M3RP: Multi-rate/Multi-range Multicast Routing Protocol for Mobile Ad Hoc Networks

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Abstract— **Group Communication services have become more and more important in mobile ad hoc networks (MANETs). The use of multicast transmission techniques in MANETs has been shown to have significant advantages in terms of reducing the redundant communications overhead and utilize network resources more efficiently. The IEEE 802.11 Standard and enhanced amendments have defined fourteen transmission rates: 1, 2, 5.5, 6, 9, 11, 12, 18, 22, 24, 33, 36, 48, and 54 Mb/s, for mobile nodes to transmit and receive data frames. According to the characteristic of modulation scheme, a higher level modulation scheme requires higher signal-to-noise ratio (SNR) and thus the transmission distance (range) is proportionally decreased by increasing the transmission rate. According to this property, the wireless ad hoc network will be formed as a new type of network named multi-rate/multi-range wireless network (M2WN). This paper presents the design and initial evaluation of the multi-rate/multi-range multicast routing protocol (M3RP), a novel on-demand ad hoc multicast routing protocol with multiple transmission rates that attempts to reduce the end-to-end transfer delay as well as to minimize the network resource consumption. We describe the operation of the M3RP and present the evaluation of its performance based on detailed simulations by comparing with the minimum-hop approach multicast ad-hoc on-demand distance vector (MAODV) routing protocol. Simulation results show that M3RP achieves higher packet delivery ratio, lower network resource consumption, and lower average end-to-end transfer delay than conventional minimum-hops approach with fixed data rate especially in heavy traffic load.**

I. INTRODUCTION

Mobile ad hoc networks (MANETs) are constructed by several mobile handsets or laptops and characterized by multi-hop wireless connectivity, changing network topology uncertainly, and the demand for efficient dynamic routing protocols. There is no stationary infrastructure or a preconstructed base station to coordinate packet transmissions or to advertise the information of network topology for mobile nodes, or nodes for short.

The first edition of IEEE 802.11 standard [3] has been approved for the open ISM (industry, science, and medicine) band in July 1999. Two fundamental modulation schemes, named as binary phase shift keying (BPSK) [18] and quadrature phase shift keying (QPSK) [9], are adopted for providing 1 Mb/s and 2 Mb/s transmission rates. For the direct sequence spread spectrum (DSSS), the 11-chip Barker sequence is chosen due to its good autocorrelation property and coding gain. In other words, the DSSS with Barker code is robust against interference/noise and time delay spread condition. By replacing 11-chip Barker code as the complementary code keying (CCK) [2], [15] or packet binary convolutional code (PBCC) [11], [16] scheme, the IEEE 802.11b standard [5] has the ability to provide four data rates 1, 2, 5.5, and 11 Mb/s in the 2.4–2.4835 GHz ISM band. To extend the lifetime of IEEE 802.11b, the IEEE 802.11g standard [6] has been discussed and designed to provide data rates 1, 2, 5.5, 11, 22, and 33 Mb/s using CCK, PBCC, PBCC-22 and PBCC-33 technologies or data rates 6, 9, 12, 18, 24, 36, 48, and 54 Mb/s using orthogonal frequency division multiplexing (OFDM) and CCK-OFDM technologies. On the other hand, the amendment of IEEE 802.11a standard [4], which adopts OFDM technology and operates in 5.15–5.35 GHz and 5.725–5.825 GHz bands, has the ability to provide eight higher data rates 6, 9, 12, 18, 24, 36, 48, and 54 Mb/s by using high-level quadrature amplitude modulation (QAM) [14]. According to above mentions, fourteen data rates (or called transmission rates) are available in the IEEE 802.11 MAC protocol. Table I lists the specifications of IEEE 802.11a, 802.11b, and 802.11g respectively. These technologies enable wireless communications to have the capability of various transmission rates.

TABLE I
SUMMARY OF IEEE 802.11 FAMILY SPECIFICATIONS

ITEM	802.11a	802.11b	802.11g
Modulation	OFDM	BPSK, QPSK, CCK, PBCC	BPSK, QPSK, CCK, PBCC, OFDM
Data rate	6, 9, 12, 18, 24, 36, 48, 54 Mb/s	1, 2, 5.5, 11 Mb/s	1, 2, 5.5, 6, 9, 11, 12, 18, 22, 24, 33, 36, 48, 54 Mb/s
Frequencies	5.15–5.35 GHz	2.4–2.4835 GHz	2.4–2.4835 GHz

With the characteristics of modulation schemes, however, a higher level modulation scheme requires a higher signal-to-noise ratio (SNR) E_s/N_o, consequently, the transmission rate of wireless communication would decrease with the transmission distance (range). Fig. 1 illustrates the expected data rate of each technology at different transmission distances. According to this property, MANETs would be formed as a new type of networks named multi-rate/multi-range wireless networks (M2WNs) [13]. An example of M2WNs is shown in Fig. 2, which nodes v_1, v_2, v_3, v_4, and v_5 are located in a two-dimensional plane and communicate with each other

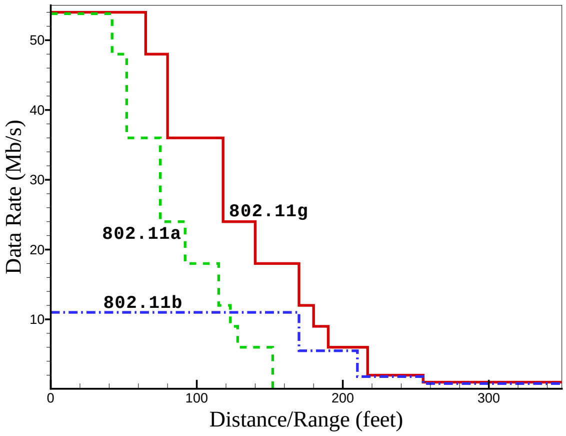

Fig. 1. The expected 802.11a, 802.11b, and 802.11g data rates at varying distances of each sender-receiver pair.

