MR2_ODMRP: Improvement of End-to-End Transmission Delay in Wireless Multicast Routing

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Abstract— With recent advances in wireless technology, the importance of the capability to use multiple transmission rates and multiple radios has been widely recognized. In this paper, Multi-Rate and Multi-Radio (MR2) characteristics are exploited to improve end-to-end transmission delay for reliable multicasts. To achieve this goal, Maximum Potential Rate (MPR) based on multiple rates and Radio based Transmission Delay (RTD) with a different number of available radios are investigated in the construction of multicast routes. Multi-rate Multi-radio On-Demand Multicast Routing Protocol (MR2_ODMRP), a protocol that makes ODMRP suitable for a MR2 environment, is proposed. An Integer Linear Programming (ILP) model is proposed to obtain the optimal tree as well as the rate and radios at each node of the tree for each multicast service. The solution is employed to evaluate the performance of the MR2-ODMRP. From the simulation, it is shown that the MR2_ODMRP produces nearly optimal solutions even in environments with a large number of nodes. It outperforms the ODMRP in wireless mesh networks. The end-to-end transmission delay is improved by a factor of four compared to the ODMRP.

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1. Introduction

In the past few years, the demand for group communication technology has significantly increased. More and more people are choosing to watch football matches and TV dramas through the internet rather than on traditional TV [1]. As a technology for group communication, a multicast delivers data to a group of users by a single transmission. The use of multicast is particularly appropriate for high data rate multimedia transmission because of its ability to save network resources. Multicast conserves bandwidth and reduces packet delay and network congestion. Thus, multicast service providers started to deliver services to multiple subscribers for online TV, online games, video conference, and distance learning.

With increased demand for these applications, multicast technology becomes an even more important research topic. Typically, multicast is used to disseminate control messages to maintain network connectivity. In the current IEEE 802.11/16 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, it has no link layer acknowledgments and thus no link layer retransmission. Because of this, unlike unicast, it is almost impossible to provide reliable multicast services. Consequently, research on QoS-guaranteed multicast has become more important.

In this paper, we address a multicast routing issue in multi-hop wireless networks. Wireless Mesh Networks (WMNs) have recently received a great deal of attention as a promising wireless network providing broadband connectivity in a multi-hop manner. Capacity enhancement has been an important design consideration in multi-hop wireless networks. It is well known that wireless interference severely limits network capacity in a multi-hop setting [2,3]. One common technique to improve overall network capacity is the use of multiple radios and multiple channels. Also, for more efficient use of bandwidth, multi-rate capability has been utilized. These three methods are considered key solutions to overcome bandwidth scarcity. The work described in this paper focuses on the effects of Multi-Rate and Multi-Radio (MR2) features on the transmission delay of multicast services.

Multicasts in a wireless network should be spectrally efficient and able to cope with higher bit error rates (BER). For this reason, a transmitter should dynamically adjust the modulation and coding scheme, a technique known as Adaptive Modulation and Coding (AMC). AMC has been used to raise the overall system capacity by providing flexibility to match the modulation and coding to the average channel condition. In a system with AMC based multi-rate [4-7], users close to the transmitter are typically assigned a higher order modulation with a higher code rate. However, the modulation order and code rate decrease as the distance from the transmitter increases.

As a result of low cost radio equipment, the use of multiple radios (network interface cards) [8, 9] in communication devices has been widely accepted. This can increase the overall network capacity significantly [10]. First, it allows multiple radios to transmit and receive packets simultaneously via orthogonal communication channels. Second, the network can utilize more of the radio spectrum. With two radios, a node can transmit on two channels simultaneously. Third, radios that operate on different frequency bands have different bandwidth, range, and fading characteristics. This improves robustness, connectivity, and performance.

Exploiting the Multi-Rate and Multi-Radio (MR2) characteristic, we address a routing problem to minimize the transmission delay for multicast service. A new metric, MR2_ETT, for routing in multi-hop wireless networks is considered. The goal of this metric is to choose a high-throughput path between a source and a destination. The metric explicitly considers the number of available radios and AMC. Based on the MR2_ETT routing metric, we propose a multicast routing protocol, which modifies ODMRP (On-Demand Multicast Routing Protocol) [11] so that it will be suitable for MR2 environments. Since the rate at each node is different, the maximum potential rate (MPR) is introduced to determine the transmission rate at each node in the route. Also, rate based transmission delay (RTD) is considered to reflect the different number of radios employed at each node. The performance of the proposed MR2_ODMRP is investigated with an Integer Linear Programming (ILP) model that solves the related optimization problems.

