A Routing Protocol for Multi-Rate Wireless Ad-hoc Networks: Cross Layer Approach

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Abstract—This paper addresses the deficiency of the traditional AODV routing protocol in handling multi-rate PHY communications. Then, we propose a new cross-layer scheme to enhance the AODV protocol namely Multi-Rate AODV (MR-AODV) to establish efficient routes in the multi-rate wireless environments. The MR-AODV introduces a new routing metric namely Path Gain that is used to select the optimal route between the source and destination nodes. The path gain considers both hop count and data rates at each hop for a given path. It also provides the optimal data rates for forward and reverse links at each hop and therefore improves the end-to-end performance. The cross layer design of MR-AODV enables acquiring information from the MAC layer and rate controlling from the network layer. The performance of the MR-AODV has been evaluated by simulation and results show significant improvement of the performance in multi-rate ad hoc network environments.

Index Terms—Ad hoc On Demand Distance Vector Routing (AODV), Multi-Rate PHY

I. INTRODUCTION

Wireless ad hoc networks are composed of a number of autonomous wireless nodes and are capable of communicating with each other over direct wireless links within the coverage or with the help of intermediary hops when they are out-of-range from each other. Therefore, each node in the network has to act as a router to provide end-to-end connectivity between two non-neighboring nodes. A number of routing protocols for such networks have been proposed in the recent years; however, due to the dynamic nature of wireless environment and the node mobility, the reactive or on-demand protocols are preferred rather than the proactive protocols.

The Ad hoc On-demand Distance Vector (AODV) protocol [1] is one of the popular reactive routing protocol that discovers the path between the source and destination nodes dynamically. In AODV, the source node searches for a new route to communicate with a destination node by broadcasting a Route Request (RREQ) packet. The neighboring nodes, which receive the RREQ packet, search for a route to the destination in its routing table. When a node finds a route in the table, it replies with a unicast Route Reply (RREP) packet to the RREQ sender. Otherwise, it forwards the RREQ packet to its neighbors. Thus the RREQ packet traverses hop by hop and reaches the destination. The destination node replies with an RREP to establish a new route. The RREP packet traverses the same path in the reverse direction. When the source node receives multiple RREP packets for the same RREQ packet, it selects the path with the minimum number of hops. AODV also uses the Hello and Route Error (RERR) packets to manage route failure and reconstruction.

The design of AODV protocol is based on the simple packet radio model where a wireless node transmits in a predefined data rate. Nowadays, 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 [2] 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 shown in the Table I. However, the receiver sensitivity ($R_s$) or the minimum received signal strength at the receiving end varies with the data rate. The receiver can receive high-rate transmissions when it receives stronger signals. Since the radio signal attenuates exponentially with distance, the higher receiver sensitivity for the higher rates cause the transmission range to drop below the range with lower data rates. As a result, the cell size decreases when wireless nodes selects higher data rates and the number of hops between two nodes increases [3], [4].

The IEEE 802.11 standard does not include any specific rate adaptation technique to utilize the multiple transmission rates efficiently, rather it leaves that as an implementation dependent issue [5]. We observe many proposed rate adaptation schemes for such devices, where the Automatic Rate Fallaback (ARF) [6] scheme is widely-adopted by the industries. 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. However, broadcast packets are never acknowledged, hence those packets are always transmitted at the highest possible rate.

The layer independent design of AODV and the ARF scheme jointly force to transmit the RREQ at the highest possible rate. As a result, the number of hops in the routes increases. Moreover, a node can be isolated from the network when it has no neighbor within the range of the highest rate. On the other hand, if the rate control were designed to allow transmitting broadcast/multicast packets at the lowest possible rate, the airtime of the RREQ packet would increase significantly. It would also flood the network during the route discovery. Therefore, the performance of AODV protocol in ad hoc networks with multi-rate supported devices depends on the tradeoff between the data rate and number of hops.

We observe a few work on routing protocol design for multi-rate wireless ad hoc networks. Awerbuch et al. [3] showed the efficiency of the medium time metric in selecting high throughput network. The SSR [7] and HT-AODV [8] routing protocols focus on the high throughput path selection. However, they do not consider the rate efficiency in transmitting the RREQ packets. Further, the destination node in HT-AODV waits for a period to receive all RREQs in different paths to select the optimum path. Chin et al. [9] proposes a Rate Adaptive Opportunistic Ad hoc Routing (ROAR) protocol that recruits neighbors of nodes on the least cost path as support nodes during the route construction process, and the protocol which works closely with the MAC layer to employ an opportunistic forwarding scheme to take advantage of the node diversity at each hop. The ROAR, however, relies on the transmission failure count for rate adaptation. Therefore, it does not adapt the rate during route request phases to propagate the requests faster.