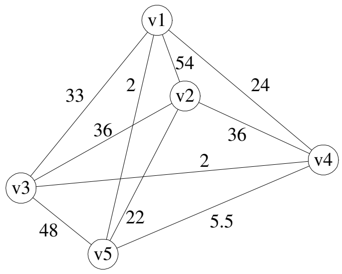

Fig. 2. An example of the multi-rate/multi-range wireless networks (M2WNs) where each number of links represents the maximal transmissible rate. The maximal transmissible rate is obtained by calculation of symbol SNR required for maximum operational packet error rate (PER).

by using different transmission rates according to received symbol SNR value. The idea is that the network resource would be used efficiently if we always adopt the highest transmission rate to transmit data frames. This is because that a higher transmission rate will spend a shorter transmission time and thus more available time slots can be reused by other transmission pairs. Furthermore, in the viewpoint of geography, the shorter transmission range it uses, the more parallel transmissions in the network it gets. The efficiency of M2WNs is not only to increase the channel reuse in a physical area by using higher modulation schemes but to improve the available network resource by using higher transmission rates as well.

Besides, transmitting packets to a specific group of hosts identified by a single destination address is the trend in modern computer networks and is referred to as multicast communications. The term *multicast* means the sending of a packet from one sender to multiple receivers with a single send operation. In MANETs, in order to facilitate the multicast mechanism, many multicast routing protocols [1], [7], [8], [12], [17] have been designed and created to provide multicast communications. However, these conventional multicast routing protocols such as on-demand multicast routing protocol (ODMRP) [8] and multicast ad hoc on-demand distance vector (MAODV) [12] would be no longer suitable for M2WNs since these protocols only consider a fixed transmission rate and using the minimum-hop count approach for routing. This implies that the minimum-hop count routing approach might use a lower data rate for routing and the obtained route would capture a longer end-to-end transmission time. Thus, it would not reflect the characteristic of M2WNs appropriately since one might choose another shorter delay multicast route to perform best performance than previous ones.

In this paper, therefore, unlike other multicast routing protocols, we proposed a novel multi-rate/multi-range multicast routing protocol (M3RP) to achieve multicast transmission with multiple rates thus enhancing the performance of multicast transmission and increasing network capacity in M2WNs. The proposed M3RP considers the total end-to-end transfer delay as well as network resource consumption thus obtains higher throughput than other approaches of multicast routing protocols.

The remainder of this paper is organized as follows. In Section II, we introduce some related works regarding the multi-rate transmission model and illustrate the multicast tree cost function. We describe the operations of the proposed M3RP in details in Section III. The performance of M3RP is simulated and analyzed in Section IV. Finally, some conclusions and remarks are given in Section V.

II. Related Works

A. The IEEE 802.11 MAC Protocol

The IEEE 802.11b Standard provides several kinds of different data rates as medium access control (MAC) protocol. In order to allow the MAC to operate with minimum dependence on the physical medium dependent sublayer, a physical layer convergence procedure (PLCP) sublayer is defined. This function simplifies the PHY service interface to the MAC services. This subclause provides a convergence procedure for the 2, 5.5, and 11 Mb/sec specifications, in which PLCP service data units (PSDUs) are converted to and from physical protocol data units (PPDUs). Before transmission, the PSDU will be appended with a PLCP preamble and header to create the PPDU. Two different preambles and headers are defined: the mandatory supported long preamble and header, which interoperates with the current 1 Mb/s and 2 Mb/s direct sequence spread spectrum (DSSS) specification (as described in [5]), and an optional short preamble and header. At the receiver, the PLCP preamble and header are processed to aid in demodulation and delivery of the PSDU. The format of the interoperable (long) PPDU includes the PLCP preamble, the PLCP header, and the PSDU. The PLCP preamble contains two messages: synchronization (SYNC) and start frame delimiter (SFD). The PLCP header contains the following fields: signaling (SIGNAL), service (SERVICE), length (LENGTH), and CCITT CRC-16. A short PLCP preamble and header (HR/DSSS/short) is defined as optional. Although short preamble and header may be used to minimize overhead and, thus, maximize the network data throughput, we do not consider in this paper. This is because that a transmitter using the short

PLCP will only be interoperable with another receiver that is also capable of receiving this short PLCP. To interoperate with a receiver that is not capable of receiving a short preamble and header, the transmitter shall use the long PLCP preamble and header.

B. The Relationship of Rate and Range

In wireless LANs, the maximal data rate that may not always be adopted due to the transmission distance between nodes is contra-proportional with the data rate. The general concept is that a higher-level modulation scheme requires a higher SNR to obtain the same specified bit error rate (BER) in respect of a lower level modulation scheme. The signal and noise energy collected at the radio and baseband processor is a function of several factors. With the proper design of transmit signal and receiver structures, incorporating such concepts as "matched filtering", the symbol SNR will satisfy the equation $E_s/N_o = P_rT_s/N_o$ where P_r is the receive signal waveform power, T_s is the symbol period, and N_o is the noise floor power spectral level. If white noise with a power spectral density level of N_o is past through a filter with impulse response $h(t)$ or transfer function $H(f)$, then the output power is equal to $N_o\|h\|^2$ where $\|h\|^2 = \int_{-\infty}^{\infty} |h(t)|^2 dt = \int_{-\infty}^{\infty} |H(f)|^2 df$ independent of the shape of $h(t)$ or $H(f)$.

The signal power observed at the input to the receiver radio is a function of several factors including transmit signal power, antenna gain, and propagation loss from the channel. A common model for propagation loss as a function of distance d takes the form $L(d) = cd^{\rho}$ where the exponent v is the critical parameter of the loss model. In free space, with a spherical radiation of transmit power, the exponent $\rho = 2$ since the area of the surface of a sphere grows with the square of the radius. The SNR calculation can be summarized by the equations that relate transmit power to receive power $P_r = P_t/L(d)$ and symbol energy to receive power $P_w\Delta_P T_s \Delta_T/N_o = P_s\Delta_P\Delta_T/N_o$ where P_w is the signal waveform power, Δ_P reflects the power overhead, and Δ_T accounts for symbol clock change relative to the reference. That is, according to above descriptions, the maximal data rate of a modulation scheme will be obtained only when the distance between two transceivers is not over its transmission distance boundary.

