation and coding schemes (MCS) and offers eight data rates between 6Mbps to 54Mbps according to the selected MCS as showed in the Table 1. Traditionally, the Automatic Rate Fallback (ARF) originally developed in [7] is 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 [8] 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 [9] 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. Both RBAR and OAR require modifications to the 802.11 standard but can increase the overall throughput.

For multi-rate wireless ad hoc networks, several proposals on routing protocol were introduced. Awerbuch et. al. in [1] showed the efficiency of the medium time metric 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 author in [10] 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 transfer a packet from MAC layer which is inherited from [1]. For mobile ad hoc networks, that simple metric does not guarantee that routing protocol can choose the most stable route. Consequently, the probability that the chosen route is broken is very high in the mobile environment. Nicolaos et. al. in [11] proposed routing metric for communication network using the new metric with connection probability approach. [11] also introduces the concept of link cost. However, they did not specify how to calculate the link cost for their routing metric. Also, all protocols mentioned above do not consider the stability of the chosen route which is critical in mobile ad hoc environments.

In this paper, consider both the stability of a route and the speed of each link, we proposed a new routing metric for mobile ad hoc networks (MANETs). The new routing metric named *"Route Selection Indicator"* guarantees a found route has high speed and stability among route candidates. It reduces the probability of link brakeage and route repair especially in case of network topology changes more frequently. Therefore, the end-to-end throughput increases significantly.

TABLE I
DATA RATE AND RX SENSITIVITY IN 802.11 OFDM PHY

Data Rate ν (Mbps)	Modulation Type	Coding	Rx Sensitivity P_{S_ν} (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

III. PRELIMINARIES

In this section, we analyze the relation of communication rate and the transmission range in the multi-rate networks. For transmitting data at a specific rate ν (i.e., ν = (6, 9, 12, 18, 24, 36, 48, 54) Mbps), the corresponding receiver sensitivity requirement is needed. Remind that the number of rate levels as well as the maximum data rate here follow the IEEE 802.11g standard [6]. Hence, if the network uses another standard, those parameters should be changed corresponding to that standard specifications. Table 1 shows the data rate and Rx Sensitivity in IEEE 802.11 OFDM PHY.

Hence, to transmit data at rate ν, the received signal strength must at least equal to the receiver sensitivity P_{S_ν}. Using the log-distance path loss model in [12] for radio propagation, the received signal strength at receiver R with distance d far away from the transmitter T is calculated as:

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

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, 1m) in dBm for signal speed 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_ν} and $\overline{d}$ = 1, we can determine the transmission range R_ν at rate ν as:

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

For mobile ad hoc networks, the relative distance between two communicating nodes is changed following time t due to the dynamic natural of network topology. Therefore, the communication rate also must be adjusted to the corresponding distance. To support the selection of data rate ν, MAC layer delivers received data packets to the network layer along with the *Received Signal Strength Indicator (RSSI)* for the packet. The RSSI provides information about receiver sensitivity P_{S_ν}. The received sensitivity P_r is used to compare with the referenced sensitivity P_{S_ν} as showed in Table I. If $P_r \geq P_{S_\nu}$, the highest possible rate ν is chosen for data transmission.

IV. PROPOSED MULTIRATE-BASED ROUTING PROTOCOL

The problem of selection the most high speed and stable route considering mobility aspect in multi-rate MANET is the main motivation of our work. In this section, first, we propose the routing metric named *"Route Selection Indicator"* to select the best route. The properties and corectness of new routing metric are showed and proved. Then, the next part will discuss about the overal operation of the proposed protocol.

A. Routing Metric

Consider a mobile ad hoc network in which any two neighboring nodes (direct communication) use the highest possible rate to communicate corresponding to their current relative distance. The mobility feature is considered in different approach: Traditionally, node mobility is modeled as node's velocity and direction [0-2π]. Instead, in this letter, the mobility is considered under the fact that the highest possible data rate will be changed when the relative distance of communication nodes change. For more details, when the node move close to or far away another node, the relative distance between two nodes has been changed. Consequently, the data rate can increase (in case the relative distance is shorter) up to the maximum supported rate (i.e., 54Mbps), or can decrease (in case the relative distance is longer) down to the minimum supported rate (i.e., 6Mbps). The connectivity is broken when the relative distance $> R_{\min(\nu)}$ (the two nodes out of communication range).