In this paper, we analyze the relationship between data rate, corresponding transmission range and number of hops in AODV protocol and find the optimal data rate for AODV control and data packets and effective routing metric. Then we propose a new cross-layer AODV routing protocol namely Multi-Rate AODV (MR-AODV) to establish efficient routes in the multi-rate wireless environments. MR-AODV propagates the RREQ packets at the optimum rate to disseminate them faster and the path selection algorithm chooses the best multi-rate path for the communication.

The rest of this paper is organized as follows: section II describes how the data rate affects the hop-by-hop communication and method of selecting optimum data rate for route discovery and route selection. We propose the modified AODV protocol for multi-rate support in Section III. The performance of the proposed protocol is given in Section IV and section V concludes the paper.

II. THE OPTIMUM DATA RATE

In this section, we present an analytical model to determine the optimum data rate for ad hoc communication. First, we relate the minimum number of hops with the data rate, and then find the gain in transmission time for selecting higher data rates. Finally, we combine them to find the optimal data rate for multi-hop ad hoc communications.

According to the wireless radio propagation model, the received signal strength at a receiver \( R \), which is \( d \) distance away from the transmitter \( T \), is expressed as:

\[
P_r = P_t - 20 \log_{10} \left( \frac{4\pi d}{c} \right) - 10\gamma \log_{10} \left( \frac{R_i}{d} \right) \text{dBm.} \tag{1}
\]

where, \( P_r \) and \( P_t \) are the receive and transmit signal power in dBm, \( 20 \log_{10} \left( \frac{4\pi d}{c} \right) \) is the free space path loss at a reference distance \( d \) (usually, 1m) in dBm for signal speed of \( c \) and frequency \( f \), and \( \gamma \) is the path loss exponent \((1.6 \leq \gamma \leq 6)\) depending on the channel condition between \( T \) and \( R \). For any modulation and coding scheme (for example, Table I), if the receive sensitivity \( P_s \) is required for transmission rate \( i \), we can determine the transmission range \( R_i \) from (1) with \( d = 1 \) and \( P_t = P_s \), as:

\[
R_i = 10^{\frac{P_r - P_s}{10}} - \frac{20 \log_{10}(4\pi d)}{10}. \tag{2}
\]

**Definition 1 (Range Gain):** The Range Gain \( G_{R_i} \) is the ratio of the transmission range for data rate \( i \) to the transmission range for the minimum data rate \( \min(i) \), which can be expressed as:

\[
G_{R_i} = \frac{R_i}{R_{\min(i)}} = 10^{\frac{-P_s + P_{s\min(i)}}{10}}. \tag{3}
\]

**Definition 2 (Hop Gain):** The Hop Gain \( G_{h_i} \) is the minimum number of hops required by the data transmission at rate \( i \) to cover the transmission range of data rate \( \min(i) \), i.e.,

\[
G_{h_i} = \left[ \frac{1}{G_{R_i}} \right]. \tag{4}
\]

The \( G_{h_i} \) shows how a data rate affects the performance of the network by increasing (decreasing) the number of hops. The 802.11 OFDM PHY transmission time for a packet is given by:

\[
t_i = t_p + t_{SIG} + \left[ \frac{16 + 8 \times L + 6}{N_{DBPS}} \right] \times t_{SYM} \tag{5}
\]

where, \( L \) is the payload size in bytes including the network and MAC overheads, \( t_p \), \( t_{SIG} \) and \( t_{SYM} \) are the PREAMBLE, SIGNAL and OFDM symbol transmission time, and \( N_{DBPS} \).
As discussed earlier, MR-AODV exploits the multi-rate capability in the in the PHY layer to route packets efficiently to the destination node. It follows the basic route discovery and routing phase of the AODV; however, it applies the rate gain for efficient propagation of the route requests and uses path gains as routing metric rather than the hop count in traditional AODV.

### III. The Multi-Rate AODV Protocol

The modified RREQ and RREP packets of the traditional AODV protocol in order to apply the Path Gain $G_P$ as the new routing metric. Since the MR-AODV follows the basic AODV protocol for the route discovery process, we keep the traditional AODV fields in these packets and append required gain fields to the packet.

