Multicast Routing Protocol with Low Transmission Delay in Multi-rate, Multi-radio Wireless Mesh Networks

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***Abstract* - With recent advances in wireless technology, the ability to use multiple transmission rates and multiple network interface cards (radios) in wireless networks has been widely recognized. In this paper, Multi-Rate and Multi-Radio (MR2) characteristics are exploited to reduce end-to-end transmission delay for reliable multicasts. To achieve this goal, a new routing metric, MR2_ETT, is introduced. It accounts for the link transmission time by considering the usable number of radios and the transmission rate on the link. This metric is used in a routing protocol that is also proposed in this work. The routing protocol, termed Multi-rate Multi-radio On-Demand Multicast Routing Protocol (MR2_ODMRP), makes ODMRP suitable for a MR2 environment. Simulation results show that MR2_ODMRP outperforms ODMRP in multi-rate or multi-radio wireless mesh networks.**

Keywords - Multicast routing protocol, Multi-radio, Multi-rate, Routing metric, Wireless Mesh Networks

I. INTRODUCTION

Wireless Mesh Networks (WMNs) have received much attention as a promising broadband access infrastructure in both urban and rural environments. Their low equipment and deployment costs extend network connectivity and make Internet services available to a larger community.

Accordingly, end users are connected to a gateway through a multi-hop mesh consisting of stationary wireless routers. However, in such a multi-hop wireless network, there are many problems to be solved for reliable communication. One of the key challenges is bandwidth scarcity. In order to overcome this shortcoming, three themes have recently been under extensive research: Multi-Rate, Multi-Radio and Multi-Channel (MR2-MC) capabilities. In this paper, the effects of Multi-Rate and Multi-Radio (MR2) features on the transmission delay of a multicast service are analyzed. A brief introduction to MR2 capabilities is given below.

A. Multi-Rate Capability

In a multi-rate wireless network, a node can dynamically adjust its link transmission rate by switching modulation schemes. It dynamically modifies the transmission rate on a particular link, in response to the variation in the Signal-to-Noise Ratio (SNR).

B. Multi-Radio Capability

Using multiple radios on a single node can significantly increase the overall network capacity, as it allows multiple radios to be used to transmit or receive packets simultaneously via orthogonal communication channels.

However, in the current IEEE 802.11 a/b/g standards, transmission rate adjustment in the MAC layer is limited to unicast traffic only, while multicast and broadcast traffic is always transmitted at the lowest possible rate. Furthermore, multicast and broadcast are not ACKed; hence, link condition feedback information is not given for adaptive modulation and rate adjustment. However, with the increasing demand for multimedia service through multicast such as video conferencing and IPTV, the latency problem has become a more important factor in multicast services.

In this paper, assuming a MAC layer with a multi-rate multicast scheme, a new routing metric and multicast routing protocol are proposed. Many researchers [3-9] have investigated Multi-Rate and Multi-Radio (MR2) characteristics in an effort to enhance the bandwidth in different schemes. Nevertheless, the flexibility afforded by MR2 has traditionally been adopted for unicast, and little progress has been made for multicast, especially in terms of creating an appropriate routing protocol.

The proposed protocol, MR2_ODMRP, modifies ODMRP [11] and makes it suitable for MR2 wireless networks. Therefore, MR2_ODMRP provides a practical method of determining multicast routes considering MR2 features. It uses the proposed metric, MR2_ETT. The metric measures the link transmission delay in an MR2 environment. In addition, a new data rate selection scheme and a Usable Radio Reflection Time Delay (URRTD) mechanism are introduced to reflect transmission delay in the route discovery process. These two methods make ODMRP easily applicable to an MR2 environment. Finally, the protocol is very simple to implement, and can therefore operate in real time without heavy overhead.

The reminder of this paper is organized as follows. First, network model and several assumptions inherent in this work are described in section II. In section III, the new routing metric MR2_ETT is introduced. In section IV, the operations of the proposed MR2_ODMRP are explained in detail. The performance of MR2_ODMRP is shown and analyzed in section V. Finally, this paper concludes in section VI.