This paper focuses on transmission delay, which is significantly affected by the number of radios and transmission rate at each node. Of course, other sources of delays such as propagation delay, queuing delay, and backoff time for the channel access influence packet delivery. However, these other sources are uncontrollable at the transmitter. Thus, in this study we focus on the transmission delay.

The remainder of the paper is organized as follows. In Section 2, we discuss related prior works. Network assumptions and a new routing metric MR2_ET are presented in Section 3. Section 4 proposes MR2_ODMRP, a new multicast routing protocol. Section 5 investigates an optimization model for multiple multicast services. The performance of the proposed routing protocol is evaluated in Section 6 and conclusions are provided in Section 7.

2. Related Work

Several routing metrics for high throughput route construction have been proposed. They include Expected Transmission Count (ETX) [12], Expected Transmission Time [13], Round Trip Time (RTT) [10], Packet Pair (PP) [14], and Weighted Cumulative Expected Transmission Time (WCETT) [13]. The ETT takes into account link quality in terms of bandwidth of the link as well as the loss rates considered in the ETX. RTT and PP are proposed to consider the delay characteristic of the links. The WCETT considers the channel reuse factor in a multiple channel environment as well as the loss rate and the link bandwidth. However, these metrics are typically designed for unicast service. Thus, modification is necessary to apply them to multicast routing. The differences between unicast and multicast are addressed in [15] and the multicast routing metrics are adapted. The authors demonstrate the performances of these modified metrics by using ODMRP (On-Demand Multicast Routing Protocol). We extend the ETT [13, 15] to Multi-Rate and Multi-Radio (MR2) environments where AMC based different rates are applied to a number of available radio interface cards.

Many researchers have investigated MR2 characteristics in an effort to increase the available bandwidth. However, the flexibility afforded by MR2 has traditionally been adopted for unicast [6, 16, 17], and little progress has been made for multicast routing. Although multicast/broadcast in Multi-Rate or Multi-Radio has been studied [4-7], the MR2 features have not been sufficiently analyzed thus far. [4-6] propose low latency routing protocols but only show the effectiveness of multi-rate capability over a WLAN environment. Also, the routing algorithm developed in [7] does not provide an optimal solution to the routing problem over a MR2 environment.

This paper focuses on an on-demand routing protocol suitable for ubiquitous networks where multimedia application traffic is instantly or sporadically generated by users. We choose the ODMRP [11], a simple and effective protocol to apply MR2 capabilities to construct routes for multicast services. In [5], a new routing protocol that exploits MR2 features for multicast is proposed. The authors of [5] note that the traditional well-known ad-hoc multicast routing protocols such as ODMRP [11] and MAODV [18] do not consider a lower delay multicast route. In this paper, we investigate low transmission delay multicast routes by exploiting MR2 characteristics.

We also consider an Integer Linear Programming (ILP) model to find optimal routes for multiple multicast groups. The ILP solution is employed to evaluate the proposed multicast routing protocol. The contributions of this paper are as follows.

1) MR2_ODMRP, a routing protocol that is suitable for MR2 wireless networks, is developed based on ODMRP. The MR2_ODMRP provides multicast routes by taking the Maximum Potential Rate (MPR) and Radio based Transmission Delay (RTD), which can be implemented in real time without heavy overhead in the construction of multicast routes.

2) An ILP model to minimize the maximum transmission delay for multiple multicast groups is provided. A multicast tree as well as the rate and radios at each node of the tree are determined for each multicast group. The proposed routing protocol is evaluated with the solution by ILP model. Even though the formulation is relatively complex, it can be easily solved by commercial software such as CPLEX.

3. Network Assumptions and Routing Metric

In this section, we first explain the network assumptions in a multi-rate and multi-radio environment.

1) A WMN with stationary wireless nodes and bi-directional links is considered. The nodes communicate with each other without an infrastructure network. A link between two nodes is defined when one node is within the transmission range of the other node and at least one common radio channel is assigned.

2) Due to the multi-rate capability, the link set in the topology can be changed depending on the transmission rate. Therefore, two graphs are defined: a *potential graph* and a *connectivity graph.* The *potential graph* has all links that are within the transmission range of each node. The *connectivity graph* contains only the links that are defined at the rate and actually selected for communication. Accordingly, the *connectivity graph* is a subset of *the potential graph.*

3) With the multi-radio feature, each node has multiple radios. Hence, a node can use

multiple radios simultaneously to transmit packets. In addition, the radios that transmit packets of the same flow are assumed to be set to the same data rate. This is because different data rates require different modulation schemes.