Figure 1 shows the modified RREQ packet structure where we append two 32-bit fields, namely Path Gain and Link Gain. The gains are represented as 32-bit single precision IEEE 854 floating point numbers. The Path Gain field is the Path Gain $G_P$ up to the previous $(k-1)$ hop of the RREQ sender (i.e., the $k$-th hop). The Link Gain is the link gain $G_{lk}$ for the selected data rate for the RREQ packet transmission toward the next hop (from k-th to the $k+1$-th hop).

The modified RREP packet structure is shown in Figure 2. It has an additional field namely Path Gain containing a single precision IEEE 854 floating point number. This field represents the reverse path gain from the destination to the $k$-th hop (or the source). The routing algorithm uses this value as the new routing metric to route the packets efficiently.

### Table II

<table>
<thead>
<tr>
<th>Data Rate (Mbps)</th>
<th>Range</th>
<th>Hop</th>
<th>Link</th>
<th>Rate $G_i = G_{hi} \times G_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.8</td>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>0.93</td>
<td>2</td>
<td>0.68</td>
<td>1.36</td>
</tr>
<tr>
<td>8</td>
<td>0.68</td>
<td>3</td>
<td>0.36</td>
<td>1.04</td>
</tr>
<tr>
<td>16</td>
<td>0.54</td>
<td>4</td>
<td>0.28</td>
<td>1.04</td>
</tr>
<tr>
<td>24</td>
<td>0.40</td>
<td>5</td>
<td>0.20</td>
<td>0.59</td>
</tr>
<tr>
<td>31</td>
<td>0.29</td>
<td>6</td>
<td>0.16</td>
<td>0.63</td>
</tr>
<tr>
<td>48</td>
<td>0.27</td>
<td>7</td>
<td>0.14</td>
<td>0.58</td>
</tr>
</tbody>
</table>

where, $t_{\min (i)}$ is the transmission time of the packet at the minimum rate and $t_a$ is the average access delay at each hop including the time to transmit the packet in the queue and MAC access delay. The access delay $t_a$ at a hop depends on the number of active neighbors and the network load in the vicinity. The $\frac{t_a + t_{\min (i)}}{t_a + t_{\min (i)}}$ is the gain in transmission time of the packet. We can assume the $t_a = 34\mu s$ (the DIFS period) in a lightly loaded environment where the packet access the medium at the minimum possible time. In dense and high load networks $t_a >> t_i$; therefore, (6) can be represented as:

$$G_i \approx \begin{cases} G_{hi}, & \text{when } t_a >> t_i \\ G_{hi} \times \frac{t_a + t_{\min (i)}}{t_a + t_{\min (i)}}, & \text{otherwise} \end{cases}$$

i.e., the number of hops in the path dominates the performance when a packet experience large access delay at each hop. Therefore, transmitting at the lowest rate would give the best performance in such a case.

Table II shows different rates with corresponding gains for the IEEE 802.11 multi-rate OFDM PHY. We observe that the rate with the smallest gain (i.e., 24Mbps) is the optimal rate in propagating the packet towards the transmission boundary. Therefore, the data rate $i$ with minimum rate gain is the optimum for RREQ packet propagation. However, for direct communication between two nodes (unicast packets within the transmission coverage), the optimum rate is the rate with minimum rate gain among the possible (maintaining the connectivity) data rates, and we name it as link gain ($G_{lk}$). Therefore, the nodes can select the rate with minimum $G_{lk}$ for transmitting the RREP and data packets.

**Path Gain**

Consider a path between two nodes $x$ and $y$ with $h$ number of intermediary hops ($h \geq 0$). Then the path gain $G_P$ can be expressed as:

$$G_P = \sum_{k=0}^{h+1} G_{lk}(k)$$

where, $G_{lk}(k)$ is the link gain for link $k$ between two nodes in the path. The path with minimum path gain in a multi-rate ad hoc network is the optimum path between two nodes. A path with larger hop count might be efficient than a path with less hop count if the path gain is smaller. The design of the proposed MR-AODV uses the path gain as the routing metric instead of the hop count in traditional AODV.
Since the destination knows the optimum data rate of the packet containing the reverse path gain in the Path Gain route entry to its routing table. Then it replies with a RREP node computes the reverse path gain using (9) and adds the where, \( \hat{G}_i(k) \) for the packet from the MAC layer and computes reverse link an entry for the destination node. It also receives the RSSI receives the RREQ packet and check their routing table for \( R \) Link Gain field of the RREQ packet, and broadcasts the packet.

