PAPER

A High Throughput On-Demand Routing Protocol for Multirate Ad Hoc Wireless Networks*

Md. Mustafizur RAHMAN†, ***Nonmember***, **Choong Seon HONG**†a), ***Member***, ***and*** **Sungwon LEE**†, ***Nonmember***

SUMMARY Routing in wireless ad hoc networks is a challenging issue because it dynamically controls the network topology and determines the network performance. Most of the available protocols are based on single-rate radio networks and they use hop-count as the routing metric. There have been some efforts for multirate radios as well that use transmission-time of a packet as the routing metric. However, neither the hop-count nor the transmission-time may be a sufficient criterion for discovering a high-throughput path in a multirate wireless ad hoc network. Hop-count based routing metrics usually select a low-rate bound path whereas the transmission-time based metrics may select a path with a comparatively large number of hops. The trade-off between transmission time and effective transmission range of a data rate can be another key criterion for finding a high-throughput path in such environments. In this paper, we introduce a novel routing metric based on the *efficiency of a data rate* that balances the required time and covering distance by a transmission and results in increased throughput. Using the new metric, we propose an on-demand routing protocol for multirate wireless environment, dubbed MR-AODV, to discover high-throughput paths in the network. A key feature of MR-AODV is that it controls the data rate in transmitting both the data and control packets. Rate control during the route discovery phase minimizes the route request (RREQ) avalanche. We use simulations to evaluate the performance of the proposed MR-AODV protocol and results reveal significant improvements in end-to-end throughput and minimization of routing overhead.

key words: *high throughput routing, multirate routing, ad-hoc networks, AODV, on-demand*

1. Introduction

In recent years, the wireless ad hoc networks have become much popular for infrastructureless topology control and distributed collaboration among the wireless nodes. Each node in such a network 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.

A routing protocol in ad hoc networks dynamically controls the network topology, and hence, determines the network performance. As of now, many routing protocols have been proposed for ad hoc networks, where the on-demand protocols like DSR [1] and AODV [2] are mostly preferred, because they save bandwidth and processing power [3]. In on-demand protocols, a node (*source*) searches for a new route to another node (*destination*), typically by flooding a *route request* (RREQ) packet throughout the network. All neighbor nodes, excepting the destination, rebroadcast the received RREQ to its neighbors. When the destination receives an RREQ, it selects the route by sending a *route reply* (RREP) packet to the source in the reverse path. In the original AODV and DSR protocols, each node is expected to forward the RREQ only once ($O(n)$ broadcasts). So, they forward the first received RREQ and discard the subsequent RREQ packets. Most of the available protocols are designed on single rate packet radio model and use *hop-count* as the routing metric. The expected transmission count (ETX) [4] and expected transmission time (ETT) [5] metrics are also proposed to select high throughput paths using link quality.

Nowadays, the physical layer enhancements for wireless communications support multiple data rates and enable nodes to select the appropriate transmission rate depending on the required QoS and the channel conditions. For example, the IEEE 802.11g PHY standard provides eight modulation and coding schemes (MCS) and thereby offers eight different data rates ranging from 6 Mbps to 54 Mbps [6]. A communication with high transmission rate requires a high signal-to-noise ratio (SNR) in the channel, and distance between the sender and receiver is one of the key parameters that determines the SNR level, since the strength of a radio signal drops exponentially with distance. Thus, there is an inherent trade-off between high transmission rate and effective transmission range [7]. MAC protocols, including the widely used IEEE 802.11 standard, do not include any specific rate adaptation technique to utilize the multiple transmission rates efficiently, rather they leave it as an open issue for the vendors. Usually, a rate adaptation technique (eg. ARF [8], RBAR [9]) at the MAC layer selects the data rate for the next transmission from the recent success or failure history. However, the rate adaptation techniques cannot detect the RREQ failures (or, successes) because the broadcast and multicast packets are not acknowledged. For this reason, a node broadcast packets at a predefined data rate: usually, at the highest or the lowest rate. Broadcasting RREQs at the highest rate covers the minimum area and increases the number of hops significantly. On the other hand, broadcasting at the lowest rate covers the maximum area, but it experiences excessive delay in the route discovery process and tends to select inefficient routes.

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†The authors are with the Department of Computer Engineering, Kyung Hee University, South Korea.
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a) E-mail: cshong@khu.ac.kr
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Several metrics for selecting high throughput paths such as *weighted cumulative expected transmission time* (WCETT) [5] and *medium time metric* (MTM) [7], [10] have been proposed for multirate wireless networks. In WCETT, the weighted expected transmission time for individual links in a path are combined into the end-to-end path metric. 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. Theoretically, these metrics are efficient in selecting the optimum route. However, forwarding the first RREQ only, which is used in the original DSR and 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 (i.e., requires $O(n^2)$ RREQ broadcasts with n number of nodes).

Bandai et al. [11] proposes a signal strength aware routing (SSR) protocol in which a node forwards a received RREQ after a *standby time*. The node first computes an appropriate data rate from the signal strength of the RREQ, and then, determines the standby time proportional to the medium time at the transmission rate. So, a RREQ through a low-rate link at an intermediary node waits for a longer period. If the node receives a copy of the RREQ through any high rate link, it discards the RREQ for the low-rate link. Thus, a RREQ through the high-rate links arrives at the destination earlier and the destination can select an appropriate route easily. Some other protocols like HT-AODV [12] and APM [13] add a delay as well after receiving the frist copy of a RREQ so that the destination can receive the RREQ through the high-rate links. To receive RREQs through all possible paths, the destination also waits for a period before sending the RREP. The standby time (or wait period) in the above protocols minimizes the number of broadcasts. However, the delays at the intermediary and destination nodes increase the route discovery time significantly. Since a high-rate RREQ transmission also disables the low-rate links, a rate control scheme during the route discovery phase can be used to keep the number of RREQ to the minimum without requiring of any delay at the intermediary and destination nodes.

In this paper, we propose a routing protocol that exploits the efficiency of a data rate for high throughput route discovery in multirate ad hoc networks, namely *multirate AODV* (MR-AODV). The combined impact of hop-count and transmission-time for a specific data rate on the end-to-end delay between two nodes is considered as the efficiency of the data rate. We show the effectiveness of the rate efficiency[†] in both the route discovery and data transmission, and thereby, we control the data rate at both operations. The rate control during the route discovery phase not only helps in selecting high throughput paths but also suppresses duplicate RREQ transmissions. We evaluate the performance of MR-AODV through simulations. Results confirm that the proposed protocol offers much higher system throughput than the current approaches.