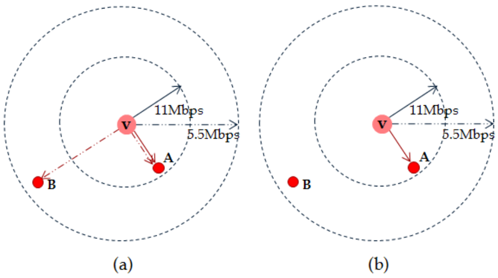


Figure 1. (a) Possibility Graph: Two links (*v*, A) and (*v*, B) are active regardless of which rate is being used. (b) Connectivity Graph: Only link (*v*, A) is active because node v chooses 11Mbps to use in communicating.

II. NETWORK MODEL AND ASSUMPTIOMN

In this section, the network model and several assumptions are explained.

1) A WMN with stationary wireless nodes and bi-directional links is considered. The nodes can communicate with each other without an infrastructure network. A link between the two nodes is defined when one node is within the transmission range of the other node. An ideal communication environment is assumed and packet loss is not considered.

2) The link in the network can clearly be active only when two nodes use the same communication channel. However, infinite orthogonal channels in the network are assumed. Accordingly, any two nodes within the transmission range can communicate with each other without co-channel interference.

3) Due to the multi-rate capability, the link set in the topology can be changed depending on the used transmission rate. Therefore, two graphs are defined: a *possibility graph* and a *connectivity graph*. While the possibility graph has all links that are active at any transmission rate, the connectivity graph contains only the links that are defined at the rate, actually chosen to communicate between the two nodes. Accordingly, the connectivity graph is a subset of the possibility graph. Fig. 1 shows the possibility and the connectivity graphs.

4) With the multi-radio feature, each node has multiple radios. Each radio at a node is assumed to use an orthogonal channel; hence, the node can use multiple radios to transmit packets simultaneously without interference. In addition, the radios that transmit packets of the same flow are assumed to be set to the same data rate.

III. ROUTING METRIC

In this section, the routing metric, termed the Multi-Rate Multi-Radio Expected Transmission Time (MR2_ETT) is introduced. To construct minimum delay multicast routes in an MR2 environment, it is necessary to design a new routing metric reflecting MR2 features in the route selection. MR2_ETT is used in the proposed routing protocol.

MR2_ETT is based on ETT [13], which is composed of information concerning the packet loss rate, *p*, and the expected transmission time of a link, which is estimated as follows.

$$ETT = \frac{1}{1-p} \times \frac{packet\ size}{data\ rate}. \tag{1}$$

In MR2_ETT, the channel condition is assumed to be ideal. Therefore, the loss rate is ignored. It is calculated by dividing the packet size by the number of radios and the transmission rate, as shown below:

$$MR2\_ETT = \frac{packet\ size}{number\ of\ radios \times data\ rate}. \tag{2}$$

It simply modifies the ETT in a manner so as to add an element of the number of radios used for packet transmissions in a link. Therefore, if a node uses multiple radios for packets, the aggregate transmission rate involves multiplication of the number of radios and the data rate at a radio.

For the end-to-end transmission delay, it is defined as the sum of the MR2_ETT values of the individual links on the path. This is the expected transmission time necessary for delivery of a packet from a source to a destination. This is represented by Equation (3).

$$ETE\_MR2\_ETT = \sum_{link \in path} (MR2\_ETT)_{link}. \tag{3}$$

It is the end-to-end MR2-ETT that is the criteria for evaluating the “goodness” of a path in the proposed protocol. The end-to-end MR2_ETT information is piggybacked on the routing control message JOIN REQUEST (JREQ) used in the route discovery process. It helps the destination node choose the best route based on the end-to-end transmission delay.

IV. PROPOSED PROTOCOL

In this section, the proposed protocol, termed Multi-Rate Multi-Radio On-Demand Multicast Routing Protocol (MR2_ODMRP), is described. First, problems of traditional routing protocols and unresolved issues in previous studies are briefly pointed out. Next, the two enhanced functions of MR2_ODMRP are explained; these make ODMRP acceptable for multi-radio multi-rate WMNs. Finally, detailed procedures of the protocol are given.