\[ \text{Path Gain} \]

\[ G_i(k) = \text{min}(G_i) \]

\[ G_p(k) = G_p^{k-1} + \hat{G}_i(k) = \sum_{h=0}^{k-1} \hat{G}_i(h) + \hat{G}_i(k) \]  

(9)

where, \( \hat{G}_i(k) \) is the estimated minimum reverse link gain for the link between \( k \)-th and \( (k-1) \)-th hop from that. If the node finds no entry in the routing table, it adds the link gain with the path gain and stores as the new path gain and broadcasts at rate with min(\( G_i \)) to its neighbors. The new path gain at the \( k \)-th hop \( G_p^k \) is computed from:

\[ K \]

\[ G_p^k = G_p^{k-1} + \hat{G}_i(k) = \sum_{h=0}^{k-1} \hat{G}_i(h) + \hat{G}_i(k) \]  

(9)

Every intermediate hops for the RREP packet in the reverse path computes the optimal data rate for the link with the RREP sender and update their own routing table with the new route. Then they forward the RREP packet in the reverse path using maximum supported data rate for the reverse link (i.e., the highest data rate that ensures connectivity between the two nodes). Therefore, the data rates between two nodes for the RREQ and RREP packets might not be the same.

\[ \text{D. The Routing Table and Route Selection} \]

The routing table for MR-AODV requires three additional attributes for controlling the data rates: Path Gain (\( G_p \)), Forward Link Rate (\( i_{fwd} \)), and the Reverse Link Rate (\( i_{rev} \)). The Forward Link Rate is the optimal data rate to forward the packet toward the destination node (i.e., \( \text{max}(G_i) \) for the link between \( k \)-th to \( (k+1) \)-th hop), and the Reverse Link Rate is the same for the reverse path (i.e., for the link \( k \)-th to \( (k-1) \)-th node).

The routing algorithm searches for a route in the route table for the destination node having the minimum path gain \( G_p \). If it finds a route, then it picks the next-hop address and the Forward Link Rate \( i_{fwd} \) from the table and routes the data packet to the next hop using the rate \( i_{rev} \). The routing algorithm at the intermediate hops follows the same method to select the path with minimum Path Gain \( G_p \). When no route is available in the table, the node issues a RREQ packet to initiate the route discovery process.

\[ \text{IV. PERFORMANCE ANALYSIS} \]

We evaluate the performance of MR-AODV routing protocol by simulations on two different topologies and compare them with traditional AODV protocol. First, we used a 26-node chain topology with a 20m inter-node distance. The load is applied at one end toward the other end. In the second case, 20 to 50 nodes are randomly placed in a 30 \times 30 terrain and loads are applied at different nodes simultaneously. In both cases, data packet size is 1000 bytes (i.e., PHY packet size 1056 bytes) and the path loss exponent (\( \gamma \)) for the channel considered to be 3.

\[ \text{A. Performance in Chain Topology} \]

The observed route discovery time and throughput of the MR-AODV protocol in the chain topology have been shown in Figure 3 and 4, respectively. We observe that the route discovery process in MR-AODV reduces the discovery time to 50\% of that in traditional AODV because of the efficient rate selection algorithm. The RREQ packets are flooded over the network rapidly, and RREP packets traverse through the most efficient path. However, the route discovery time for the same distance varies on the RREQ broadcast timing by each hop. The route discovery time reduces when the node near the transmission boundary of the previous hop broadcasts the
B. Performance in Random Topology

The comparative throughput performance of MR-AODV and traditional AODV has been shown in Figure 5. The throughput in both protocol downgrades when either the number of nodes or the distance increases. Still, the MR-AODV shows better performance than the traditional AODV because of the efficiency in path selection.

V. CONCLUSION

In this paper, we consider a new routing metric namely Path Gain for the multi-rate PHY in wireless ad hoc networks and propose an efficient routing protocol to select the most efficient routes using the Path Gain metric. The proposed MR-AODV disseminates the Route Request (RREQ) packets very rapidly toward the destination for which the route discovery process takes almost 50% time than that of the traditional AODV protocol. The selection of path with the minimum Path Gain also improves the network throughput in multi-rate wireless ad hoc networks.

The design of MR-AODV protocol requires support from the lower layers to control the PHY data rate as well as to receive information for the path selection algorithm. It also requires not to use any rate controlling algorithms in the MAC layer. Although the MR-AODV protocol show better performance in terms of route discovery time and network throughput, the fairness of flows and effect of increasing the transmission range are still to be analyzed.

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