The remainder of this paper is organized as follows. In Sect. 2, we discuss on the efficiency of a chosen data rate and introduce the rate dependent metrics for high throughput path selection. We present the proposed MR-AODV protocol in Sect. 3. The performance of MR-AODV is given in Sect. 4. Finally, we conclude the paper in Sect. 5.

2. Preliminaries

In this section, we analyze the combined impact of the hop-count and transmission time for a specific data rate on a multi-hop route between two nodes and thereby determine the overall efficiency of the rate. We make use of the rate efficiencies to determine the optimal rates for broadcast and unicast communications. Finally, we discuss how we can incorporate the rate efficiency in the routing metric.

Let, the multirate MAC protocol in a node supports a set of m distinct data rates $\{r_i | i = 0, 1, 2, \cdots, m-1\}$ for communications, where $r_i < r_j, \forall i < j$. The transmission-range and -time for a rate r_i are $\mathcal{R}(r_i)$ and $t(L, r_i)$, respectively, where L is the size of the packet in bytes. Usually, $t(L, r_i)$ depends on the PHY layer specifications[††], and by definition, $t(L, r_i) > t(L, r_j), \forall i < j$.

Since the *delivery time* of a packet at a specific transmission rate r_i, $t_{del}(r_i)$, depends not only on $t(L, r_i)$ but also on the MAC delays, we consider it as the time from the packet arrival at the MAC layer until the transmission of the last bit of the packet; i.e.,

$$t_{del}(r_i) = \bar{t}_a + t_r + t(L, r_i), \quad (1)$$

where, $\bar{t}_a$ is the average access delay at the MAC layer and t_r is the time to reserve the channel using RTS/CTS handshaking. The average access delay includes the busy channel time, DIFS and the random backoff duration, while the t_r includes RTS and CTS transmission time plus the inter-frame spaces before data transmission; i.e., $t_r = t(L_{rts}, r_0) +$

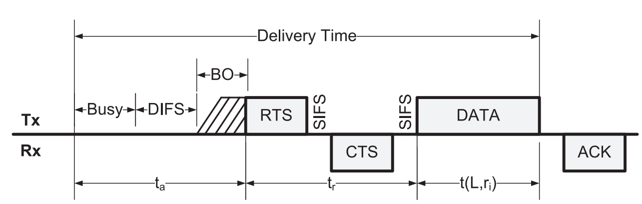


Fig. 1 Packet delivery time.

[†]The terms ‘rate efficiency’ and ‘efficiency of a data rate’ are used interchangeably throughout this paper.

[††]In this paper, we use the following formula in 802.11 OFDM PHY to compute the value of $t(L, r_i)$:

$$t(L, r_i) = t_P + t_{SIG} + \left\lceil \frac{16 + 8 * L + 6}{N_{DBPS}} \right\rceil * t_{SYM},$$

where, t_P, t_{SIG} and t_{SYM} are the PREAMBLE, SIGNAL and OFDM symbol transmission time, respectively, and the N_{DBPS} is the number of coded bits per OFDM symbol for the selected data rate r_i.

Table 1 MCS Rate and corresponding Gains in IEEE 802.11 OFDM PHY (γ = 3.0, CW = 7, L = 1056).

Rate (Mbps) r_i	bits/SYM N_{DBPS}	Sensitivity (dBm) $P_s(r_i)$	Gains: Hop $\mathcal{G}_{hop}(r_i)$	Delivery-time $\mathcal{G}_{del}(r_i)$		Rate $\mathcal{G}(r_i)$	
				$t_r = 0$	t_r = 128 ms*	$t_r = 0$	t_r = 128 ms*
06	24	−82	1	1.00	1.00	1.00	1.00
09	36	−81	2	0.70	0.73	1.41	1.45
12	48	−79	2	0.55	0.59	1.11	1.17
18	72	−77	2	0.40	0.45	0.81	0.90
24	96	−74	2	0.33	0.38	0.66	0.76
36	144	−70	3	0.25	0.31	0.76	0.93
48	192	−66	4	0.22	0.28	0.88	1.11
54	216	−65	4	0.19	0.25	0.78	1.02

*For the IEEE 802.11g PHY, t_r = 0.128 ms

$t(L_{cts}, r_0) + 2 \times t_{SIFS}$ (see, Fig. 1). If a transmission does not use RTS/CTS handshaking, then $t_r = 0$.

The receiving circuitry at a receiver demands for a minimum signal power to receive and correctly translate a packet into data, which is known as *receive sensitivity* of the receiver. For any given receiver, the higher the data rate, the less sensitive will be the receiver because more power is required at the receiver to support the higher data rate. Therefore, the receive sensitivity is generally stated as a function of data rate and we denote it by $P_s(r_i)$ for a data rate r_i. The sensitivity column in Table 1 shows the required receive sensitivity for different rates in the IEEE 802.11g PHY standard. The transmit power, P_{tx}, and $P_s(r_i)$ together set the communication range $\mathcal{R}(r_i)$ for the rate r_i. Using the log-distance path loss model for radio propagation [14], we can determine $\mathcal{R}(r_i)$ for a transmission by the following equation:

$$\mathcal{R}(r_i) = 10^{\frac{P_{tx} - P_s(r_i) - 20\log_{10}(4\pi f/c)}{10\gamma}}. \tag{2}$$

Here, $20\log_{10}(4\pi f/c)$ is the free space path loss at unit distance, in dBm, whereas f and c denote the frequency and speed of the carrier, respectively, and γ is the attenuation factor ($1.8 \le \gamma \le 6$). Since $P_s(r_i)$ increases with higher rates, the communication range shrinks, and thus, the high rate links in a path increase the hop-count.

2.1 Rate Efficiency

According to Eq. (2), transmissions at rate r_0 can reach the maximum range $\mathcal{R}(r_0)$ in single hop. Further, transmissions at any higher rate than r_0 requires one or more intermediary hops to reach the same distance as $\mathcal{R}(r_0)$. The number of intermediary hops for a rate r_i depends on its range $\mathcal{R}(r_i)$. The overall efficiency (or, *gain*) of a data rate r_i, hereinafter we call it *rate gain* $\mathcal{G}(r_i)$, can be defined as follows.

Definition 1 (Rate Gain): We define the gain of a rate r_i as the ratio of the total time required to deliver a packet to the maximum range at r_i to the delivery time of rate r_0. Therefore, the rate gain is,

$$\mathcal{G}(r_i) = \frac{\left\lceil \frac{\mathcal{R}(r_0)}{\mathcal{R}(r_i)} \right\rceil \times t_{del}(r_i)}{t_{del}(r_0)}, \tag{3}$$

where, $\left\lceil \frac{\mathcal{R}(r_0)}{\mathcal{R}(r_i)} \right\rceil$ is the required number of hops for r_i to cover the maximum range $\mathcal{R}(r_0)$ with an exact distribution of nodes; i.e., the intermediary hops are separated from each other by a distance of $\mathcal{R}(r_i)$. In Eq. (3), without loss of generality, we deal with the medium access and transmission delays only considering their significance in medium utilization, and hence, in multi-hop path selection.

