A Connection Entropy-based Multi-Rate Routing Protocol for Mobile Ad Hoc Networks

Cao Trong Hieu and Choong Seon Hong
Department of Computer Engineering, Kyung Hee University,
Gyeonggi-do, Republic of Korea
{hieuct, cshong}@khu.ac.kr

This paper introduces a new approach to modeling relative distance among nodes under a variety of communication rates, due to node's mobility in Mobile Ad-hoc Networks (MANETs). When mobile nodes move to another location, the relative distance of communicating nodes will directly affect the data rate of transmission. The larger the distance between two communicating nodes is, the lower the rate that they can use for transferring data will be. The connection certainty of a link also changes because a node may move closer to or farther away out of the communication range of other nodes. Therefore, the stability of a route is related to connection entropy. Taking into account these issues, this paper proposes a new routing metric for MANETs. The new metric considers both link weight and route stability based on connection entropy. The problem of determining the best route is subsequently formulated as the minimization of an object function formed as a linear combination of the link weight and the connection uncertainty of that link. The simulation results show that the proposed routing metric improves end-to-end throughput and reduces the percentage of link breakages and route reparations.

Categories and Subject Descriptors: Systems & Architecture [**Network and Communications**]: General Terms: Routing, Wireless Communication.

Additional Key Words and Phrases: Routing Protocol, Mobile Multi-rate ad hoc Network, Connection Entropy

1. INTRODUCTION

Wireless mobile ad-hoc networks are composed of a number of autonomous wireless nodes under the consideration of dynamic topology due to node's mobility. Each node is assumed to have identical power and processing capacity. Hence, there is no backbone node in this communication scenario. Those nodes are capable of communicating with each other over direct wireless links within the coverage or with

the help of intermediary nodes when they are out of range from each other. Therefore, each node in the network has to act as a relay node to provide end-to-end connectivity between two non-neighboring nodes. A number of routing protocols for such networks have been proposed in recent years. Researchers traditionally classify these protocols as proactive protocols, reactive protocols, or a hybrid of the two, based on the way they find new routes or update existing ones. Proactive routing protocols keep routes continuously updated, while reactive routing protocols react on demand. However, the reactive or on-demand protocols are preferred, rather than the proactive protocols, due to the dynamic nature of wireless environment and the node mobility. Routing algorithms are required to be flexible and to adapt quickly with the changing of network topology and demand patterns. These algorithms must be able to operate under unexpected conditions of the network and must recover quickly from component failures.

Routing algorithms aim at discovering the best route between a source node and a destination node. The best route is typically determined based on the topology of the network, i.e., the links existing between the nodes, and some costs associated with every link in the network. In wired networks, the cost associated with every link could be the traffic delay between the nodes, which relates to the capacity of the link [C.Huitema 2000; Tanenbaum 1999]. If routing of wired networks relies on the traffic delays between the nodes, then the traffic delays between the nodes may change continuously with time, even if the capacity of the corresponding links remains fixed. The reason is that the nodes corresponding to links with low traffic delays will be utilized more often than others. Consequently, the traffic delays of the links between such nodes will essentially increase.

In wireless networks, the cost associated with every link can also be the per packet delay time or the data rate of the link. In the case of ad hoc mobile networks, the topology of the network and the data rates of the links change continuously since the nodes are free to move relative to each other at variable speeds [Toh 2001; Royer and Toh]. In such a case, some of the links might be eliminated, while other links might be created with time. This reveals the critical role of route maintenance for ad hoc mobile networks.

More specifically, in the multi-rate mobile ad hoc networks, there is a direct relationship between the rate of communication and the transmission range. The communication rate is mainly affected by communication range and the path loss exponent, depending on the channel condition between the two communicating nodes. Since distance is one of the primary factors that determine wireless channel quality, there is an inherent trade-off between high transmission rate and effective transmission range. A low-speed link can cover the distance to the destination in few hops, while a high-speed link requires more hops to reach the destination. As such, 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. Therefore, always choosing high-throughput links does not mean that we can achieve the highest throughput route between source and destination at a specific period. Also, at an instant in time, a high throughput link may quickly be degraded, due to node mobility.