Let N is the number of times that two communication nodes have to adjust data rate corresponding to their relative distance within the observation time interval Δt. We introduce an average rate $\bar{\nu}_{i,j}(\Delta t)$ of a link between intermediate node i and j in a route as following equation

$$\bar{\nu}_{i,j}(\Delta t) = \frac{1}{N+1}\sum_{k=1}^{N+1}\nu_{i,j} \tag{3}$$

Hence, the relative distance between any pair of intermediate nodes (i,j) during the time interval Δt is transformed into their averaged rate $\bar{\nu}_{i,j}(\Delta t)$ without concerning how many times those two nodes go near/far each other in any direction over time interval Δt.

Links with rate fluctuation will not be preferred to choose, so that we give a penalty for more fluctuated links (which have N large) by defining the parameter $\alpha_{i,j}(\Delta t)$ as

$$\alpha_{i,j}(\Delta t) = \frac{\bar{\nu}_{i,j}(\Delta t)}{\log(N+2)} \tag{4}$$

The denominator in Eq. (4) is $log(N+2)$ to avoid infinity value of $\alpha_{i,j}(\Delta t)$ when $N=0$ (link with no rate change during the time Δt).

For the set I_n of the number of intermediate nodes in the route, the coefficient $l_{i,j}$ of link (i,j) is defined as

$$l_{i,j}(\Delta t) = \frac{\alpha_{i,j}(\Delta t)}{\sum\limits_{(i,j)\in I_n}\alpha_{i,j}(\Delta t)} \tag{5}$$

in which $\sum\limits_{(i,j)\in I_n} l_{i,j}(\Delta t) = 1$. Note that $l_{i,j}(\Delta t)$ always greater than 0 because for a valid route, there exists at least one link in that route.

A robust routing protocol in MANET must choose the most stable and high speed route under the consideration of node's mobility. Motivated by that challenge, we propose a so called *"Route Selection Indicator"* $RSI(\Delta t)$ as

$$RSI(\Delta t) = -\frac{1}{C(I_n)}\sum_{(i,j)\in I_n} l_{i,j}\log l_{i,j} \tag{6}$$

in which I_n is the number of intermediate nodes in the route and $C(I_n)$ is the number of links associating with I_n (hence, $C(I_n) = I_n + 1$).

Lemma 1: The value of $RSI(\Delta t)$ satisfies the following condition: $0 < RSI(\Delta t) \leq \frac{\log C(I_n)}{C(I_n)}$.

Proof: First, in Eq. (5) we have $0 < l_{i,j}(\Delta t) \leq 1$, so $\log l_{i,j}(\Delta t) \leq 0$ leads to $RSI(\Delta t) > 0$. Next, for non-negative number sequence $\{l_{i,j}\}$, using *Log sum inequality* [13] we have

$$RSI(\Delta t) \leq \frac{1}{C(I_n)}\log\sum_{C(I_n)}\sum_{C(I_n)} l_{i,j} \leq \frac{\log C(I_n)}{C(I_n)}$$

Hence, $0 < RSI(\Delta t) \leq \frac{\log C(I_n)}{C(I_n)}$. ■

The problem of selecting the best route becomes the problem of choosing a route with maximum $\alpha_{i,j}(\Delta t)$ and $RSI(\Delta t)$ values of the route. Therefore, the following properties of a route will be satisfied when those maximize problems are achieved:

Theorem 1: The route with maximum $\alpha_{i,j}(\Delta t)$ and $RSI(\Delta t)$ is the most stable and can avoid link's bottleneck.

Proof: From Eq. (4), maximize $\alpha_{i,j}(\Delta t)$ itself has to minimize N. Hence, nodes with the relative distances which do not or infrequently change during the time interval Δt are preferred to use. Also, from *lemma* 1, the equality holds ($RSI_{\max}(\Delta t) = \frac{\log C(I_n)}{C(I_n)}$) iff $l_{i,j}(\Delta t) = 1/C(I_n)$. This implies that $l_{i,j}$ of any link in the route must have the equal value with maximum $\alpha_{i,j}(\Delta t)$. Moreover, if there exists one link that has data rate much lower than other links in the route, $RSI(\Delta t)$ will be reduced and that route will not be chosen. The example given below will make it more clear. Suppose we have two routes with 4 link values $\{l_{i,j}\}$ as {0.25, 0.25, 0.25, 0.25} and {0.3, 0.3, 0.3, 0.1} respectively. Using Eq. (6) we can calculate the value of the former $RSI^{(1)}(\Delta t) \simeq 0.3466$ that is greater than the value of the later $RSI^{(2)}(\Delta t) \simeq 0.3284$. Therefore, the later will not be used for delivering data because it contains a bottleneck link ($l_{i,j} = 0.1$). ■

Theorem 2: The route with maximum $\alpha_{i,j}(\Delta t)$ and $RSI(\Delta t)$ has the highest speed among route candidates.