C. The Cost Estimation Function

Unlike familiar ODMRP and MAODV, M3RP estimates the multicast tree cost (MTC) by considering the contention delay as well as the transmission time by using different transmission rates to determine multicast routing decision. Therefore, in order to exactly calculating the cost of multicast tree, we introduce the multicast tree cost estimation function of M3RP first.

For simplicity, we assume the PHY in M2WNs be able to support n transmission rates $r_1, \ldots, r_n$ ($r_1 < \ldots < r_n$), and the corresponding maximal transmission distances are denoted as $d_1, \ldots, d_n$ ($d_1 > \ldots > d_n$), respectively. The topology of the MANET is modeled by an undirected graph $G = (V, E_r, W_x, W_e)$ where V is the set of nodes, E_r is the set of links with transmission rate r between neighboring nodes, $W_x : V \rightarrow \Re^+$ (where $\Re^+$ denotes the positive real number) is the node weight function, and $W_e : E_r \rightarrow \Re^+$ is the edge weight function with transmission rate r. The edges represent *logical* connectivity between nodes, i.e., there is an edge between two nodes u and v if they can hear each others local broadcast. Note that the graph G might be formed with several different topologies since different transmission rates might lead to different topologies as shown in Fig. 11. Since the nodes are mobile, the network topology graph changes with time.

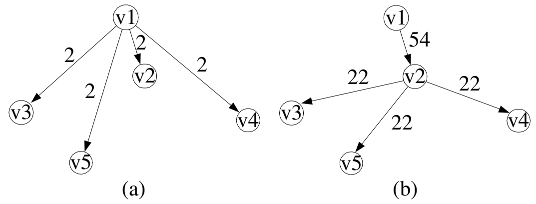

Fig. 3. An example of multicast transmission in MANETs. (a) The conventional fixed rate and minimum-hop approach. (b) The proposed M3RP.

An *instance* I of multicast routing problem consists of a set of *sources* S ($S \subseteq V$) and a set of *receivers* R ($R \subseteq V$). The set $M = S \cup R$ is referred to as *members* of the multicast group. For a given graph G and instant I, a multicast routing algorithm defines a *multicast tree*, which determines the path followed by each packet sent by a source on its way to all members. Note that a multicast tree may contain some nodes which are not multicast group members. These nodes are referred to as *forwarding nodes* and the set is denoted by F.

Assume n frames are queued in node i and the $(n+1)$th frame would spend a queuing delay

$$Q(i) = \sum_{k=1}^{n} \left(D_k(r_{ij}) + \frac{L_k}{r_{ij}}\right) \tag{1}$$

where $D_k(r_{ij})$ represents the expected contention delay of the k-th queuing frame of node i, r_{ij} is the maximal available transmission rate from node i to node j, and L_k is the frame length of the k-th frame. The queuing delay estimation function $Q(i)$ is given in [13]. Consider a multicast tree $T = (V_m, E)$ where $V_m = M \cup F$. We use V_m to distinguish nodes of multicast tree T from nodes of graph G. The multicast tree cost can be simply calculated by summing up transmission costs of F (including multicast source node). The MTC function is given as follows:

$$C(T) = \sum_{i \in F} \left(Q(i) + E_r(i,j)\right) \tag{2}$$

where $E_r(i,j) = \{L/\max r_{ij} \mid j \in V_m\}$. The term $\max r_{ij}$ represents the highest available transmission rate which can reach all of its successors.

TABLE II

SUMMARY OF ABBREVIATIONS

BID	:	Broadcast ID
GID	:	Multicast group ID
GSN	:	Multicast group sequence number
HC	:	Hop count
MSIP	:	Multicast source IP/address
MTC	:	Multicast tree cost
PTT	:	Path transmission time
RIP	:	Receiver IP/address
RREP	:	Route reply packet
RREQ	:	Route request packet
RSN	:	Receiver sequence number
SIP	:	Source IP/address

TYPE	BID	MSIP	GID	GSN	MTC

(a) ADVERT packet format

TYPE	BID	SIP	GID	GSN	PTT	HC

(b) JREQ packet format

TYPE	SIP	RIP	GID	GSN	MTC	PTT

(c) JREP packet format

TYPE	RIP	GID	GSN	MTC

(d) JACK packet format

TYPE	RIP	GID

(e) LEAVE packet format

TYPE	BID	SIP	GID	GSN	PTT	HC

(f) REPAIR packet format

TYPE	SIP	RIP	GSN	MTC	PTT

(g) MTCU packet format

Fig. 4. The frame format of multicast control messages of proposed M3RP.

III. THE MULTI-RATE/MULTI-RANGE MULTICAST ROUTING PROTOCOL (M3RP)

In this section, we describe the proposed M3RP in detail. A common idea in designing M3RP is to achieve higher network resource utilization. Table II lists the abbreviations that we will use in this paper.

A. The Initiation Process

A node should notify other nodes of the multicast messages in the network periodically if it wants to be a multicast source (MS). In the proposed M3RP, a multicast group announcement process is invoked when a node attempts to establish a multicast session. The purpose of this process is to invite other nodes, which are interested in the multicast session, to join the multicast group. Initially, an MS would flood advertisement (ADVERT) packets, which is shown in Fig. 4(a), to all nodes in the network. The GID is used to identify the multicast group and the GSN is used to determine the freshness of the multicast group. The GSN is increased by one when an ADVERT is created. The ADVERT is sent in base transmission rate (e.g., 2 Mb/s) since the lowest transmission rate achieves the longest transmission distance, and thus reaches maximum number of nodes. Every node which received the ADVERT has to forward the packet to their neighbors in order to propagate this message in networks. Fig. 5(a) illustrates the announcement process of the initiation process where node v_1 broadcasts an ADVERT for announcing the multicast session.

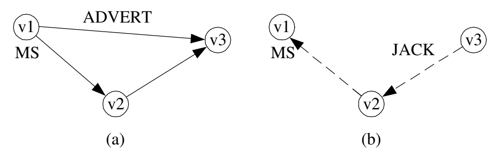

Fig. 5. The initiation process where node v_1 represents the MS and node v_3 is an intended node.