By separating the distance and time components, we can rewrite Eq. (3) as:

$$\mathcal{G}(r_i) = \left\lceil \frac{\mathcal{R}(r_0)}{\mathcal{R}(r_i)} \right\rceil \times \frac{t_{del}(r_i)}{t_{del}(r_0)}. \tag{4}$$

The first term in Eq. (4) indicates the impact of a chosen data rate on hop-count (minimum number of links required), and the latter gives the normalized cost in time. Thus, $\mathcal{G}(r_i)$ gives the trade-off between delivery time and effective transmission range of a rate. We define these two components as *hop* and *time* gain, respectively.

Definition 2 (Hop Gain): The hop gain $\mathcal{G}_{hop}(r_i)$ of a rate r_i is the minimum number of wireless links required by the transmissions at rate r_i to cover the maximum range, $\mathcal{R}(r_0)$; i.e.,

$$\mathcal{G}_{hop}(r_i) = \left\lceil \frac{\mathcal{R}(r_0)}{\mathcal{R}(r_i)} \right\rceil \simeq \left\lceil 10^{\frac{-P_s(r_0)+P_s(r_i)}{10\gamma}} \right\rceil. \tag{5}$$

Definition 3 (Time Gain): The time gain $\mathcal{G}_{time}(r_i)$ of a rate r_i is the ratio of the delivery time of a packet at rate r_i to its delivery time at the minimum data rate and is given by:

$$\mathcal{G}_{time}(r_i) = \frac{t_{del}(r_i)}{t_{del}(r_0)}. \tag{6}$$

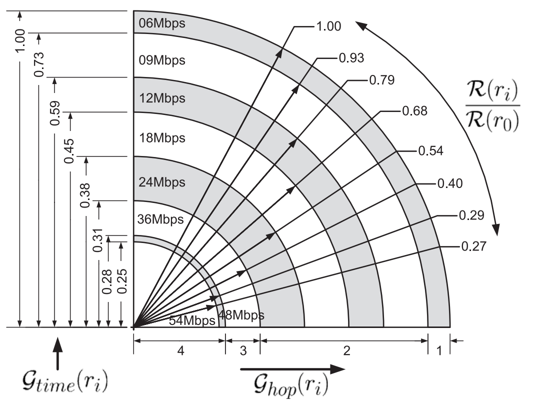


Fig. 2 Hop and time gains for different rates in the IEEE 802.11g PHY ($\gamma = 3.0$, $t_a = 50\,\mu$s, $t_r = 0.128$ ms and $L = 1056$).

The attenuation factor (γ) or the surrounding channel condition at a node controls the value of $\mathcal{G}_{hop}(r_i)$. Higher rates perform better with large value of γ, because the signal power drops with distance at a higher rate. On the other hand, $\mathcal{G}_{time}(r_i)$ depends on two parameters: the contention window (CW) value at a node and the packet size. In a high contention region or an error-prone channel, the average CW value at a node is high; hence, $\mathcal{G}_{time}$ increases significantly. We list the rate gains for the IEEE 802.11g supported rates in Table 1 for a typical indoor environment with $\gamma = 3.0$ and $L = 1056$. Figure 2 illustrates the hop and time gains for the same environment with RTS/CTS handshaking at the MAC layer. A value in the horizontal and vertical axes in the figure shows, respectively, the required number of hops and delivery time of a data rate r_i with respect to the corresponding value of r_0. For convenience, we also show the relative coverage of a data rate with respect to the maximum coverage $\mathcal{R}(r_0)$ in the radial direction. We see that a higher rate offers faster delivery of packets in 1-hop but it cannot guarantee faster delivery in multi-hop communications. Again, the transmissions at a rate between 9 Mbps and 24 Mbps require same number of hops to cover $\mathcal{R}(r_0)$; however, 24 Mbps offers better delivery time among them.

2.2 Optimal Rate for Multi-Hop Communications

From above discussion, it is clear that a rate of transmission that produces the minimum $\mathcal{G}(r_i)$ gives the highest throughput in multi-hop communication. Hence, the optimal data rate $\tilde{r}$ can be expressed as:

$$\tilde{r} = \arg\min(\mathcal{G}(r_i)). \tag{7}$$

In Table 1, 24 Mbps has the minimum $\mathcal{G}(r_i)$ (shaded row). So, it is the high throughput rate for that specific condition. When several rates carry the minimum $\mathcal{G}(r_i)$, all of them are equally efficient; however, the lowest rate among these rates reduces contention in the vicinity.

A node in an ad hoc network can use $\tilde{r}$ for network flooding. Broadcasts at $\tilde{r}$ disable the low-throughput links with a node; and therefore, the network is expected to be flooded very quickly through the high throughput links. However, in case of a unicast (single hop) communication, the distance and/or channel condition between the peers and the antenna radiation patterns may not allow transmissions at some of the supported rates. In other words, a receiver may get a weaker signal than the sensitivity of a data rate and thereby, the nodes cannot communicate using that rate. Thus, the optimal data rate for unicast transmissions $\tilde{r}_u$ can be defined as the rate at which the nodes can communicate and has the minimum $\mathcal{G}_{time}(r_i)$; i.e.,

$$\tilde{r}_u = \underset{P_p \geq P_s(r_i)}{\arg\min}(\mathcal{G}_{time}(r_i)), \tag{8}$$

where, P_p is the signal strength of a packet at the receiver. Therefore, the highest possible rate in a particular wireless link is optimum for the link, since it delivers a packet in the shortest time. A receiver node of a link can determine $\tilde{r}_u$ for the link using the received signal strength of a packet P_p from the sender. For example, if a node receives a packet with $P_p = -72$ dBm, then it determines $\tilde{r}_u = 24$ Mbps because $P_s(24\text{ Mbps}) < -72\text{ dBm} < P_s(36\text{ Mbps})$; i.e., the P_p at the receiver does not support transmissions at a higher rate through the link. When a routing protocol uses $\tilde{r}$ for RREQ broadcasts in order to flood the network quickly, then for all links in the network, $\tilde{r}_u \geq \tilde{r}$.