This study starts from ODMRP which is a representative multicast protocol for wireless multihop networks. However, it only considers a fixed transmission rate and also does not take into account the multi-radio capability of communication devices. In addition, in many studies [3], [5] dealing with routing in a multi-rate environment, the route discovery process and the rate adjustment process are separated. Furthermore, as the control messages used for finding routes are relayed at the lowest rate, the correct link state of the path used to deliver packets at a higher rate are not reflected. The imprecise link state information constructs unstable routes and causes frequent packet losses.

A. Modifications of ODMRP

In MR2_ODMRP, two additional schemes are involved.

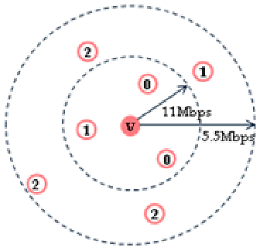


Figure 2. Max Potential Rate

These determine the transmission rate and the amount of time to be delayed at each node on the path. These two functions are aimed at designing MR2_ODMRP so as to be practical in multi-rate, multi-radio multi-hop wireless networks. As ODMRP uses a minimum-hop count approach for routing decision, some modifications are needed to consider a shorter delay multicast route in MR2 environment. In this paper, two new functions are introduced: *1) Transmission rate selection scheme* and *2) Usable Radio Reflection Time Delay mechanism.*

1) Transmission rate selection scheme

The aim of this scheme is to determine the data rate at which multicast traffics can be delivered as quickly as possible to all nodes distributed over the network. As MR2_ODMRP is a reactive routing protocol similar to ODMRP, the scheme has to be effective wherever member nodes are placed. Therefore, the method selects the best transmission rate to deliver both control message and multicast packets to all member nodes as quickly as possible. The rate is defined as *Max Potential Rate* in this paper.

The *Max Potential Rate* (*MPR*) is the data rate in which the highest amount of traffic is delivered to the two-hop neighboring nodes per unit time. To obtain MPR, this scheme probes each data rate (r) to be used by a node (v) among the rate set (R) and the number of available radios (k) of the neighboring nodes $Ne(v,r)$ within a one-hop range. In this scheme, the neighboring nodes do not include the sender that delivers the message to the node v. It then selects the rate that can be obtained from the function through Equation (4). In this function, the neighboring nodes are described as all reachable nodes at a probed data rate in a possibility graph.

$$MPR_v = \max_{r \in R}\{r \times \sum_{j \in Ne(v,r)} k_j\}. \tag{4}$$

Here, *Potential* is defined as the value of the multiplication of the probed data rate and the number of radios of all nodes within the transmission range of that rate. This scheme selects the rate that has the maximum potential value. This idea comes from the fact that the higher rate and the more usable radios have greater potential to deliver more traffic during a certain period of time.

For easy understanding, an example is given in Fig. 2 involving a node v and seven neighboring nodes. It is assumed here that the node v chooses one transmission rate, either 11Mbps or 5.5Mbps, according to the Max Potential Rate principle. The number marked on the nodes indicates the number of usable radios at the nodes. If node v uses 11Mbps, the one-hop neighboring nodes receive packets faster compared to when it uses 5.5Mbps as the transmission rate. However, in this case, only one radio can relay the packets to the two-hop neighboring nodes. Thus, the potential value is 11: 11×(0+0+1)=11. On the other hand, at the 5.5 Mbps, although the one-hop transmission rate is low, the number of radios for the relay is higher; thus potential is 44: 5.5×(0+0+1+2+2+2+1). As a result, node v should use 5.5Mbps as the message delivery rate.

Notice that the definition of the neighboring node (*Ne(v,r)*) excludes the transmitter of the message that node v receives. It aims that delivery should be made to all receivers. If there is only a transmitter within the transmission range of node v at a rate, *potential* becomes zero. Zero potential prevents the intended rate being used and node v has to search lower data rate for MPR. The idea of deleting the transmitter from the neighboring node set can reduce the possibility of failing to deliver the message to all nodes in the network.