Each node has to maintain a *request table* that records the related information of announced multicast groups when receiving an ADVERT. The format of request table is shown as follows:

- GID
- MSIP
- MTC
- Expiration time of the multicast group

where the GID is treated as a multicast group entry and the expiration time is refreshed when receiving a new ADVERT. The MTC of ADVERT is set zero in the beginning stage since there is no multicast member yet. This request table will be used when a node wishes to join a multicast group later.

B. Joining a Multicast Group

An intended node might join the announced multicast group after receiving an ADVERT packet. First, the node checks the MTC of its request table whether it is zero or not. If the MTC is zero, the node could reply a join acknowledgment (JACK) packet to an MS via unicasting if it acquires a route to the MS. On the contrary, the intended node has no route to the MS and has to initiate a *route discovery process* to find a route to the desired multicast group. We will discuss this scenario later. The frame format of JACK is shown in Fig. 4(d). Each intermediate node which receives the JACK would establish a multicast group table for further information. Taking Fig. 5(b) for example, node *c* replies a JACK to MS (node v_1) for joining the multicast group. Node v_2 is the intermediate node and receives the JACK from node v_3. It will record this information and becomes a forwarding node of the multicast group for node v_3 positively. The MTC is equal to the *path transmission time* (PTT) of $v_3 \rightarrow v_2 \rightarrow v_1$. The PTT is the estimated end-to-end delay that a packet expects to spend on transmission from source to destination. The estimation function of PTT is given in [13] and the link is considered as asymmetric in two directions. Taking Fig. 5(b) for example, the PTT of path $v_1 \rightarrow v_2 \rightarrow v_3$ is different from path $v_3 \rightarrow v_2 \rightarrow v_1$ in M2WNs. Notice that an entry of records would be eliminated from the request table if the record exceeds its valid time. The valid time would be reset if the node receives a new ADVERT packet.

Otherwise the MTC is not zero and the intended node would initiate a route discovery process to find a minimum cost route to the multicast group. In route discovery process, the intended node uses the lowest transmission rate to broadcast a join request (JREQ) packet, as shown in Fig. 4(b), for finding the route to the multicast group. To support route discovery process, a routing table should be maintained in each node. The routing table of M3RP is same as AODV [10] except the additional field PTT. The route discovery process will be terminated when JREQ reaches V_m, which have a "fresh enough" membership of the multicast group. To recognize the membership of multicast group, the multicast member and forwarding node should maintain a multicast group table. The format of the multicast group table is shown as follows:

- GID
- GSN
- MSIP
- HC to multicast group source
- Direct receivers
- Forwarding data rate
- MTC
- Expiration time of the multicast group

The GSN is used to verify how freshness of the multicast tree is and is updated when nodes acquire a change of the multicast tree. The notification and update of the change of multicast tree is illustrated in Section III-E. New entries are created in this table when the node becomes a multicast member or forwarding node of the multicast group. The direct receivers field records successors of the node in multicast tree. The forwarding rate indicates the maximum data rate which is used to serve its successors and the MTC is the evaluated cost (e.g., delay time) by $C(T)$ that will be spent in transmitting a packet from source to all multicast members. The expiration time of the multicast group is updated by periodically announced ADVERT.

When a node receives a JREQ, it will check whether it satisfies the JREQ or not. If it satisfies the JREQ, it would reply a join reply (JREP) along the reverse path back to the intended node. Otherwise, it would recalculate the PTT and broadcast the JREQ to its neighbors. The route discovery process algorithm is shown in Fig. 6. This process involves two sub-processes — the reverse route establishment and forward route setup process — to assist the setup process:

1) Reverse Route Establishment: An intermediate node will record the intended node's IP as the routing table entry and the predecessor's IP as the next hop information of the reverse route when it receives a new JREQ. The reverse route may later be used to reply a JREP back to the intended node. An intermediate node may receive several duplicate JREQs from different forwarding nodes. These JREQs carry different values of PTTs. The intermediate node will choose the lowest cost path as the reverse route and drop other JREQs if their PTTs are not the lowest one. If the receiving node is the multicast member or the forwarding node, it will compare its recorded GSN with the received JREQ's GSN. If its GSN is greater than JREQ's GSN, it recalculates the PTT and then unicasts the JREP with current MTC back to the intended node. Otherwise, the node estimates the expected delay and updates the PTT value of received JREQ, and then rebroadcasts the JREQ to its neighbors. The replying node may also receive several JREQs after replying a JREP. It will reply a new JREP back to the intended node if it receives a lower PTT than previous one.

ROUTE DISCOVERY

```
Input: JREQ
Begin
  IF a duplicate JREQ THEN
    IF PTT ⩾ recorded PTT THEN
      drop this JREQ;
    ELSE
      updates this PTT and records as a reverse path;
    ENDIF
  ELSE
    IF it is a multicast member or forwarding node THEN
      IF GSN ⩽ recorded GSN THEN
        PTT ← Q(i) + MTC into JREP and reply to predecessor;
      ELSE
        PTT ← Q(i) + PTT into JREQ and rebroadcasts to neighbors;
    ELSE
      PTT ← Q(i) + PTT into JREQ and rebroadcasts to neighbors;
    ENDIF
  ENDIF
End
```

Fig. 6. The algorithm of route discovery process.

2) Forward Route Setup: When an intended node broadcasts a JREQ for joining a multicast group, it may receive more than one JREP since each forwarding node of the multicast tree will reply a JREP back to the intended node when it receives the JREQ. The replied JREP will route to the intended node along the reverse path. The intended node, after received the first JREP, will wait for a time period to collect other JREPs. Upon the time up, the intended node will choose a JREP with the least PTT and reply a JACK back to the selected node to establish the forward route. Note that only one of JREPs would be selected to prevent the routing loop. A Node will become a multicast forwarding node when it receives a JACK. After receiving the JACK, the node will record the GID as an entry in multicast table for multicast forwarding information. The MTC recorded in the JACK is the new multicast tree cost of adding the new branch of former multicast tree. This process will continue in progress until JACK reaches the destination. The GSN is increased by one to indicate the MTC is changed. Like MAODV, M3RP utilizes the GSN to ensure all multicast trees are loop-free and contain the freshest multicast tree information.