In the mobile environment, the variation of the relative distance between two
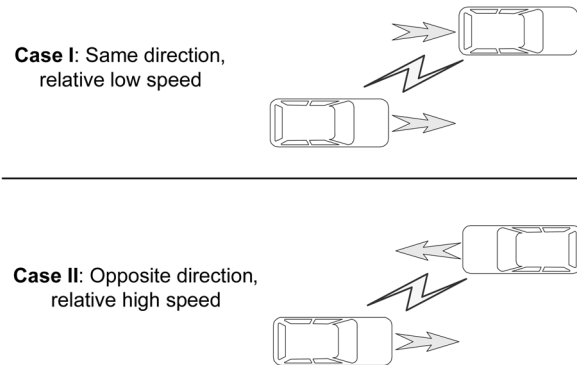
Figure 1. An example of relative distance due to node's mobility.

communicating nodes is critical. Figure 1 illustrates two movement scenarios that more or less affect the variation of communication rate between two nodes. In case I, in which the communicating nodes move in the same direction with the same or nearly the same speed, the relative distance will not be changed or be changed slowly. Hence, the link is stable during the communication time. In reverse case (case II), if two communicating nodes move in the opposite direction, even with slow speed for each node, then the relative distance between them varies quickly, causing the link's throughput instability. In this paper, to avoid selecting an unstable route even if that route has high data speed, we investigate the connection uncertainty of a link in the context in which some nodes move more infrequently than some other nodes in the networks. Hence, by choosing those stable nodes for the communication route, we can reduce the probability of link breakage and route reparation. Moreover, the route speed is to be considered along with route stability in the proposed routing metric.

The remaining parts of this paper are organized as follows. Section 2 discusses some existing work in routing for MANETs in general, as well as for multi-rate wireless networks in specific. Next, Section 3 introduces the related parameters used in the routing metric. The multi-rate routing is proposed in Section 4, followed by protocol operation in Section 5, and the performance analysis is given in Section 6 to show the effectiveness of the new routing metric in terms of throughput improvement, link breakage, and route repair deduction. Finally, Section 7 provides some discussion and conclusions about the paper.

2. RELATED WORK

A lot of routing protocols have been proposed for the wireless ad hoc networks, which follow one of two major strategies: proactive one such as in DSDV [Perkins and Bhagwat 1994] and OLSR [Clausen and Jacquet 2003] or a reactive (on demand) one, such as in AODV [Perkins and Belding-Royer 1999] and DSR [Johnson et al. 2001]. These protocols were originally designed for single-rate networks, and thus, have used a shortest path algorithm with a minimum hop count metric to select paths. Min hop is an excellent criterion 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 data rate links for transmission.

The Ad hoc On demand Distance Vector (AODV) protocol [Perkins and Belding-Royer 1999] is one of the popular reactive routing protocols, that discover 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 a 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 are 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 due to hop count, and hence, it does not utilize the higher link rates for data transmission.

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 and the radio channel conditions. For example, the IEEE 802.11g standard [IEEE 2007] with OFDM technology support eight modulation and coding schemes (MCS) and offers eight data rates between 6Mbps to 54Mbps, according to the selected Modulation and Coding Scheme (MCS), as shown in the Table I.

The Automatic Rate Fallback (ARF) protocol, originally developed in [Kamerman and Monteban 1997], has been widely-adopted by the industries to determine the transmission rate. In ARF, the node first transmits packets to a particular destination at the highest data rate and then 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 [Holland et al. 2001] allows the receiving node to select the rate. This is accomplished by using the Signal-to-Noise Ratio (SNR) of the Request To Send (RTS) packet to choose the most appropriate rate. The Clear To Send (CTS) packet is used to ACK that rate to the sender. The Opportunistic Auto Rate (OAR) protocol presented in [Sadeghi et al. 2002] 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 IEEE 802.11 standard but can increase the overall throughput.

The author in [Fan 2004] 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 transfering a packet from the MAC layer which is inherited from [Awerbuch et al. 2004]. For mobile ad hoc networks, that simple metric does not guarantee that a routing protocol can choose the most stable route. Consequently, the probability that the chosen route is broken is very high in the mobile environment.