Under actual operation using the proposed protocol, it is assumed that all nodes recognize the nodes within one-hop range by periods. Once a message reaches to a node, it calculates MPR. Thus, nodes use the rate for relaying control messages during the route discovery process, as well as for multicast packet delivery when providing actual services. As the control message for the route discovery process is transmitted at the same rate used for data transmissions, routes are constructed with reliable links and the packet delivery ratio is increased.

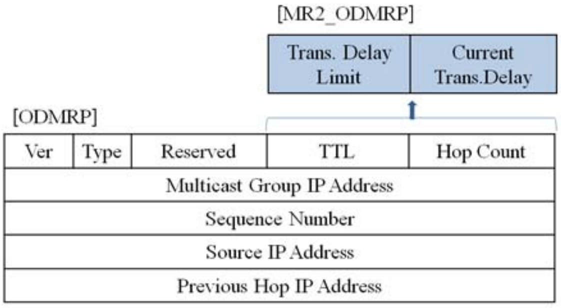
2) Usable Radio Reflection Time Delay Mechanism

Another way to reflect MR2 features in the ODMRP is through the time delay mechanism. This is called the *Usable Radio Reflection Time Delay* (URRTD) mechanism. In a multi-radio environment, multiple radios can be used to transmit packets simultaneously; hence, the number of usable radios affects the transmission delay. This therefore provides a solution to the problem associated with reflecting the number of radios at each node to the route discovery process.

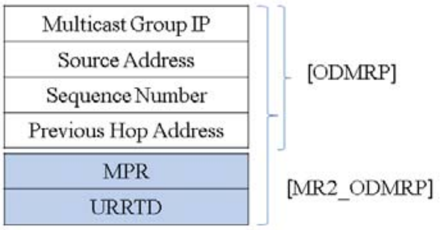
In ODMRP, the route discovery process selects the shortest path in terms of the hop count. However, in MR2_ODMRP, the destination nodes select the route that delivers the message in the least amount of time. In other words, the route with minimum transmission delay is chosen and actually used to deliver multicast traffic. As the transmission delay information is piggybacked on the control message, it is necessary to postpone the delivery of the control messages which pass through nodes with fewer usable radios. Therefore, the route in the message that is received by member nodes late is not selected. For this reason, URRTD is defined as follows;

$$URRTD_v = \frac{1}{k_v} \times \frac{s}{MPR_v} \times \alpha \quad for \quad v \in V_N, k_v \neq 0. \tag{5}$$

The URRTD accounts for the deferring time estimated from



(a) Join Request Message



(b) Message Cache

Figure 3 Message Cache and JREQ frame formats

number of radios (k_v) that are currently available for the multicast traffic at each node (v) along with the packet size (S) and the MPR (α is a scaling parameter). This value is in inverse proportion to the number of radios (k_v) available. Therefore, the more radios remain possible, the shorter time delay happens.

The URRTD mechanism is applied to only the node included in the node set (V_N) that has at least one available radio. Nodes with no available radios do not relay the control message. Accordingly, the node with only one available radio relays the message after the amount of a packet delivery time and the more available radios the node has, the shorter the deferring time of the node experiences.

B. Overview of the MR2_ODMRP

The operation of the proposed protocol is based on the ODMRP. However, there are two differences: 1) MR2_ODMRP uses a minimum transmission delay approach, 2)For the route discovery process, it uses a transmission rate selection scheme and a time delay mechanism, as explained in the previous subsection. The information about end-to-end transmission delay on the path is piggybacked on the routing control message JOIN REQUEST (JREQ). In addition, the transmission rate and the amount of usable radio information from these two functions are stored in *Message Cache* of each node.

1) Packet and Table Format

Before explaining the details of the new protocol, the changes of entries in the control messages, Message Cache and JREQ, will be introduced. The frame formats of JREQ and Message Cache are given in Fig. 3.