To construct minimum delay multicast routes in an MR2 environment, it is necessary to design a new routing metric reflecting MR2 features on the route selection method. Thus, Multi-Rate Multi-Radio Expected Transmission Time (MR2_ETT) is introduced for the proposed routing protocol and the optimization model.

The proposed MR2_ETT is based on ETT [13], which is equal to the expected amount of time it takes to successfully transmit a packet of some fixed size on a link. It is composed of information concerning the packet success delivery rate of forward and reverse links, p_f and p_r, respectively, and the link bandwidth, as delineated in Equation (1).

$$ETT = \frac{1}{p_r \times p_f} \times \frac{Packet\ Size}{Bandwidth}. \tag{1}$$

ETT stems from the Expected Transmission count (ETX) metric proposed in [12] to take into account the quality of the links. The ETX metric measures the expected number of transmissions needed to successfully send a unicast packet across a link. The derivation of ETX starts with measurement of the underlying packet loss probability in both the forward and reverse directions, denoted by 1- p_f and 1-p_r.

We should note that ETT is for unicast routing. Different aspects have to be considered to design a link quality metric for multicast. First, the link quality in multicast routing should be considered in a unidirectional manner. The loss rate of a packet in unicast is estimated link by link in a bidirectional manner. It is not appropriate for multicasts because a multicast or broadcast is not ACKed. Accordingly, there is no reverse transmission to inform whether the delivery was successful. Second, one transmission of multicast data covers all users within a transmission range. Thus, it is necessary to consider the aggregate loss rate of a packet of all neighbors. As the coverage range changes according to the transmission rate, the expected number of receivers covered with the transmission is changed. Furthermore, the simultaneous use of multiple radios at a node is not explicitly applied to estimate the expected transmission time. Therefore, in accordance with the permitted channel bandwidth, various transmission rates and number of used radios should be considered in a new routing metric to assess the transmission time.

The proposed routing metric, MR2-ETT, first considers an average forward link success delivery rate, p_{af}. This variable is the average of all the radios to all neighbors on all rates. The aggregate transmission rate is considered to take into account various data rates by different radios. With n different radios we propose the following expected transmission time:

$$MR2\_ETT = \frac{1}{p_{af}} \times \frac{Packet\ Size}{\sum_{i=1}^{n} Data\ rate_i} \tag{2}$$

To assess the average forward link success delivery rate, we assume that link conditions of one-hop neighbors are available. Consequently, the main feature of MR2_ETT is application of adaptive modulation and coding and the forward link condition. Also, this metric can be applied to an environment where each node uses a heterogeneous interface card. As for the end-to-end transmission delay, it is defined as the sum of the MR2_ETT values of links on the path, represented by Equation (3).

$$End\_to\_End\ MR2\_ETT = \sum_{link \in path} (MR2\_ETT)_{link} \tag{3}$$

4. MR2_ODMRP

This section introduces the proposed Multi-Rate Multi-Radio On-Demand Multicast

Routing Protocol (MR2_ODMRP). It starts from the ODMRP, which is a representative multicast protocol for wireless multi-hop networks. Note that the ODMRP considers only a fixed transmission rate. Furthermore, it does not take into account the multi-radio capability of communication devices.

4.1 Modifications of ODMRP

To improve the delay of multicast routing in a multi-rate, multi-radio wireless environment, the following two functions are added to the ODMRP: A) *A transmission rate selection scheme* and B) a *radio based transmission delay mechanism*.

The goal of transmission rate selection is to determine the data rate that minimizes the expected transmission delay over the network. Under a multi-rate multi-radio environment, it is necessary to consider the tradeoff between the transmission rate and range as well as the available number of radios.

The *Max Potential Rate* (*MPR*) is the maximum rate at which a message is delivered to the two-hop neighbor nodes. To obtain the *MPR*, the scheme searches for the data rate $r \in R$ that can be transmitted by a sender i with N_j available radios of neighbor nodes $j \in N(i, r)$ within one-hop range. It then selects the maximum rate, as in Equation (4). In the equation, the neighbor nodes are all reachable nodes at a probed data rate r in a *potential graph*.

$$MPR_i = \max_{r \in R}\{r \times \sum_{j \in N(i,r)} N_j\} \tag{4}$$

Note in Equation (4) that the rate is defined as the multiplication of the probed data rate and the number of radios of all nodes within the transmission range of that rate. The scheme selects the rate that has the maximum potential value. Also, note that a higher rate with more radios has greater potential to reduce the transmission delay.