For multirate wireless ad hoc networks, several works for routing protocol were proposed. Awerbuch et al., in [Awerbuch et al. 2006], showed the efficiency of the medium time metric in selecting a high-throughput route. The authors in [Fan 2004] 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 the delay time for the transfer of a packet from the MAC layer, which is inherited from [Awerbuch et al. 2006]. For mobile ad hoc networks, that simple metric does not guarantee that the routing protocol can choose the most stable route. Consequently, the probability that the chosen route is broken is high in the mobile environment. Nicolaos et al. in [Karayiannis and Kaliyur 2006] proposed a routing metric for a communication network using the new metric with connection probability approach. These authors also introduced the concept of link cost. However, they did not specify how to calculate the link cost for their routing metric.

In this paper, we define a link weight based on the relative distance and data rate of two communicating nodes. Also, we exploit the stability aspect of connection entropy in [Karayiannis and Kaliyur 2006]. Considering both the stability of a route and the speed of each link (represented by the link weight which is combined with the probability of that link existing in the route), we proposed a new routing metric for mobile ad hoc networks (MANETs). The new routing metric guarantees that a found route has high speed and stability among route candidates. Therefore, this reduces the probability of link brakeage and route reparation, especially in the case of more frequently changing network topology.

3. PARAMETERS SUPPORTING MULTI RATE ROUTING FOR MANETS

The proposed multi-rate routing for an Mobile Ad hoc Networks environment deals with the mobility problem by a totaly new approach. The traditional way to find an efficient routing metric for MANET is to deal with velocity and direction of node mobility. Instead, in this paper, the mobility is considered, given the fact that the data rate will be changed and the chosen route is stable or not. Therefore, we define *Link Weight* (as the representative of data rate) and *Connection Uncertainty* (as the representation of route stabilization) in this section. Those parameters are used for further calculation of the routing metric in the next section.

3.1 Calculating Link Weight from the MAC Layer

For transmitting data at a specific rate v (v = (0, 6, 9, 12, 18, 24, 36, 48, 54) Mbps), the corresponding receiver sensitivity requirement is needed. In which, $v = 0$ means that node x and node y do not directly connect, due to interference or being out of

Table I. Data Rate and Rx Sensitivity in 802.11 OFDM PHY.

Data Rate v (Mbps)	Modulation Type	Coding	Rx Sensitivity P_{S_v} (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

communication range. Remember that the number of data rate, as well as the maximum data rate, here follow the IEEE 802.11g standard [IEEE 2007]. Hence, if the network uses another standard, then those parameters should be changed according to that standard's specifications. Table I shows the data rate and Rx Sensitivity in IEEE 802.11 OFDM PHY.

Hence, to transmit data at rate v, the received signal strength must at least equal the receiver sensitivity, P_{S_v}. The received signal strength at receiver R with distance d far away from the transmitter T is calculated as:

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

in which, P_r and P_t are the receive and transmit signal power in dBm, $20\log10\left(\frac{4\pi\overline{d}f}{c}\right)$ 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 $P_r = P_{S_v}$ and $\overline{d} = 1$, we can determine the transmission range R_v at rate v as:

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

The transmission range is used for calculating Link Weight as follows:

Definition 3.1. (*Link Weight*) The Link Weight (w_{jk}^v) at rate v of the link from the j-th to the k-th is the ratio of the transmission range for the minimum data rate $\min(v)$ to the transmission range for data rate v.

$$w_{jk}^v = \frac{R_{\min(v)}}{R_v} = 10^{\frac{P_{S_v} - P_{S_{\min(v)}}}{10\gamma}} \tag{3}$$

Obviously, the Link Weight ($w_{jk}^v > 1$) and R_v will never be greater than $R_{\min(v)}$ because, in this case, the link will be broken, because the two nodes out of communication range. Hence, the object is to find the best link with maximum link weight.

3.2 Modeling the Connection Uncertainty of a Route

Consider a mobile ad hoc network with n nodes and p_j^i as the probability that node j-th of the network stays at the i-th position in the route. At the initial stage of network formation, all nodes compete to be selected in a position of a route with the connection probabilities of the values in the range [0,1]. At the final stage of the routing process, the connection probability of selected nodes belonging to the route will take the value 1, while others will take the value 0 to determine the legitimate route. In reality, the connection probability should be network parameters such as node available bandwidth, distance to the communicating node, or remaining energy which depend on the design routing metric. Let l be the maximum number of links of possible routes from the source node s to the destination node d, so that, in the worst case, there is only one route, and all nodes participate in a route as a chain topology, such that $l=n-1$. Since there are only ($N=n-2$) nodes (exclude two end nodes) competing to occupy the remaining position of total l links, and, thus, the probability distribution is complete for a legitimate route, the set of connection probability is satisfied:

$$\sum_{j \in N} p_j^i = 1, \ (2 \le i \le l) \tag{4}$$

The set of connection probability forms ($l \times n$) metric $\mathbf{P} = [\mathbf{p}_j^i] \in \mathbf{R}^{1 \times n}$. Note that, for a legitimate route, since each node of the network cannot occupy more than one position, the connection probability (p_j^i) satisfies the condition $p_j^i p_j^r = 0$ ($1 \le j \le n$, for all $r \ne i$).