2.3 Routing Metric Based on Rate Gain

Now, we describe how the rate gain can be used as a criterion for selecting the high throughput paths in multi-hop networks. In a multi-rate multi-hop network, a path between two nodes can be considered as an ordered set of unicast links from the source to the destination, where each link carries an weight according to the data rate at each link. Since the $\mathcal{G}_{time}(r_i)$ of $\tilde{r}_u$ in a particular link k (k-th link in the path) gives the minimum required delivery time of a data packet over the link, we use it as the weight of the link, denoted by *link gain* ($\mathcal{G}_l(k)$). For example, according to Table 1, if the distance between two end nodes of link k allows communication at 54 Mbps through the link, then $\mathcal{G}_l(k) = 0.25$. Similarly, when the link supports 24 Mbps then $\mathcal{G}_l(k) = 0.38$. Further, we denote a path p_i with l links by: $p_i = \{\mathcal{G}_l(k) | k = 1, 2, \cdots l\}$. Suppose, there are three paths $p_1 = \{0.31, 0.28, 0.38, 0.25\}$, $p_2 = \{0.59, 0.73\}$ and $p_3 = \{0.38, 0.31, 0.38\}$ available from the source S to the destination D with different link gains. A routing metric that maximizes the minimum link-gain links (or, minimizes the maximum link-gain links) tends to select a *max-hop* path; i.e., it would choose p_1 that requires 4 hops to reach the destination. On the other hand, a *min-hop* metric that maximizes the maximum link-gain links (or, minimizes the minimum link-gain links) selects the path p_2 with two low link rates. However, we observe that path p_3 is efficient in balancing the hop-count and delivery time than the other two. We introduce the concept of rate-gain in the routing metric so that it can select such an efficient route between a source-destination pair.

According to the definition of *rate gain* and descriptions in Sect. 2.2, we observe that the data rate $\tilde{r}$ at a link suits best for multi-hop communications; i.e., a path having $\mathcal{G}_l(k) = \mathcal{G}_{time}(\tilde{r})$ at every links balances the cost of hop-count and delivery time and offers an optimal performance for a particular source-destination pair. So, the value of $|\mathcal{G}_l(k) - \mathcal{G}_{time}(\tilde{r})|$ shows the efficiency of a particular link in the time dimension with respect to the optimal rate $\tilde{r}$. Thus, for a path p from a source to a particular node (the destination or an intermediary hop) with l number of links, the cumulative value of $|\mathcal{G}_l(k) - \mathcal{G}_{time}(\tilde{r})|$ gives the end-to-end efficiency of the path and we use that as the routing metric M. Hence,

$$M = \sum_{k=1}^{l} (|\mathcal{G}_l(k) - \mathcal{G}_{time}(\tilde{r})|) . \tag{9}$$

Thus, a path p_i is a high throughput path than path p_j when $M_i < M_j$, where M_i and M_j are the metrics for the paths p_i and p_j, respectively. Note that, the metric M in Eq. (9) favors neither the high-rate bound nor the low-rate bound paths. Rather, it promotes the path where each of the links has a gain close to the optimal gain $\mathcal{G}_{time}(\tilde{r})$. For the example paths p_1, p_2 and p_3 described above, the routing metrics at the destination node D are, respectively, $M_1 = 0.3$, $M_2 = 0.56$, and $M_3 = 0.07$. Eventually, D will select the most efficient path p_3. If multiple paths have the same metric value at a node, then the path with least number of hops (or, links) can be selected to reduce contention in the network. Unfortunately, the cumulative value of $|\mathcal{G}_l(k) - \mathcal{G}_{time}(\tilde{r})|$ (in Eq. (9)) does not carry the hop-count information separately. So, a routing protocol has to pass the cumulative value of $|\mathcal{G}_l(k) - \mathcal{G}_{time}(\tilde{r})|$ and hop-count together for routing decisions.

To get an alternate option, we atomize Eq. (9) and separate the hop-count and time components of M as:

$$M = l \times \left|\mathcal{G}_p - \mathcal{G}_{time}(\tilde{r})\right| . \tag{10}$$

Here, $\mathcal{G}_p$ is the average link gain of the path p; i.e., $\mathcal{G}_p = \frac{1}{l}\sum_{k=1}^{l} \mathcal{G}_l(k)$. The $\mathcal{G}_p$ of a path, named as *path gain*, indicates the overall quality of the path in terms of the delivery time per link (of the path) and $|\mathcal{G}_p - \mathcal{G}_{time}(\tilde{r})|$ shows the average link efficiency of a path with respect to that in an ideal optimal path. To use Eq. (10) for calculating M at a node, the routing protocol should pass the $< l, \mathcal{G}_p >$ pair during the route discovery phase. Note that, Eq. (9) and Eq. (10) give the same value of M when every link in a path has a $\tilde{r}_u \geq \tilde{r}$ (or, $\tilde{r}_u \leq \tilde{r}$), and a routing protocol can use either to compute M at a node.

However, for a path having some links with $\tilde{r}_u > \tilde{r}$ and some others with $\tilde{r}_u < \tilde{r}$, the values of M through Eq. (9) and Eq. (10) will be different. In such a case, a metric computed using Eq. (10) may also create loops in a path. Since the proposed routing protocol in this paper uses $\tilde{r}$ for RREQ broadcasts, all links in the network will have $\tilde{r}_u \geq \tilde{r}$; and therefore, the routing protocol can use either Eq. (9) or Eq. (10) to compute the value of M. We choose the form in Eq. (10) as it gives a better understanding of the trade-off between hop-count and delivery time for a path. Further, when the $< l, \mathcal{G}_p >$ pair passes hop-by-hop, it enables the routing protocols to use M, l (e.g., min-hop) or G_p (e.g., MTM) or, any combination of them as the routing metric.

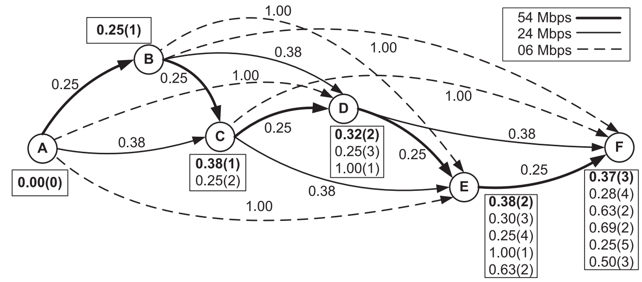


Fig. 3 An example of using the path gain metric with 3 supported rates. All paths source at A and the link gains are taken from Table 1 (with RTS/CTS handshaking). The table at a node shows the available path gains with corresponding hop-count at the node.

Figure 3 illustrates example routes from node A in a network for 3 data rates: 6, 24 and 54 Mbps. The routes ABD and ACD use two links to reach node D and have the same path gain of 0.32. However, the route ABCD uses three links to reach D with path gain 0.25. Since $M_{ABD} < M_{ABCD}$, the path ABD (or ACD) offers higher throughput than that of path ABCD. These paths also give higher throughput than the direct path AD. Similarly, the path ACE (0.38(2)) and paths ACEF and ABDF (0.37(3)) are the most efficient routes for nodes E and F, respectively.