Taking Fig. 7, for example, consider a sequence of multicast join processes in the MANET. Nodes v_1, v_2, and v_3 represent the MS, forwarding node, and multicast member, respectively. Node v_5 is a new intended node and would like to join the multicast group. Initially, node v_5 does not have a route to the MS and then performs the route discovery process for finding a route to the multicast group. First, node v_5, shown in Fig. 7(a), broadcasts the JREQ to its neighbors and JREQ reaches node v_4. Node v_4, after receiving the JREQ, then broadcasts forward the JREQ to its neighbors (nodes v_2 and

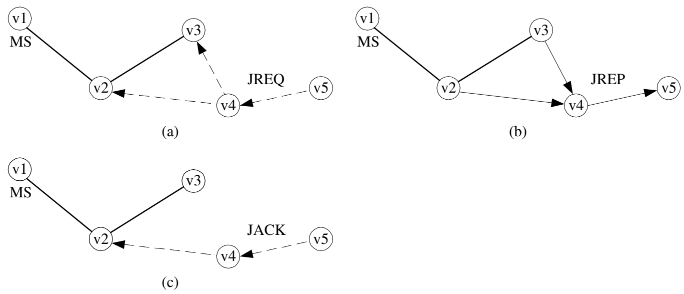

Fig. 7. The join process where node v_5 is a new intended node and the MTC is nonzero.

FORWARDING ROUTE SETUP

```
Input: JACK
Begin
    IF the destination node THEN
        adjust the maximum transmission rate to reach all successors;
    ELSE  // the intermediate node
        IF there is an entry in the multicast table for the GID THEN
            adjust the maximum transmission rate to reach all successors;
            forward the JACK to next hop;
        ELSE  // not the forwarding node yet
            adjust the maximum transmission rate to this node, record the
            GID, GSN, and MTC into multicast table;
            forward the JACK to next hop;
        ENDIF
    ENDIF
End
```

Fig. 8. The algorithm of forwarding route setup process.

v_3). Node v_2 is currently the forwarding node and node v_3 is the multicast member. These two nodes will reply a JREP back to the intended node v_5 immediately. After a time period, node v_5 would choose the minimum cost route ($v_2 \rightarrow v_4 \rightarrow v_5$) and reply a JACK via unicast to node v_2 for establishment of this route. Node v_4 automatically becomes a forwarding node after receiving the JACK shown in Fig. 7(c).

C. Leaving a Multicast Group

A multicast member can revoke its membership at any time if it does not want to be a multicast member any more. If a node wishes to leave the multicast tree, it ought to invoke a node pruning process. If the multicast member is a leaf node (no succeeding nodes follow it) of the multicast tree, it only unicasts a LEAVE message, shown in Fig. 4(e), to its predecessor on the multicast tree. The predecessor, after receiving this LEAVE message, will delete the related multicast group information from its multicast table according to the multicast member deletion algorithm shown in Fig. 9. Otherwise, the multicast member is an intermediate node of the multicast tree and then changes its role as a forwarding node.

D. Multicast Tree Maintenance

Since the topology of MANETs is changed frequently, the multicast tree should be maintained timely while there is any change of the link of multicast tree. There are three different kinds of link's change listed as follows:

Case 1: the link's data rate becomes a higher value.

MULTICAST MEMBER DELETION

```
Input: LEAVE
Begin
    IF still has successors in its downstream THEN
        delete the node ID from multicast table;
        recalculate the new maximum transmission rate;
        IF has a change of transmission rate THEN
            update the new transmission rate and sending a MTC update
            information to the multicast source;
        ELSE
            do nothing and EXIT;
        ENDIF
    ELSE  // no successors in its downstream
        IF a member of the multicast group THEN
            remove itself from the forwarding node;
        ELSE  // no more being a forwarding node
            send the LEAVE message to its predecessor;
            remove itself from the forwarding node;
        ENDIF
    ENDIF
End
```

Fig. 9. The algorithm of multicast tree pruning process.

If a multicast member moves closer to its predecessor, the forwarding data rate may be changed to a higher value than previous data rate (e.g., from 2 Mb/sec to 5.5 Mb/sec). The change of transmission rate can be noticed by periodically increasing the transmission rate of the forwarding node to test the result. If the test succeeds, the forwarding node adjusts the new forwarding data rate according to its current receiving nodes. Otherwise, the forwarding node continuously uses previous rate to forward data. We note that the number of successor nodes may be more than one. Therefore, the data rate will not be raised if there is any one successor that cannot receive the data due to the increment.

Case 2: the link's data rate becomes a lower value or link has broken.

When a new node joins the multicast tree with a lower data rate or a multicast member moves far away from the forwarding node, the link's data rate may change to a lower value than previous data rate (e.g., from 11 Mb/sec to 5.5 Mb/sec). This status can be determined by the receiver when it misses the upcoming data. There are two kinds of possible that the mobile node moves out the original transmission range and needs lower data rate to communicate, or the link is broken due to moving out the lowest data rate's transmission range. In either condition, the receiver will broadcast a repair packet (REPAIR), shown in Fig. 4(f), with the lowest transmission rate to require a route reconstruction. This process is same as join process as described in Section III-B.

Case 3: a shorter route to the multicast source.

A multicast member may receive a duplicate packet from different senders. This situation may be caused by two reasons. One is due to moving into other forwarding node's transmission range and the other is due to the change of transmission rate by the forwarding node. Fig. 10 shows a multicast member v_6 moving into a member and forwarding node v_1 and receiving the multicast data from it. The node v_6 will notice that there is a shorter route to the source via node v_1 by comparing the hop count indicated in the data packet.

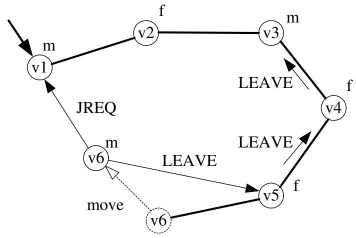

Fig. 10. The static network topology with 100 nodes.

Thus, node v_6 sends a JREQ to node v_1 following the join process and migrates to node v_1. After successfully switching to the new predecessor, node v_6 will send a LEAVE packet to its old predecessor for forwarding route pruning. As this example, after receiving the LEAVE, nodes v_5 is a forwarding node and sends a LEAVE to v_4 for forwarding route pruning. The forwarding route pruning will be processed until reaching a node which still has successors or is a multicast member.