We can observe that the distribution function of connection probability $\{p_1^i, p_2^i, p_3^i, ..., p_n^i\}$ is a variable, so that we can apply Shannon entropy [Shannon 1948] to calculate the connection entropy of the MANET:

$$H(\mathbf{P}) = -\frac{1}{1-1} \sum_{i=2}^{1} \sum_{j=1}^{n} p_j^i \log_2 p_j^i \ (\text{bits}) \tag{5}$$

Lemma 3.2. *The connection entropy $H(\mathbf{P})$ has the values lying on the following condition*: $0 \le H(\mathbf{P}) \le \log_2 \mathbf{n}$.

Proof. First, as the definition of information entropy $H(\mathbf{P}) = \mathbf{E}_\mathbf{P} \log_2 \frac{1}{\mathbf{P}}$, and obviously, $0 \le p_j^i \le 1$. So that $H(\mathbf{P}) \ge \mathbf{0}$. Next, using Jensen's inequality [Cover and Thomas], if f is a convex function and X is a random variable, then

$$Ef(X) \ge f(EX) \tag{6}$$

Moreover, if f is strictly convex, then the equality in Eq. (6) implies that $X = EX$ with probability 1 (i.e., X is a constant). Apply to Eq. (5), we have

$$H(\mathbf{P}) = \frac{1}{1-1} \mathbf{E} \log_2 \sum_{i=2}^{1} \sum_{j=1}^{n} \mathbf{p}_j^i$$

$$\le \frac{1}{1-1} \sum_{i=2}^{l} \log_2 E \left(\sum_{j=1}^{n} p_j^i \right) = \frac{(l-1)\log_2 n}{(l-1)} \tag{7}$$

Hence, $0 \le H(\mathbf{P}) \le \log_2 \mathbf{n}$.

We can observe that, if the values p_j^i of $\mathbf{P}$ are 0 or 1, then the connection entropy is minimized, and $H(\mathbf{P}) = \mathbf{H_{min}} = \mathbf{0}$. In this case, $\{p_j^i\}$ defines the least uncertain route. $H(\mathbf{P})$ reaches its maximum value $H(\mathbf{P}) = \mathbf{H_{max}} = \log_2 \mathbf{n}$ iff $p_j^i = 1/n$, $\forall i, j$. In this condition, we have the most uncertain route that must be avoided in order to select stable routes.

3.3 Associating Link Weight with Connection Uncertainty

For a link belonging to a route, we need to define and use its weight to choose the best route. Most existing proposals do not give any details about how to calculate and assign a weight for a communication link. In section 3.1, we have already proposed a comprehensive calculation of link weight. As discussed above, w_{jk} denotes the weight of the link from the j-th to the k-th node of the network. That link exists with probability of connection p_j^i. 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 calculated as:

$$W^i(v, \mathbf{P}) = \sum_{j=1}^{n} \sum_{k=1}^{n} p_j^{i-1} w_{jk}^v p_k^i \sum_{j=1}^{n} \sum_{k=1}^{n} p_j^i w'_{jk}^v p_k^{i+1} \tag{8}$$

The average link weight for each position in the route can be defined as

$$W(v, \mathbf{P}) = \frac{1}{1-1} \sum_{i=2}^{1} W^i(v, \mathbf{P})$$

$$= \frac{1}{1-1} \sum_{i=2}^{l} \left(\sum_{j=1}^{n} \sum_{k=1}^{n} p_j^{i-1} w_{jk}^v p_k^i \sum_{j=1}^{n} \sum_{k=1}^{n} p_j^i w'_{jk}^v p_k^{i+1} \right) \tag{9}$$

The proposed routing metric will use the average link weight as a factor to select the best route.