Fig. 3(a) describes the frame format of the JREQ of the MR2_ODMRP. It has the same length and fields as the JREQ of ODMRP. Each frame of the ODMRP has TTL and Hop Count fields consisting of a 16-bit code which indicates the maximum number of hops that this packet can traverse and the number of hops traveled so far by this packet, respectively. The difference of the JREQ in the proposed MR2_ODMRP from that of the ODMRP is that it has fields for *Trans. Delay Limit* and *Current Trans. Delay* information instead of TTL and Hop Count. Tran. Delay Limit is the delay requirement of the services and Current Trans. Delay is the transmission time spent so far

A Message Cache is maintained by each node to detect duplicates and to provide the next hop information of routes, basically. As MR2_ODMRP has two enhanced functions, the information from the functions is additionally stored in the Message Cache, as shown in Fig. 3(b). The information can be added with just several bits, and the extra storage cost is negligible.

2) Group Establishment and Route Setup

In MR2_ODMRP, as in ODMRP, group membership and multicast routes are established and updated by the source on demand. This occurs in two phases: 1) route request followed by 2) route reply.

In the route request phase, when a multicast source has packets to send, it periodically broadcasts advertising messages to the entire network. This message is called the JREQ. If a node receives the message, the node checks the MPR and URRTD on its own. Next, it rebroadcasts the message at the MPR after the URRTD, if the JREQ is not a duplicate and the *Current Trans. Delay* does not exceed the *Trans. Delay Limit*. Then, it stores the Multicast ID in the cache, and reserves the available radios for the multicast group. The node does not forward the JREQ for other multicast groups until it receives a JOIN REPLY (JREP) for which one of the entries matches its own ID, or until the Timeout Interval expires before the receipt of a JREP.

The route request process is terminated when JREQ reaches the destination node. After receiving the first JREQ packet, the destination waits an appropriate amount of time to discover some possible routes. The destination selects the route that has the minimum *Current Trans. Delay.* And then it creates a JREP which contains the next hop IP address of a multicast group.

All other procedures including setting the FG_FLAG, joining the group and leaving the group are kept the same as in the ODMRP.

V. PERFORMANCE ANALYSIS

In this section, the performance of the proposed protocol is evaluated through a comparison with ODMRP. In the simulation, IEEE 802.11b and IEEE 802.11 a/g networks are considered, of which size is 1000m $\times$1000m. An alternative rate-range relationship of a commercial IEEE 802.11a/b product [17], [18] is utilized to perform a sensitivity analysis of the proposed protocol with different rate-range relationships. The received signal strength at the receiver is solely dependent on distance between two nodes according to