Likewise, in the second reason that caused by forwarding node lowering its transmission rate, a node may receive duplicate multicast packet and will follow the switching process as mentioned above to join a new predecessor. These processes will optimize the multicast transmission performance and reduce the cost of the multicast tree.

E. Synchronization

The M3RP uses the MTC to estimate and select a lowest cost route to the multicast tree. Therefore, to make each multicast member have the up-to-date MTC value concurrently, all members have to synchronize the MTC timely if any topology changes. To alleviate the synchronization overhead, the MTC value is updated over the whole multicast members only when the MTC is changed due to new intended nodes joining or connected nodes leaving the multicast group or topology changes causing by mobility.

When a multicast member that generates the JREP receives the JACK from the intended node, it will send a MTC update (MTCU) message, shown in Fig. 4(g), to the multicast source for multicast tree cost updating. Each MTCU message contains the following field: <SIP, RIP, GSN, MTC, PTT>. The MTC is the current MTC value recorded in the multicast routing table of the MTCU's originator and the PTT is the new added cost from the new joining node. Once the multicast source receives the MTCU, it will compare the MTCU's GSN value with its GSN value indicated in its multicast routing table. The new MTC value plus the PTT value will be updated if the MTCU packet has a larger GSN value. After updating the new MTC value, the multicast source piggybacks the new MTC value with the multicast data packet to synchronize this value over all multicast members.

IV. Simulations and Results

A. Simulation Environment

In order to evaluate the performance of the M3RP, we also develop a detailed simulation model based on the distributed coordination function (DCF) of IEEE 802.11 WLANs [3]. In simulation runs, realistic system parameters (e.g., the direct sequence spread spectrum (DSSS) physical specification) as described in the IEEE 802.11 MAC protocol are used (parameters are listed in Table III). The RTS/CTS exchange precedes data frame transmission and data frame is followed by an ACK. The frame arrival rate of each mobile node follows the Poisson distribution with a mean λ packets per second (pps), and the frame length is an exponential distribution with a mean of m octets, which including PHY and MAC header.

TABLE III

System Parameters in Simulations

Parameter	Normal Value
Transmission rate	2, 5.5, 11 Mb/s
Transmission range (2 Mb/s)	100 m
Transmission range (5.5 Mb/s)	60 m
Transmission range (11 Mb/s)	30 m
RTS frame length	160 bits
CTS frame length	112 bits
ACK frame length	112 bits
A Slot Time	20 μs
Radio propagation delay	1 μs
SIFS	10 μs
DIFS	50 μs
PLCP preamble + PLCP header	192 μs
MAC header	34 octets
CW min	31 slots
CW max	1023 slots
Multicast Data Length	512 octets

In the simulation environment, we design three different simulation models for simulations. The first model, shown in Fig. 11, is a randomly generated network topology with 100 fixed nodes in a 400 m $\times$ 400 m square area. Each node has three transmission ranges of 30 m (11 Mb/sec), 60 m (5.5 Mb/sec), and 100 m (2 Mb/sec), respectively. During the simulation time, we perform different multicast packet generation rate of the multicast source between 25 pkt/sec and 400 pkt/sec to observe the three metrics: the packet delivery ratio, the network resource consumptions, and the average end-to-end transfer delay from the multicast source to all members. The mean data length is 512 bytes (i.e., about 103 slots time in 2 Mb/sec data rate).

The second simulation model is a randomly generated model and two numbers of nodes (50 and 100 nodes) are simulated in the square area of same size. Each simulation result is obtained by averaging the results from 10 different random seeds. The third simulation model is the mobility model and each mobile node is free to move anywhere within this square area and chooses a speed from uniform distribution between 0 and 5 m/sec. This work continues throughout all the simulation period and causing continuous changes of the network topology. There were no network partitions throughout the simulation. Each simulation run persists 60 seconds (3×10^6 slots time). We use MAODV to compare with the M3RP. Other simulation parameters are shown in Table III.

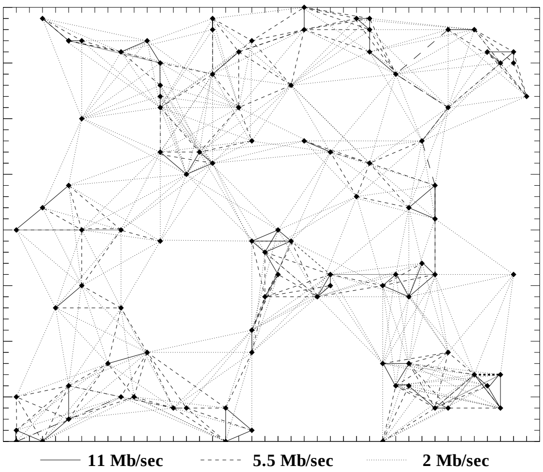

Fig. 11. The static network topology with 100 nodes.

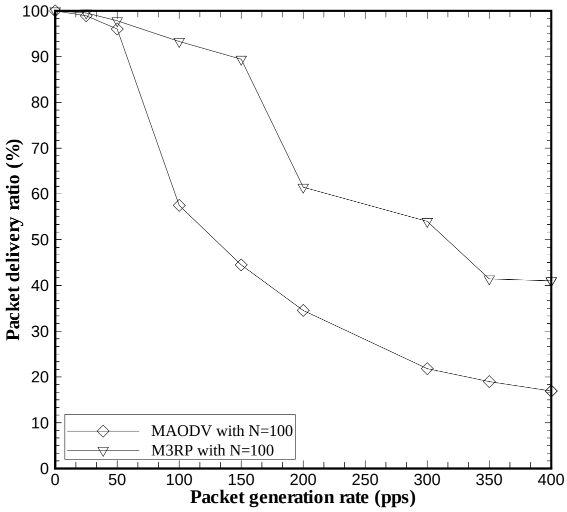

Fig. 12. The comparison of packet delivery ratio of MAODV and M3RP by varying the packet arrival rate.