4. THE MULTI-RATE MANET ROUTING METRIC

In the MANET environment, the connectivity among nodes always changes, due to node mobility. A robust and stable routing protocol must be the protocol which is designed to deal with the mobility problem. As mentioned above, in this paper, we model the mobility aspect based on its effect on data rates as well as node connectivity. For more detail, at the initial stage, suppose that p_j^i is the probability that node j-th of the network stays at the i-th position in the route. Also, depending on the position of that node and the nodes occupying the previous and next positions in the route, the corresponding link weight can be determined in the Eq. (8). When the node moves closer to or farther away from 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., 54 Mbps), or can decrease (in case the relative distance is longer) down to the minimum

supported rate (i.e., 6 Mbps). The connectivity is broken when $R_\nu > R_{\min}(\nu)$ (the two node out of communication range). Utilizing this relation, we actually transform the mobility aspect (traditionally based on node's velocity vector) into link weight, which is variable following node distance. Moreover, taking into account the stability of the network, we develop a routing metric with the consideration of connection entropy $H(\mathbf{P})$. A route can be chosen if it has minimum connection uncertainty and maximum link weight. The minimum uncertainty of the connection ensures the stability of the route, hence, reducing the probability of link brakeage and route reparation.

The multi-rate MANET routing metric, therefore, can be developed by determining the connection probability metric $\mathbf{P}$ and link weight that minimizes

$$M(\nu, \mathbf{P}) = \alpha H(\mathbf{P}) + \frac{(1-\alpha)}{\mathbf{W}(\nu, \mathbf{P})} \tag{10}$$

under the constraint in Eq. (4)

$$\sum_{j \in N} p_j^i = 1, \ (2 \leq i \leq l)$$

subject to minimize $H(\mathbf{P})$ and maximize w_{jk}^ν

The routing metric in Eq. (10) is defined in terms of the weighted parameter $\alpha \in (0,1)$. The weighted parameter determines the cooperative effect of the entropy and the link weight on the objective function $M(\nu, \mathbf{P})$. If $\alpha \to 0$, then the effect of the entropy term in Eq. (10) is eliminated, and the routing process is almost exclusively based on the maximization of the average link weight. As the value of α increases, the effect of the entropy term also increases and the maximization of the link weight $W(\nu, \mathbf{P})$ plays an increasingly dominant role. On the contrary, if $\alpha \to 1$, then the entropy term is dominant, and minimization of $M(\nu, \mathbf{P})$ implies minimization of the connection entropy $H(\mathbf{P})$.

The proposed routing metric requires cross-layer support from the MAC for the computations of link weight. The 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} from which the network layer computes the transmission range in Eq. (2) and the Link Weight following the Eq. (3).

5. PROTOCOL OPERATION

The process of finding a single route from source to destination is based on the route discovery procedure of AODV, described in the section 2. Also, the RERR message is used for route maintenance when link brakeage occurs. However, to determine the better route among route candidates, the operation of the proposed protocol must be modified to work with the new routing metric, as follows.

Like any other weight/cost based routing protocol, our protocol allows duplicated RREQs to retransmit to find a better route within an acceptable time in the route discovery phase. Each time source node sends a new RREQ message, the message contains an unique ID to differentiate with others. In this paper, we limit the number of RREQ messages with different IDs equal to the number of 1-hop neighbors of the

source node in order to limit the route discovery time. Therefore, in the optimal case, there will be a maximum m route candidate (with m as the number of 1-hop neighbors of the source node). When an intermediate node receives a duplicated RREQ message, it will calculate a new link weight and compare it with the existing one. If the new value is better (higher), it will update that value and forward it to the next hops. Otherwise, the intermediate node will discard the duplicated RREQ message.

When receiving the RREQ, each node calculates its own link weight, following the Eq. (3). To do this, 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 with the network layer by delivering the received signal strength (or, the RSSI) along with a received packet. From this parameter, the network layer can calculate the link weight and select the appropriate data rate according to the corresponding distance. The process is repeated until RREQ reaches the destination. The destination after receiving all RREQs calculates $M(v, \mathbf{P})$ for each received RREQs. The RREQs with minimum $M(v, \mathbf{P})$ will be chosen and the RREP will be sent backward through the selected route with the information of all other route candidates. That information will be used when route error occurs.