Proof: To maximize $\alpha_{i,j}(\Delta t)$, an intermediate node will choose the highest possible rate to communicate with the next hop in the route. The process is the same for all links in the route. Also, maximize $RSI(\Delta t)$ guarantees that the route will not have link bottlenecks. Therefore, the selected route will have the highest speed among route candidates. ■

Theorem 3: The route with maximum $RSI(\Delta t)$ prefers to choose the route with minimum number of hops.

Proof: From *lemma* 1, $RSI_{\max}(\Delta t) = \frac{\log C(I_n)}{C(I_n)}$. So when the number of intermediate nodes increase, we have

$$\lim_{C(I_n)\to\infty} \frac{\log C(I_n)}{C(I_n)} = 0$$

This means for route 1 with $C(I_n^{(1)}) > C(I_n^{(2)})$ of route 2, $RSI^{(1)}(\Delta t) < RSI^{(2)}(\Delta t)$. Hence, the theorem is proved. ■

B. Protocol Operation

The process for route discovery and maintenance are based on the Route Request (RREQ), Route Reply (RREP) and Route Error (RERR) exchange as the same as traditional AODV protocol with some modifications presented below. Instead of hop count, we use *"Route Selection Indicator"* 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 received signal strength (or, the RSSI) along with a received packet so that the network layer can select the appropriate data rate to adjust with the corresponding distance.

Each node maintains a routing table about its neighbors for calculating RSI. The additional information table for each neighbor is followed the format:

$$\{N, \{\nu_{i,j}(t_k)\}, |t_{ref} - t_{1st}|\};$$

where, $\{\nu_{i,j}(t_k)\}$ is the list of data rates that two nodes have used in the observation time Δt and $\{t_k\}$ is the time values at which data rate changes. t_{1st} and t_{ref} are the first value of $\{t_k\}$ sequence and current reference time respectively. Hence, $\Delta t = |t_{ref} - t_{1st}|$ is the observation time and its value can be changed in proportion to the active of nodes in the network. We will discuss this parameter more detail in the section V. Each time the data rate changes, node will update $N = N+1$, add $\nu_{i,j}(t_k)$ value to the sequence of $\{\nu_{i,j}(t_k)\}$, and check the value of $|t_{ref} - t_{1st}|$. If $|t_{ref} - t_{1st}| \geq \Delta t$, the stored information in the period before the interval Δt is removed. Hence, a node only stores the data rate's history from the past to the recent time within Δt period.

When a node receives a RREQ, it calculates $RSI(\Delta t)$ using Eq. (6) based on the received RSSI and the stored information of the previous RREQ sender in its routing table. Then the RREQ is forwarded to the next hop with updated $RSI(\Delta t)$ value. The process is repeated until a specific RREQ reaches destination. When a RREQ with the same ID with previous RREQ arrives a node, that node calculates and checks the value of new $RSI(\Delta t)$. If the value of new $RSI(\Delta t)$ is greater than the previous value, it will update that value and forward that RREQ copy. Otherwise, it will discast that duplicated RREQ to avoid route discovery overhead because the route with lower $RSI(\Delta t)$ will not be chosen. The destination after received RREQ with highest $RSI(\Delta t)$ will send the RREP with $RSI(\Delta t)$ value backward the source in the reverse route and a node that receives the RREP adds the new route in its own routing table. Each time source node receives an update RREP with higher $RSI(\Delta t)$ value, it will use the updated route for delivering data.

V. Performance Analysis

We evaluate the performance of proposed multi-rate routing protocol (named RSI) using *NS-2* [14] to compare with traditional AODV [4] and Medium Time Metric (MTM) [1]. The network includes 100 nodes randomly distributed over a 200m x 200m 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 packet size is set to 1000 bytes are applied in the source nodes. The random way-point mobility model is used with maximum speed 20m/s. The simulation results that we show are the geometric means over 50 simulation times.

As mentioned above, first, we study the impact of Δt value to the performance of RSI. We set the value of Δt to 3s, 4s and 5s and observe the end-to-end throughput under mobility effect. The Fig. 1 shows that at low speed, Δt almost does not affect the performance of RSI. Only from speed 10m/s, the longer observation time Δt helps RSI select the better route, hence, the average throughput is a little bit increased. However, longer observation time requires nodes to store more information so that we choose the value of Δt=3s for further experiments below.