B. Simulation Results

In the first experiment, we study the influence of multicast traffic load on two multicast protocols by varying the packet generating rate. We use two multicast sources and the multicast group size is set ten (excluding multicast source). The packet dropping will be caused by buffer overflow, packet collisions, and congestions. Fig. 12 shows the packet delivery ratio of the MAODV and M3RP under different packet generating rates, respectively. We can see that M3RP gets higher packet delivery ratio than MAODV under high packet generation rate. This is because that M3RP considers maximum transmission rate as well as minimum number of transmission times to transfer multicast packets. Therefore, M3RP would provide higher packet delivery ratio than minimum-hop approaches with fixed data rate under high traffic load.

Fig. 13 illustrates the network resource consumption ratio of the MAODV and M3RP. The network resource is defined

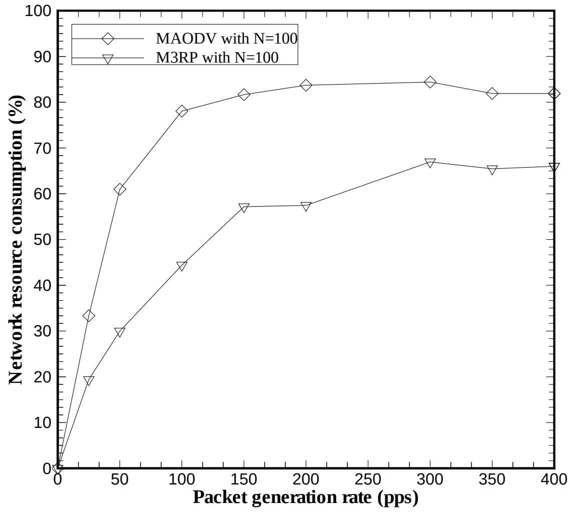

Fig. 13. The comparison of network resource consumption ratio of MAODV and M3RP by varying the packet arrival rate.

as all available time slots during the simulation. The M3RP consumes less network resource time than MAODV since M3RP uses the end-to-end transfer delay to be the metric of selecting route from source to destination. This is because that, according to the calculation of the MTC, M3RP would construct a lower cost multicast tree for multicast transmissions. Consequently, the transmission time is shorter and more resources (time slots) will be available to further use.

The average end-to-end transfer delay is shown in Fig. 14. We can see that M3RP performs lower end-to-end transfer delay than the MAODV since the M3RP considers the transfer delay as well as the consumption of network resource. M3RP not only consumes lower network resource but also minimizes the average end-to-end transfer delay. This consequence of using multiple data rates to transmit multicast packets in wireless ad hoc networks shows that M3RP is an efficient protocol for multicast transmissions.

In the following experiments, the simulation topology is generated randomly in order to evaluate the performance of proposed protocol in different topologies. Fig. 15 shows the packet delivery ratio of M3RP and MAODV in different number of nodes. We can see that M3RP gets higher performance in both 50 and 100 nodes conditions. This implies that M3RP takes advantage of shorter delivery time and thus has more sufficient time slots to deliver more packets. Moreover, it is an important key that shorter transmission time will get higher successful transmissions especially in the highly changeable networks such as MANETs.

Fig. 16 and Fig. 17 show the network resource consumption ratio and the average end-to-end delay, respectively. We can see that M3RP can use less network resource to achieve lower end-to-end multicast transmission delay and thus promotes the performance of multicast transmissions. This is a good advantage to use multi-rate to transmit multicast.

In Fig. 18, we investigate the average end-to-end transfer

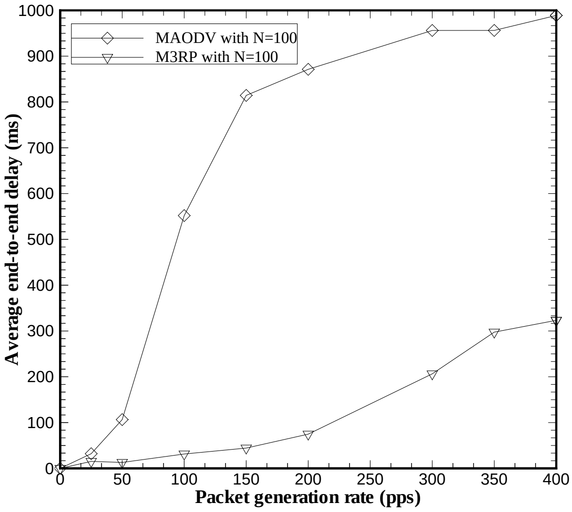

Fig. 14. The comparison of average end-to-end transfer delay of MAODV and M3RP by varying the packet arrival rate.

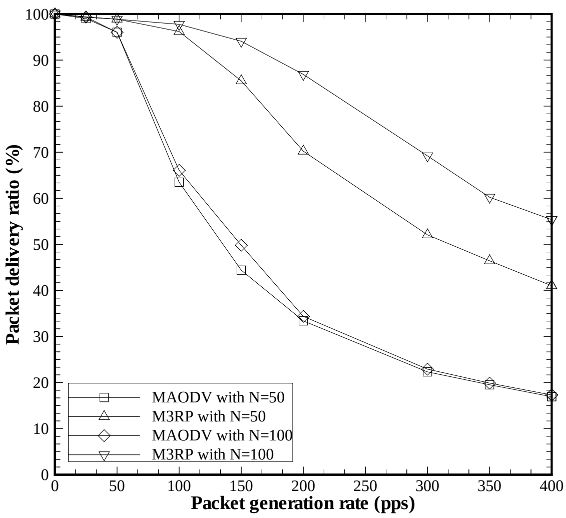

Fig. 15. The comparison of average packet delivery ratio of MAODV and M3RP by varying the packet arrival rate.

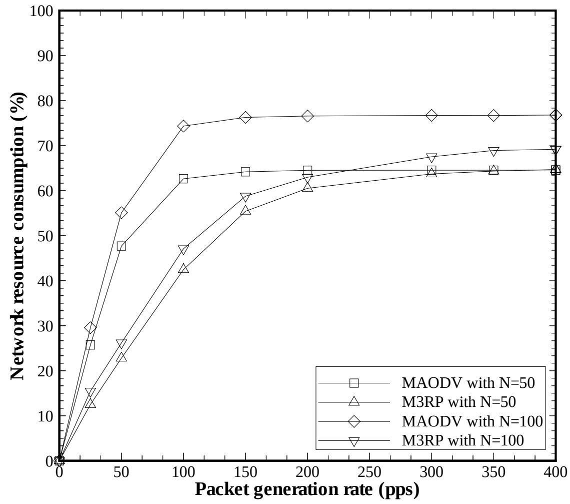

Fig. 16. The comparison of network resource consumption ratio of MAODV and M3RP by varying the packet arrival rate.