When the selected route is broken due to a link's breakage or a node's failure, the RERR will be sent back to the source node. The source node then uses the best existing backup route to deliver data. In the worst case, when all possible backup routes are unavailable, the source node will initiate the route discovery again.

6. PERFORMANCE ANALYSIS

We evaluate the performance of proposed multi-rate routing metric using *NS-2* [NS2] to compare with the traditional AODV protocol based on the hop count metric. The network includes 100 nodes randomly distributed over a 250m×250m area. The IEEE 802.11g standard is used. In a typical office environment, the maximum range of 802.11g is about 100 feet (33 meters) at the lowest speed (6 Mbps). Hence, this random topology ensures that nodes can use a specific data rate v ($v = (0, 6, 9, 12, 18, 24, 36, 48, 54)$ Mbps). UDP flows, with the packet size is set to 1024 bytes, are applied in the source nodes. The random waypoint mobility model is used with a maximum speed of 10 m/s. The path loss exponent (γ) value is normally in the range of 2 to 6 (where 2 is for propagation in free space, 6 is for relatively lossy environments). In this paper, we use $\gamma = 3$ to calculate transmission range R_v following the Eq. 2. The performance metrics are obtained from the results of 50 simulation runs.

First, we observed the route discovery time and determined that the proposed routing metric takes slightly more time for the average route discovery than AODV, as shown in the Figure 2. In the figure, the discovery time increases sharply when the distance between source and destination increases. This is because the longer distance needs more intermediate nodes to reach the destination. Therefore, more medium access contentions, which cause more time consumption, will occur. AODV allows only one RREQ per node to find the minimum hop route. Each node is expected to forward the RREQ only once. Hence, apparently its discovery time is minimized. The proposed protocol is designed to select the route with higher speed. Hence, with the same distance from source to destination, it may use more intermediate nodes than AODV,
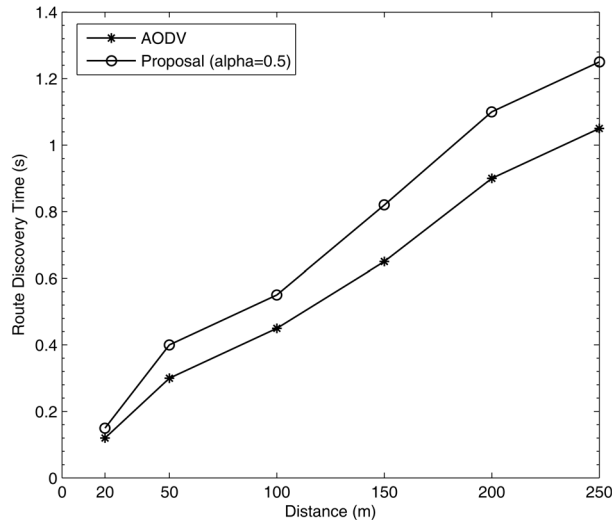
Figure 2. Route discovery time.

with the minimum hop count metric. Furthermore, duplicated RREQs are allowed when the higher value of link weight needs to be updated, and different RREQ messages are used to find the best route among route candidates. This procedure also takes additional time for route discovery. This extra discovery delay commonly occurs for routing metrics which are not based on the shortest path, but, in this paper, the tradeoff is worthy of throughput improvement and route stabilization.

Second, for validating the robustness of route stabilization using the proposed routing metric, we observed the percentage of link breakage that causes route reparation and compare it with that of traditional AODV. In the case of AODV, using the minimum hop to reach the destination means that the distance between the two intermediate nodes is large (that almost reaches or reaches the minimum supported rate). Under the node mobility, the probability that communicating nodes are outside of communication range is high. Hence, the probability of a broken link is high. For the proposed protocol, Figure 3 shows that in both cases ($\alpha = 0$, 0.5, 1), the multi-rate metric sharply reduces the percentage of broken links. Even for the case $\alpha = 0$ (the link weight is important), the selected route is also stable. The reason is that the link weight $W^i(v, \mathbf{P})$ is also a function of the connection probability metric $\mathbf{P}$, and will select links with high connection probability values. Hence, the link weight itself, once to be maximized, can ensure the selection of stable links.