Second, we study the effect of mobility to the percentage of broken links in the network. From this experiment, the observation time Δt is set to 3s. The Fig. 2 shows that RSI outperforms AODV and MTM in case of link breakage reduction. In all cases, the percentage of broken links increases sharply when mobility speed increases. However, RSI keeps it around 17% at speed 20 m/s, less than a half compare to that of AODV (around 36% at speed 20 m/s). MTM chooses route with optimal deliver time but it does not resist to node mobility, so the percentage of broken links is also high. At speed 20 m/s, there is approximate 34% of broken links in case of MTM. Only RSI chooses the route with maximum $RSI(\Delta t)$, so it guarantees that the selected route is the most stable one.

Third, we evaluate the average end-to-end throughput under the mobility condition. At any speed, RSI is much better than AODV and MTM. As showed in the Fig. 3, at 2m/s, the average throughput of RSI is a little bit higher than that of MTM and AODV. When the node mobility is high, even though the throughput is downgraded rapidly, RSI throughput deduction is less severe than the observing protocols. Hence, at 10m/s, the throughput in RSI is about 25% and 37% higher than that of MTM and AOVD respectively. At 20m/s, the throughput of RSI is over 3 times than that of AODV and over 2 times than that of MTM (6.3Mbps compare to 2.5Mbps and 1.6Mbps respectively). Finally, another important factor that effects the end-to-end throughput is path length. To study that impact, we evaluate the performance of RSI, MTM and AODV with different path lengths under mobility speed at 5m/s and 10m/s. MTM utilizes the smallest medium transmission time

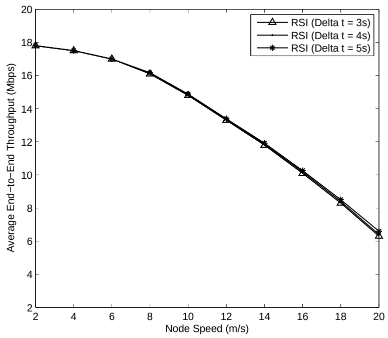

Fig. 1. Observation Time Δt Vs. Mobility.

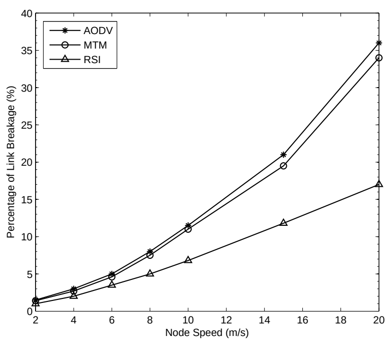

Fig. 2. Percentage of Broken Links Vs. Mobility.

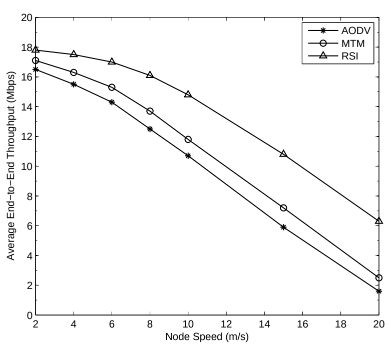

Fig. 3. Average Throughput Vs. Mobility.

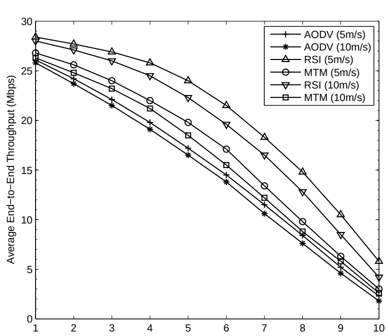

Fig. 4. Average Throughput Vs. Path Length.

links, hence, it performs better than AODV. But under the mobility effect, its throughput is deducted rapidly. Hence, as showed in the Fig. 4, RSI outperforms AODV and MTM at any distance. Especially, the throughput improvement is high at long distance route.

VI. Concluding Remarks

The proposed routing protocol in this paper supports high throughput and stable route selection for multi-rate MANETs. The motivation of this work is from the fact that the relative distance between mobile nodes can be directly referred to the maximum possible rate that those nodes can use for transferring data. Hence, maximizing the *"Route Selection Indicator"* (RSI) based on the measurement of link rate fluctuation within time interval Δt, we can choose the best route for a specific source/destination pair under the network mobility effect. The corresponding proofs and simulation results have demonstrated that the proposed modeling can be applied for multi-rate MANETs which offer the stable connectivity and Quality of Service (QoS) applications.

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