3. Proposed Multirate AODV Protocol

The design goal of our MR-AODV routing protocol is twofold: a) discovering high-throughput paths between the source-destination pairs, and b) minimizing RREQ storms in the network as much as possible. We modify the AODV protocol by changing the hop-count metric to the rate efficiency based metric, M. We also allow duplicate RREQ broadcasts from intermediary hops. We control the broadcast data rate and filter RREQs with inefficient path gains at intermediary hops to keep the number of duplicate RREQ as low as possible.

MR-AODV enables a node to choose and control the data rate for a packet. We assume that 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 for future communications. Each MR-AODV node uses a routing table (or cache) for multi-hop communications. The table maintains the route entries in the following format to allow multirate communications:

{*destination, path gain, next hop, data rate*};

where, the *data rate* is the optimum unicast data rate $\tilde{r}_u$ to send packets to the next hop. A node adds/updates an entry in the table when it receives a RREP packet from the next hop. The routing algorithm at a node searches for a route to the destination in the table with the minimum M value[†]. The node transmits data packets to the next-hop using the designated data rate when it finds a route in the lookup table. When no such route is available in the table, the node initiates a route discovery process.

Like other on-demand routing protocols, MR-AODV uses the RREQ and RREP packets for route discovery. The source address and sequence number fields in the RREQ jointly identifies a unique RREQ instance in the network. Two fields, namely *path gain* and *hop count*, in the RREQ packet jointly represent the routing metric M[††]. The *path gain* field is a 32-bit IEEE 854 floating point number representing $\mathcal{G}_p$ of the (sub-)path from the source to a RREQ sender. The RREP packet also contains the *path gain* field that represents the end-to-end path gain for the selected route. An RREP sender delivers the optimal unicast rate $\tilde{r}_u$ for a link through a *forward rate* field. The *forward rate* field in the RREP is the highest possible data rate between the RREP receiver (k-th hop) and the RREP sender ($(k+1)$-th hop) (i.e., in the reverse direction).

3.1 The Route Discovery Process

An MR-AODV source node initiates the route discovery process by broadcasting a RREQ packet at a rate r_i. We discuss on the data rate for RREQ broadcasts in the next subsection. The *path gain* and *hop count* fields in the initial RREQ packet are set to 0. These fields are updated when a RREQ traverses hop by hop. Just after receiving a RREQ from the previous hop (or, the source), a node computes $\mathcal{G}_l(k)$ from the receive signal strength and then computes $\mathcal{G}_p$ up to the node using the computed $\mathcal{G}_l(k)$ along with the *path gain* and *hop count* fields in the received RREQ. The node uses the receive signal strength further to determine the *forward rate* (i.e., $\tilde{r}_u$) for the inbound link from the RREQ sender. If the node is not the *destination*, it updates the *path-gain* field of the RREQ with the computed $\mathcal{G}_p$ and increments the *hop count* field value by 1 for rebroadcasting.

A node, except the destination, forwards the received RREQ with updated *path gain* and *hop count* fields if it receives the request for the first time. A duplicate RREQ is forwarded by the node only when the newly arrived RREQ carries a better M than that of the previously sent RREQ. For example, in Fig. 3, node C receives the RREQ from A and forwards that. When it receives a copy of the request from B for the path ABC, it does not forward the newly received RREQ because $M_{ABC} \nless M_{AC}$. On the other hand, although node D first receives the RREQ from A (if A broadcasts the RREQ at 6 Mbps) and forwards that to the next hop, it forwards the successive RREQ for path ACD or ABD depending on the arrival sequence. Therefore, a node always cache the recently forwarded RREQ to compare it with a newly received RREQ. Note that, MR-AODV guarantees a loop free route discovery by controlling the data rate of RREQ broadcasts. A duplicate RREQ loops back to a node with a higher M value than that of the loopless copy. So, a loop creating RREQ is never forwarded.

The destination node also computes the $\mathcal{G}_l(k)$, $\mathcal{G}_p$ and *forward rate* ($\tilde{r}_u$) after receiving a RREQ. The first request at the destination is replied with an unicast RREP packet. The destination sets the *path gain* and *forward rate* fields of the RREP packets to the computed $\mathcal{G}_p$ and $\tilde{r}_u$. If it receives another RREQ through a better path later, it overrides the previous route by sending a new RREP. The RREP propagates toward the source in the reverse path and a node that receives the RREP adds the new route in its own routing table. An intermediate hop computes the *path gain* and *hop count* for the route from the reference node to the destination using the corresponding fields in the RREP packet and cached RREQ. Since a node updates the *forward rate* field in the RREP with the computed $\tilde{r}_u$ value for the link, the received RREP at a node supplies the *forward rate* for the next link. Thus, every intermediate hop receives the data rate for the next hop. The route discovery process ends when the last RREP reaches the source.