Next, we evaluate our routing metric incase of $\alpha = 0.5$ (balance between link weight and stable route) to observe end-to-end throughput. Figure 4 shows that the throughput in all cases downgrades when either the number of intermediate nodes increases or the distance between source and destination increases. However, the proposed routing metric outperforms at any distance. Especially, when the distance increases, the throughput of AODV deducts much faster than that of our proposal. At the distance of 200m, the proposed metric outperforms AOVD around two times (16.8
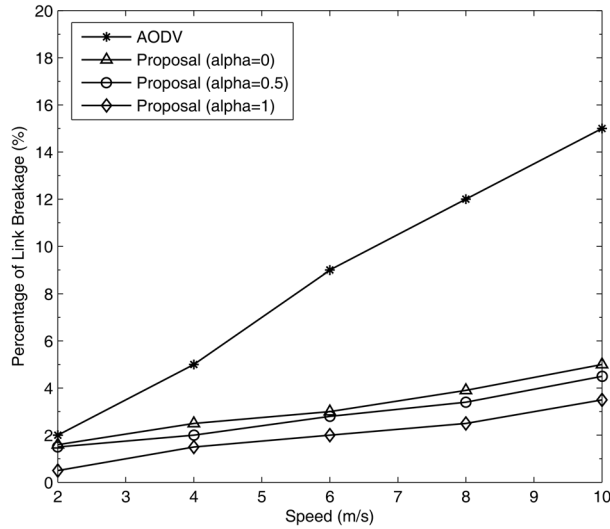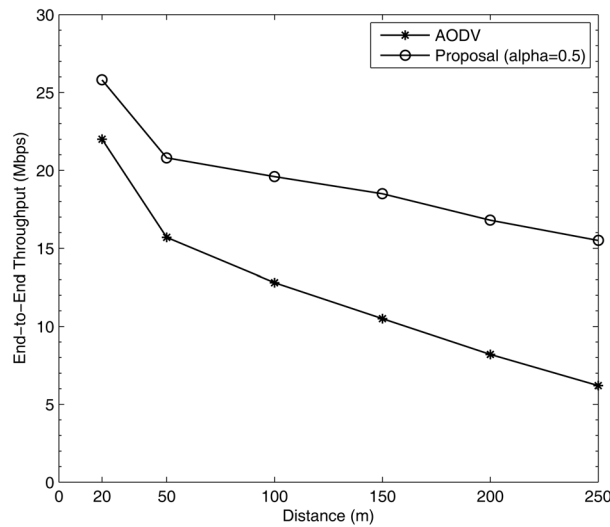
Figure 3. Percentage of broken link.

Figure 4. Average end-to-end throughput.

Mbps and 8.2 Mbps, respectively), and at the distance of 250m, outperforms AOVD almost 2.5 times (15.5 Mbps and 6.2 Mbps, respectively). This improvement is achieved because the proposed routing metric selects higher speed and a more stable route than traditional AODV, as described above.

Finally, network throughput is observed to compare with traditional AODV. We study the impact of node mobility and traffic load on network throughput. Initially, we fix 10 flows with the packet size of 1024 bytes and packet rate of 30 pkts/s to study the effect of node mobility. Figure 5 shows that node mobility affects the performance
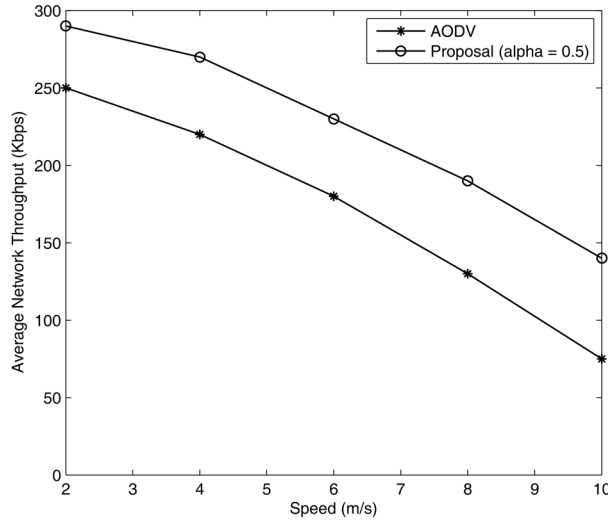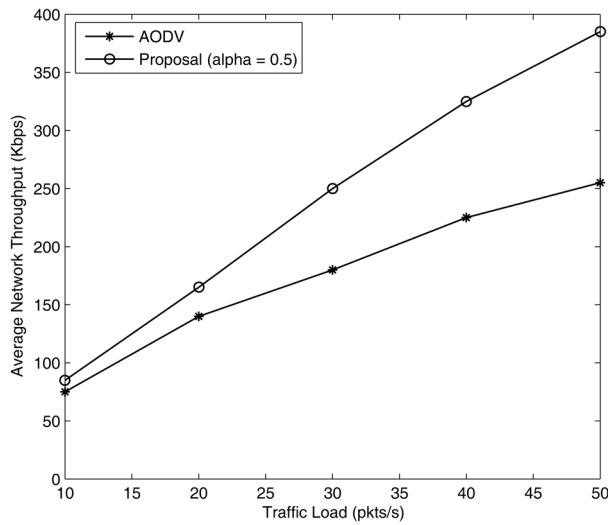
Figure 5. Impact of mobility on network throughput.