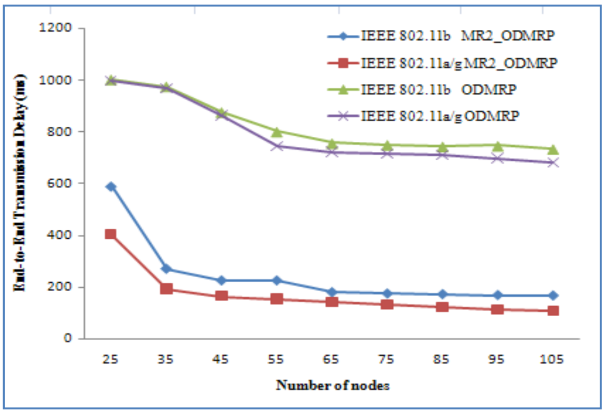


Figure 4. Transmission delay comparison between MR2_ODMRP and ODMRP

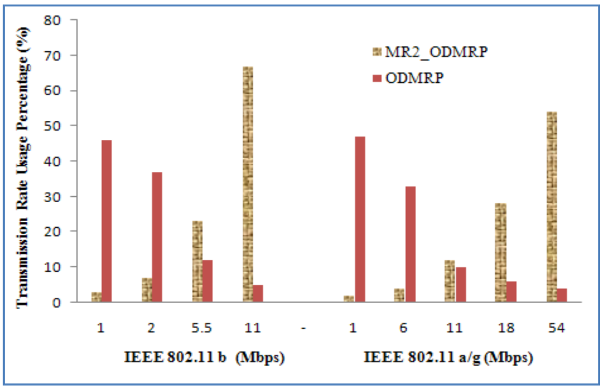


Figure 5. The transmission rate usage of MR2_ODMRP and ODMRP

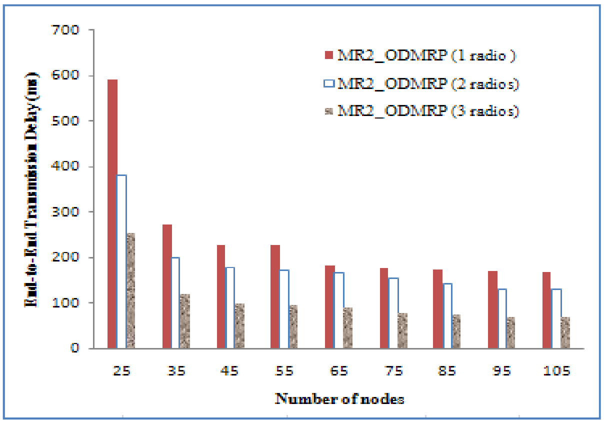


Figure 6. Transmission delay vs. number of radios

the two-ray ground propagation model. 1000-byte packets are used. Twenty different random topologies are generated for varying numbers of nodes using a uniform random distribution in the network area, which ranges from 25 to 105. The proposed protocol is then applied to each topology to compute the end-to-end transmission delay. Several critical parameters are varied, including the available number of radios, the node density, and the effective data rates, in order to analyze the sensitivity of each factor that could affect to the transmission delay.

A. MR2_ODMRP vs. ODMRP

The performance of the proposed protocol, MR2_ODMRP against the performance of ODMRP is presented in Fig. 4. The ODMRP does not take MR2 capabilities into account during its operation. Therefore, its performance would be expected to be poorer than MR2_ODMRP. As shown in Fig. 4, MR2_ODMRP shows better performance compared to ODMRP across the range of numbers of nodes in both IEEE802.11 b and IEEE 802.11a/g networks. The performance of MR2_ODMRP and ODMRP in the IEEE 802.11b environment is poor, as this band has a relatively low maximum transmission rate. However, as the number of nodes increases, the difference between IEEE 802.11b and a/g becomes small. Additional nodes in the topology indicate that a higher data rate is likely to be used due to the high node density.

B. Transmission Rate Usage

In this subsection, the transmission rates of MR2_ODMRP and ODMRP are shown. From the result shown in Fig. 4, the end-to-end transmission delay of MR2_ODMRP is shorter than that of ODMRP. The superior performance of MR2_ODMRP stems from the data rate usage, as shown in Fig. 5. The results are the averaged values of 20 topologies with nodes ranging from 35 to 75 and with 5 members in one multicast group.

C. The number of Radios

Fig. 6 shows the relationship between the transmission delay and the number of radios at each node. The delay performance improves as the number of radios increases. A greater number of radios results in greater bandwidth to the nodes, which makes packet delivery faster via the orthogonal channels allocated to each radio.

VI. CONCLUSION

This study presents a new routing protocol (MR2_ODMRP) that constructs multicasting routes in multi-rate, multi-radio wireless mesh networks. The proposed routing protocol modifies ODMRP to make it acceptable in multi-rate and multi-radio environments. Adding a rate selection scheme and a time delay mechanism to the ODMRP, the route construction process can determine the best transmission rate and the number of radios for the packet delivery. As route construction and radio allocation are implemented simultaneously during the route discovery process, the complexity of the protocol is reduced. Simulation results show that the proposed protocol offers an improvement up to a factor of three in terms of the transmission delay over the ODMRP in IEEE 802.11 a/b/g WMNs. The proposed approach provides an effective solution to the problem of long transmission delays in multicast in multi-hop wireless networks.

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