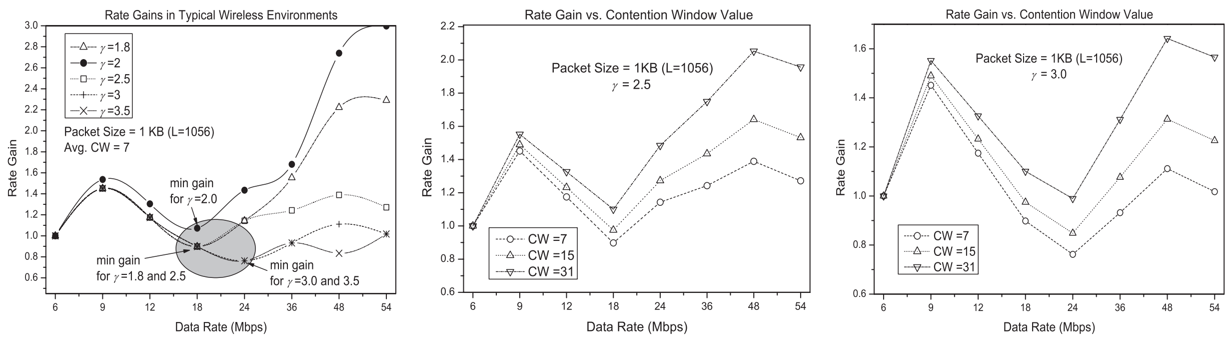
3.2 Rate Control During Route Discovery

In MR-AODV, intermediate nodes broadcast the initial as well as the subsequent route requests with a better M value during the route discovery phase. We allow duplicate RREQ broadcasts to find the best path between the source and destination. A node may receive an RREQ for a low-throughput path first due to the MAC level randomness. It may also receive RREQs for low-throughput paths in an multirate environment if the data rate of the RREQ is chosen inappropriately. In the example scenario shown in Fig. 3, node D receives the first copy of RREQ from A if A broadcasts the RREQ at the lowest data rate (6 Mbps). If D gets access to the medium before B or C, it forwards the initial RREQ. It forwards a duplicate RREQ again when it receives RREQs from B and/or C later. However, if node A broadcasts the RREQ at 24 Mbps, then D is receives the first RREQ either from B or C and does not forward a duplicate RREQ. Therefore, duplicate RREQ transmissions can be further minimized by controlling the data rate during the route discovery phase. An MR-AODV node uses specific data rates for RREQ broadcasts and RREP replies to keep the RREQ broadcasts to the minimum. Rate controlling in RREQ and RREP transmissions not only reduces the number of duplicate RREQ transmissions but also removes the low-throughput links from the paths in the presence of high-throughput links.

3.2.1 RREQ Forwarding Rate

Since the transmissions at rate $\tilde{r}$ theoretically gives the maximum throughput in multi-hop communications, a MR-AODV node broadcasts the RREQ packets at $\tilde{r}$ to disable the links with lower data rates. It also guarantees a

[†]The Routing Table may contain multiple routes for the destination.



(a) (b) (c)

Fig. 4 Rate Gain vs. attenuation factor (γ) and contention window size (CW): (a) impact of γ (with CW=7), (b) impact of CW (with γ = 2.5), and (c) impact of CW (with γ = 3.0).

loopfree operation in the route discovery phase with the metric M in Eq. (10), because, the value of M for a RREQ increases when the RREQ traverse a new link. However, it is difficult to find the $\tilde{r}$ for the nodes at runtime, because the attenuation factor γ and the contention window value (CW) change dynamically with surrounding environments and network conditions. In order to observe how these factors affect the $\mathcal{G}(r_i)$, we use different values of γ and CW in Eq. (5) and Eq. (1), respectively, and thereby compute the corresponding rate gains for the IEEE 802.11g data rates. Figure 4 demonstrates the results for these test cases. In Fig. 4(a), we see that either 18 Mbps or 24 Mbps gives the minimum $\mathcal{G}(r_i)$ value in the typical outdoor and indoor environments ($1.8 \leq \gamma \leq 3.5$). The CW value only increases or decreases the $\mathcal{G}(r_i)$ values proportionally (see Figs. 4(b) and 4(c). So, the attenuation factor is the dominant in selecting the $\tilde{r}$. A node can select and use the appropriate $\tilde{r}$ for RREQ broadcasts only when it is able to estimate the value of γ for the surrounding environment. Since present development in wireless technologies is still in immature state in the runtime estimation of channel condition (and thus, the value of γ), a MR-AODV node can pick any rate from the best two rates for a wide range of γ as $\tilde{r}$ when it is unable to estimate the value of γ for the surrounding environment. For example, an IEEE802.11g device can choose either 18 Mbps or 24 Mbps for this purpose. Note that, broadcasting RREQs at any higher rate than r_0 might raise the connectivity issue in the network. Therefore, a rate adaptation during the route discovery is also necessary in MR-AODV, and we leave this issue for future work.

3.2.2 RREP Forwarding Rate

A node can use the optimum unicast rate $\tilde{r}_u$ to forward the RREP packets in the reverse path. However, the wireless links are usually likely to be asymmetric due to antenna directivity, multipath fading, etc. So, the signal strength in the reverse link may vary from that in the forward link. As a result, transmissions at $\tilde{r}_u$ might not reach to the destination node with the required $P_s(\tilde{r}_u)$. Therefore, it is safe to use the minimum rate r_0 for this purpose as it offers the maximum tolerance.

3.3 An Example Operation of MR-AODV

We use the 6-node topology in this example as shown in Fig. 3. Node A initiates the route discovery process in search of a route to node F. It broadcasts an RREQ with *path gain*=0 and *hop count*=0 at 24 Mbps. B and C receives the RREQ with power −65 dBm and −75 dBm, respectively. Since the signal power at D is below −74 dBm, which is required to receive a packet at 24 Mbps, node D is unable to receive the RREQ from A. Node B and C computes $\mathcal{G}_p$ as 0.25 and 0.38, respectively, according to the received signal strengths. They also determine and cache the *forward rate* for the links AB and AC, respectively. Then they rebroadcast the RREQ at the same rate (24 Mbps) with updated *path gain* and *hop count* as shown in the figure. The sequence of RREQ forwarding from B and C depends on firing of backoff counters at the nodes. If C forwards the RREQ before B, nodes B, D and E receives that and computes the path gain as 0.25(2), 0.32(2), and 0.38(2), respectively. Node B discards the RREQ, because it does not offer a better route, whereas D and E computes the path gains as they receive the request for the first time. If B forwards it before C, the latter also discards the RREQ and D computes the gain as 0.32(2). It should be noted that, whatever the order is, node D computes the same path gains for paths ABD or ACD, and it discards the RREQ for path ABCD, because it receives a prior RREQ from B or C with a better M. Node F receives the first RREQ from D (or E) and responds with an RREP packet with the end-to-end *path gain*=0.37 and *hop count*=3. It discards the duplicate requests from E (or D) because the duplicate RREQ does not offer a better path. The *forward rate* field in the RREP is set to $\tilde{r}_u$ depending on which RREQ reaches node F first: 54MBps, if the first RREQ comes from E, 24 Mbps otherwise. The RREP propagates through any of the paths FECA, FDCA or FDBA, depending on the RREQ broadcast sequence. Each hop updates the *forward-rate* field in the RREQ with the cached *forward-rate* for the reverse link.

4. Performance Analysis

We study the behavior of the proposed MR-AODV routing protocol by simulations and evaluate its performance. We take a 500 m×500 m terrain for simulation and place N number of wireless nodes in uniform random fashion. 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. The distribution of nodes in a case gives a connected network with 24 Mbps links; i.e., a node in the network has at least one path to communicate with any other node at 24 Mbps (or lower rates). Initially, we pick a source-destination pair randomly from the set of N nodes and apply a UDP flow at the source. The MAC payload size for a UDP packet is set to 1000 bytes (i.e., L = 1056 bytes). We use this scenario to study how MR-AODV behaves in networks with different sizes. We also run simulations with a number of source-destination pairs in a network later to evaluate its performance with multiple flows.