Figure 6. Impact of traffic load on network throughput.

of routing protocols seriously, especially at the high speed. When the speed is high, link breakage occurs more frequently, so that the network throughput is downgraded. To examine the impact of traffic load, the network is setup with 10 simultaneous flows, and data packets are injected from 10 to 50 pkts/s, with a packet size of 1024 bytes under the nodes movement speed of 5 m/s. Figure 6 shows that, when the traffic load increases, the achieved network throughput of all routing protocols is also increased. However, throughput does not increase at the expected rate with increasing loads. Indeed, network congestion and collision occur more frequently when

the network has simultaneous flows with high traffic loads. For AODV, the network throughput increases very slowly with increasing loads. The reason is that AODV always chooses the route with minimum hops, so that the transmission range/ interference range is large. Therefore, the adjacent communications are interfered, and the total network throughput is downgraded. In contradiction, our protocol prefers to use a high data rate and stable links. Hence, the broken links and interference are limited. Consequently, our protocol outperforms AODV in terms of both the effect of node mobility and traffic load.

7. CONCLUSIONS

In this paper, we proposed a new routing metric for the multi-rate mobile ad hoc network. The proposal is motivated by the reality that the routing metric in MANETs must use not only high throughput but also a more stable route. By modeling the mobility aspect as the variation of the level of maximum data rate that connecting nodes can use when they move close to or far away from other nodes, we relate the mobility problem with link weight and stability. Therefore, our new routing metric can reduce the probability of route reparation due to broken links and outperforms AODV in cases of both end-to-end throughput and network throughput.

The proposed metric requires support from the lower layers to calculate link weight and uses the appropriate transmission rate. Also, the route discovery time is slightly longer than the minimum hop count metric. In the future, we will apply the new metric for multi-path MANETs routing. The multi-path can be used for route backup or simultaneous transmission. Also, the effect of network density will be considered for the performance comparison of routing protocols.

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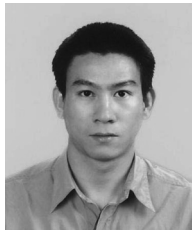
Cao Trong Hieu   received his B.S. degree in Electronic and Telecommunication from Hanoi University of Technology, Hanoi, Vietnam, in 2003. He received his M.S. degree in Computer Engineering in 2007 and is currently a Ph.D Candidate in the Department of Computer Engineering at Kyung Hee University, South Korea. His research interests are cross-layer design, routing, and secure routing for wireless mesh and mobile ad hoc networks.

Choong Seon Hong   received his B.S. and M.S. degrees in electronic engineering from Kyung Hee University, Seoul, Korea, in 1983 and 1985, respectively. In 1988 he joined KT, where he worked on Broadband Networks as a member of the technical staff. In September 1993, he joined Keio University, Japan. He received his Ph.D degree at Keio University in March 1997. He had worked for the Telecommunications Network Lab at KT as a senior member of the technical staff and as a director of the networking research team until August 1999. Since September 1999, he has been working as a professor of the School of Electronics and Information, Kyung Hee University. He has served as a Program Committee Member and an Organizing Committee Member for International conferences, such as SAINT, NOMS, IM, APNOMS, E2EMON, CCNC, ADSN, ICPP, DIM, WISA, BcN, and TINA. His research interests include ad hoc networks, network security, and network management. He is a member of IEEE, ACM, IEICE, IPSJ, KICS, KIISE, and KIPS.