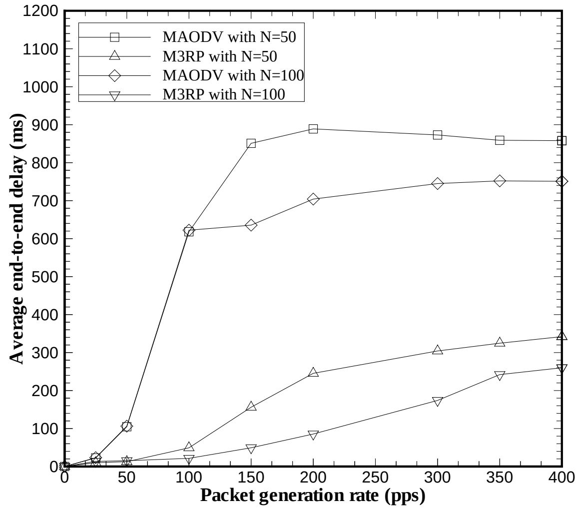

Fig. 17. The comparison of average end-to-end transfer delay of MAODV and M3RP by varying the packet arrival rate.

delay under different group sizes with a fixed packet generation rate of 100 pps. We can see that M3RP sustains lower end-to-end transfer delay in average 21 ms under different group sizes. On the contrary, the end-to-end transfer delay of MAODV increases following the increment of the multicast group size. This is because that MAODV use the hop count as the metric to find a shortest route to the multicast source and may involve other nodes to forward the packets. However, M3RP considers the minimum cost of the MTC to join the multicast tree, thus the total end-to-end transfer delay will be obviously lower than MAODV.

In the last experiment, we study the influence of mobility on the performance of M3RP and MAODV. The control packet ratio is defined as the total control packets over the delivered data packets. Fig. 19 shows that M3RP needs more control packets to maintain a low-cost multicast tree for delivery when packet generation rate is high. However, considering the packet loss ratio shown in Fig. 20, M3RP has lower packet loss ratio than MAODV in heavy network traffic since M3RP uses MTC to maintain the multicast tree and thus changes a suitable multicast tree to the new topology timely.

V. Conclusions

In this paper, we propose a multi-rate/multi-range multicast routing protocol (M3RP) for multicast routing in mobile ad hoc networks (MANETs). A tree cost function is designed for the M3RP, which leads the M3RP to construct a multicast tree with lower network resource consumption and lower end-to-end transfer delay than conventional minimum-hops approach with fixed data rate. We present a series of performance

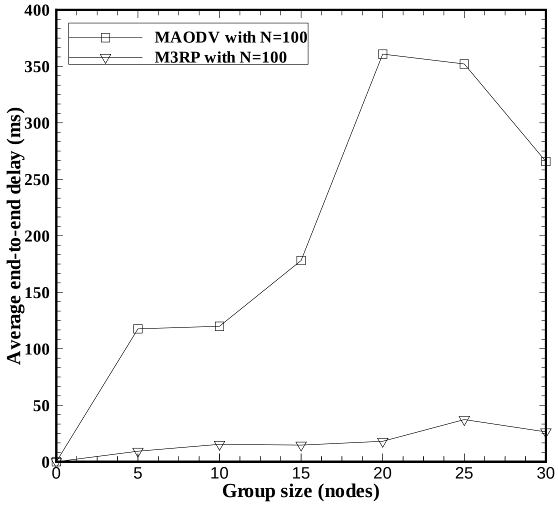

Fig. 18. The comparison of average end-to-end transfer delay of the MAODV and M3RP by varying the group size.

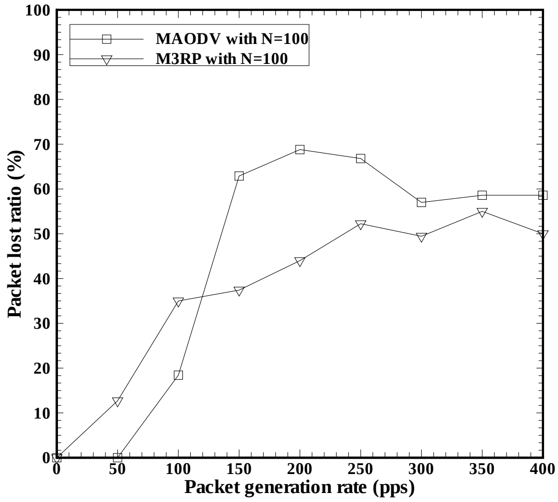

Fig. 20. The comparison of packet loss ratio of the MAODV and M3RP by varying the packet arrival rate.

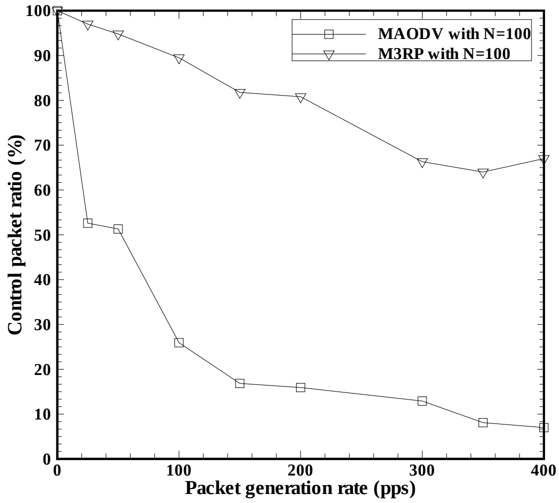

Fig. 19. The ratio of control packets of the MAODV and M3RP by varying packet arrival rate.

evaluation of M3RP and compare it to MAODV, which has been shown to perform well and is perhaps the previously best-studied on-demand multicast protocol for ad hoc networks. Simulation results show that M3RP outperforms MAODV even though it is in heavy traffic load.

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