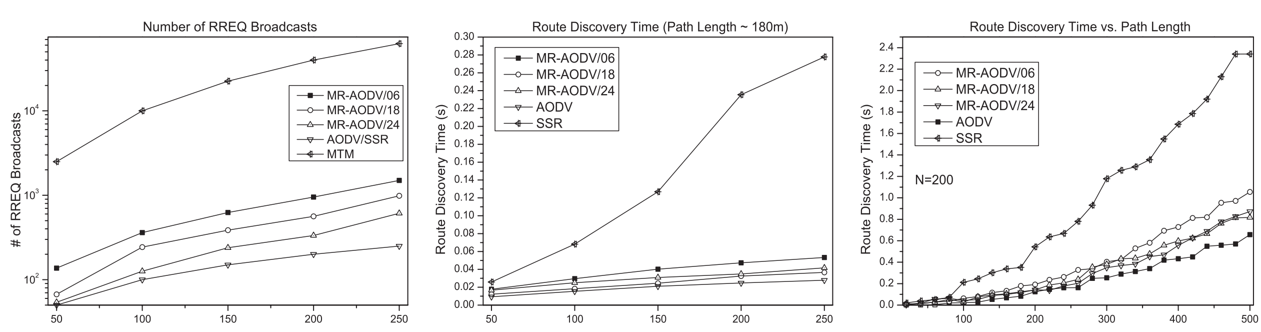
We use the log-distance path loss model for radio propagation with $\gamma = 3.0$ that represent an indoor environment with obstacles. The packet error rate (PER) in the channel is considered to be less than 10% for 1KB packet size. With the chosen transmit power and $P_s(r_0)$ in Table 1 (maintaining the mentioned PER) we get the maximum transmission range of a node $\mathcal{R}(r_0) = 93.00$ m. However, at the end of this section, we show the MR-AODV behavior with a randomly chosen RREQ broadcast rate. In that case, we use a random γ value for a node ranging from 2.5 to 3.5, and $\mathcal{R}(r_0)$ changes accordingly.

In simulations, unless otherwise specified, the proposed MR-AODV protocol uses three RREQ broadcast rates: 18, 24 and 6 Mbps. We denote these MR-AODV versions as MR-AODV/18, MR-AODV/24 and MR-AODV/06, respectively. In simulating the existing protocols, we use 6 Mbps for RREQ broadcasts. The result that we show is the geometric mean over 20 simulations in a network instance.

4.1 Single Flow Performance

In this section, we study MR-AODV behavior at different network sizes and evaluate its performance. First, we investigate the effect of duplicate RREQ and broadcast rate control during route discovery. We compare the results of routing overheads with different schemes in Fig. 5. Figure 5(a) shows the average number of RREQ broadcasts as a function of N. The number of RREQ broadcasts in MTM grows as a power of 2 because the destination needs to get all possible combinations before selecting the route. The theoretical upper limit for MR-AODV is also N^2 as the protocol allows duplicate RREQ forwarding from a node. However, a duplicate RREQ passes through an intermediate hop only when it carries a better M than the previously forwarded copy; therefore, we observe a significant reduction in RREQ broadcast in MR-AODV. In most of the cases, an intermediate hop receives the best M within first few RREQs and discards the subsequent copies. So, the average number of RREQs in MR-AODV is less than 4% of its theoretical limit. It is below 2.5% and 1.5% in MR-AODV/18 and MR-AODV/24, respectively, because the rate control during RREQ broadcasts filters out the inefficient links further according to their transmission ranges. The number of RREQ in the traditional AODV and SSR protocols is the minimum because they allow only one RREQ per node.

We plot the average route discovery time (delay) for the protocols in Fig. 5(b) for approximately 180 meter source-destination distance. We observe that the traditional AODV gives the best performance compared to others. In general, MR-AODV takes more time than that of AODV for the duplicate RREQ transmissions. The route discovery delay for MR-AODV is measured as the period starting from the time of RREQ broadcasting by a source to the time that the source receives the RREP for the best route. In relative comparison between the MR-AODV versions, we observe that MR-AODV/18 outperforms the others. The MR-AODV/06 experiences long delay for comparatively large number of RREQs in a neighborhood and the RREQ messages in MR-AODV/24 propagate slowly due to the shorter range.



(a) (b) (c)

Fig. 5 Routing overheads with single flow: (a) the average number of RREQ broadcasts for a *route request*, (b) the average *Route Discovery Time* when the source-destination pair is approximately 180 m away from each other, and (c) the average route discovery time for different path lengths (with $N = 200$).

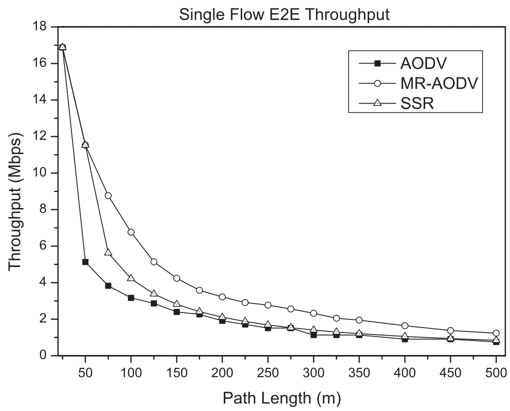


Fig. 6 End-to-End Throughput for single flow.

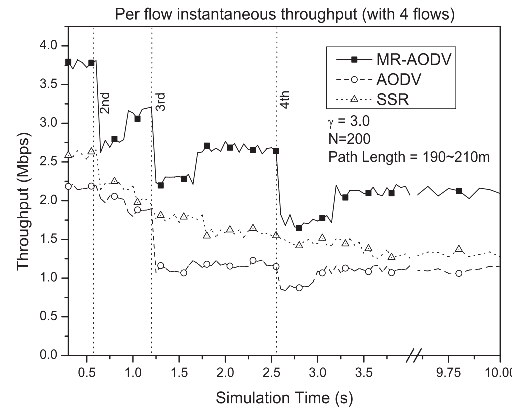


Fig. 7 Instantaneous end-to-end throughput with 4 flows. The flows start at 0.00 s, 0.60 s, 1.20 s and 2.60 s time instants. The route discovery phase for the first flow is not shown in the figure.

Overall, we observe a 40% to 90% increase in the route discovery delay with MR-AODV compared with the traditional AODV, while the increase is about 50% to 490% in SSR. The overhead in SSR is very high due to the long standby times at the intermediary and destination nodes. Since route discovery time in a protocol also depends on the distance between source and destination, we plot the observed results with different distances in Fig. 5(c).

Figure 6 shows the single flow throughput with the protocols for different path lengths. As shown in the figure, the proposed MR-AODV gives improved performance compared with the AODV and SSR counterparts. The improvement is about 60% to 170% compared with the traditional AODV depending on the length of the path. It should be noted here that the MR-AODV/06, MR-AODV/18 and MR-AODV/24 shows the same performance as they select the same path for a source-destination pair. In comparison with the traditional AODV, the SSR protocol gives better performance in a shorter path (about 17% to 55% with path length less than 150 m). However, its performance drops with longer paths (about 5% to 11%), because the high throughput links in a path increases the number of hops which in turn increases the delivery time in the path.

4.2 Performance with Multiple Flows

To study the behavior of MR-AODV in a multi-flow environment, we take a network topology with N=200. We pick four source-destination pairs with path lengths between 190 to 210 meters and apply UDP flows at the sources at 0.00 s, 0.60 s, 1.20 s and 2.50 s time instants. The instantaneous per-flow throughput (average) is shown in Fig. 7. In general, per flow average throughput gradually decreases with the number of active flows in the network due to inter-flow contention and interference. The amount of throughput decrease in a flow depends on the number of segments (or links) in the path that share (or contend) with other flows. We observe high throughput for an active flow in MR-AODV as it selects the high-throughput paths using the path-gain metric. However, throughput for an active flow drops about 20% to 35% temporarily during the route discovery phase of a new flow due to a comparatively large number of RREQ broadcasts in the network. SSR is advantageous at this point because a node broadcasts the RREQ after a standby period; thus, an ongoing flow is not affected severely. So, we observe a gradual decrease in throughput with SSR. Since SSR uses high rate links for data transfer, data packets experience intra and inter flow interference at a higher rate. Therefore, MR-AODV shows about 13% to 79% increase in per flow throughput than SSR. In stable conditions (i.e., ignoring the route discovery period), the improvement is about 47% to 79%.

4.3 Performance in a Dynamic Environment

The previous subsections show the benefit of using a *path-gain* based metric of the MR-AODV protocol with a constant γ value and a node determines the $\tilde{r}$ using the known γ value. In this section, we present MR-AODV performance with single flow in more complex scenario where the value of γ ranges from 2.5 to 3.5 at different regions and the nodes select either 18 Mbps or 24 Mbps as $\tilde{r}$ blindly (without knowing the value of γ). In simulation, we consider three cases: a) all nodes select 18 Mbps as $\tilde{r}$ (MR-AODV/18), b) all nodes select 24 Mbps as $\tilde{r}$ (MR-AODV/24), and c) nodes randomly select either 18 Mbps or 24 Mbps as $\tilde{r}$ (MR-AODV/RAND). We also compute the theoretical throughput with the actual $\tilde{r}$ at the nodes. The results are shown in Fig. 8. We observe 4% to 18% loss in throughput than the theoretical one for using inappropriate $\tilde{r}$ by the nodes. The MR-AODV/18 and MR-AODV/24 show better performance in 18 Mbps bound and 24 Mbps bound paths, respectively. The performance of MR-AODV/RAND depends on how many nodes select the actual $\tilde{r}$ for the surrounding environment. Overall, in the simulation, we observe an adverse performance with MR-AODV/RAND because the most of the nodes picks a wrong $\tilde{r}$ runtime. When we compare the result with Fig. 6, we see improved performance of MR-AODV than the traditional AODV and SSR protocols even with a fixed or random $\tilde{r}$. With randomly se-

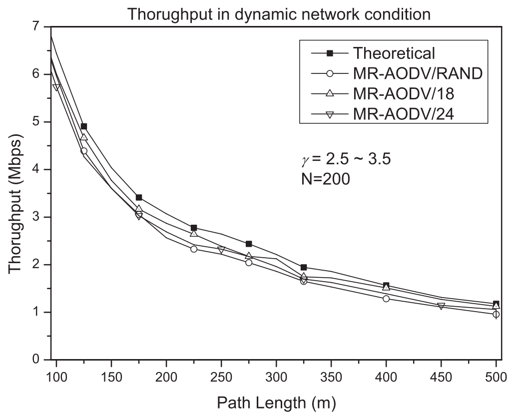


Fig. 8 Throughput performance of MR-AODV in a stochastic environment.

lected $\tilde{r}$ at the nodes, the throughput in MR-AODV is about 20% to 120% higher than the traditional AODV.

5. Conclusion

This paper analyzed the limitation of existing routing protocols, which select a *high-rate bound* or *minimum-hop bound* route in multirate multi-hop communication. Observations show that the efficiency of a data rate depends on the tradeoff between its transmission range and time, and routing performance can be greatly improved if the rate efficiency is taken into consideration for route selection.

The proposed MR-AODV protocol adopts the accumulated rate efficiency as routing metric and broadcasts the RREQ packets at an efficient data rate. While the former selects the high throughput path between the source and destination, the latter keeps the RREQ broadcasts as low as possible. For practicality, we considered implementation of MR-AODV based on IEEE 802.11g specification. Our extensive simulation study showed that MR-AODV discovers high-throughput paths with fewest possible RREQ broadcasts and enhances the network performance significantly. The MR-AODV protocol is considered the most preferable in a lightly loaded wireless ad hoc network to realize high-throughput route discovery.

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Md. Mustafizur Rahman received the B.Sc. (Hons.) degree in applied physics and electronics and the M.Sc. degree in computer science from the University of Dhaka, Bangladesh, in 1997 and 1999, respectively. He joined the University of Dhaka in 1997, where currently he is an assistant professor with the Department of Computer Science and Engineering. He is currently working toward the Ph.D. degree in Computer Engineering at the Kyung Hee University, South Korea. His research interest includes Multiple Access Protocols, Routing and Network Security in Wireless Mobile Ad Hoc and Sensor Networks.

Choong Seon Hong received the B.S. and M.S. degrees in electronics engineering from Kyung Hee University, Seoul, Korea, in 1983 and 1985. In 1988, he joined KT, where he worked on NISDN and Broadband Networks as a Member of Technical Staff. In September 1993, he joined Keio University, Japan. He received the Ph.D. degree at Keio University in March 1997. He worked for the Telecommunications Network Lab, KT as a Senior Member of Technical Staff and as the Director of the Networking Research Team until August 1999. Since September 1999, he has worked as a Professor of the School of Electronics and Information, Kyung Hee University. His research interests include network management, network security, sensor networks, and mobile networking. He is a Member of IEEE, IPSJ, KISS, KIPS, and KICS.

Sungwon Lee received the B.S. and the Ph.D. degrees from Kyung Hee University, Korea. He is a professor of the Computer Engineering Departments at Kyung Hee University, Korea. Dr. Lee was a senior engineer of Telecommunications and Networks Division at Samsung Electronics Inc. from 1999 to 2008. He is a editor of the Journal of Korean Institute of Information Scientists and Engineers: Computing Practices and Letters.