For better understanding, an example is given in Fig. 1 involving node i and seven neighboring nodes. Node i needs to decide the transmission rate at either 11Mbps or 5.5Mbps to maximize the *Potential Rate*. The number marked on each node indicates the number of available radios. If node *i* transmits at 11Mbps, the one-hop neighboring nodes receive packets earlier than the rate at 5.5Mbps. However, in this case, only one radio is available to relay packets to the two-hop neighboring nodes. Thus, the potential rate is 11×(0+0+1) = 11. On the other hand, at 5.5 Mbps the number of radios for the relay is higher and the potential rate becomes 5.5×(0+0+1+2+2+2+1) = 44. As a result, the *MPR* is obtained with 5.5Mbps.

Another option for the route construction is to employ *Radio based Transmission Delay* (*RTD*). In a multi-radio environment the number of available radios affects the transmission delay. *RTD* provides a solution to multicast route construction by reflecting the number of available radios at each node on the route discovery process. In the ODMRP, the route discovery process selects the shortest path in terms of the hop count. However, in the MR2_ODMRP, a destination node selects the route that delivers the message with the least amount of time. In other words, the route with minimum transmission delay is selected to deliver multicast traffic. As the transmission delay information is piggybacked on the control message, with a limited number of radios it is necessary to postpone the delivery of control messages so that route messages received late by member nodes are not selected. For this reason, *RTD* at node *i* can be defined as follows:

$$RTD_i = \frac{1}{N_i} \times \frac{s}{MPR_i} \times \alpha \quad for \;\; i \in V \tag{5}$$

RTD represents the waiting time before each node relays a route discovery message. It is the time delay estimated from the *MPR* and the available number of radios N_i for the multicast packet of size *s*. α is a scalable parameter that reflects the delay by a co-channel link in the two hop co-channel interference range. In Equation (5) note that *RTD* is applied only to the node included in the node set *V* that has at least one available radio.

RTD helps reduce traffic load over the network caused by duplicated control messages. It can accumulate several duplicate route discovery messages (JOIN REQUEST) transmitted from neighbor nodes and relay the message with the least transmission delay.

4.2 Overview of the MR2_ODMRP

MR2_ODMRP reduces transmission delay by incorporating a rate adjustment process into the route discovery through *MPR* and *RTD*, 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). The transmission rate (*MPR*) and the delay time (*RTD*) are stored in the *Message Cache* of each node.

The format of the JREQ of the MR2_ODMRP has the same length and fields as the JREQ of the ODMRP. Each frame of the ODMRP has TTL and Hop Count fields consisting of a 16-bit code that indicates the maximum number of hops that this packet can traverse and the number of hops traveled. The difference in 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. The *Tran. Delay Limit* is the delay requirement of the services and *Current Trans. Delay* is the transmission time spent so far.

In the MR2_ODMRP, group membership and multicast routes are established and updated by the source on demand. This occurs in two phases: 1) *route request* and 2) *route reply*. Readers who are interested in the process are recommended to refer to [19].

5. Optimization Model

This section provides an ILP formulation for the multicast tree that minimizes the maximum end-to-end transmission delay.

5.1 Notations

1) The topology of an MR2 WMN is modeled as a bidirectional graph $G \in (V, E)$, where V and E are the set of nodes and wireless links, respectively. The graph $G \in (V, E)$ is from the

potential graph explained in Section III. In the graph, the link $(i, j) \in E$ is defined for all nodes j within the transmission range of node i at the lowest rate.

2) Variable r_{ij} is employed to indicate the transmission rate at link (i, j). Due to the multi-rate capability, graph G has different topologies according to the data rate at each link. Accordingly, the *connectivity graph* is represented by $G_r = (V, E_r)$, $G_r \subset G$. E_r is the link subset for the transmission rate $r \in R$. The neighbor nodes also depend on the transmission rate. Hence, the neighbor node set of node i, $N(i, r)$, is the set of nodes within the transmission range of node i at data rate r.

3) A group $k \in$ K consists of its source $k(s)$, and m members, $k(1),\ldots, k(m) \in M_k$. The message size of group k is s_k.

4) Variable n_{ij} is the number of radios employed at link (i, j) such that n_{ij} has a value in the set N.

5.2 ILP formulation

The formulation needs to provide a solution to the following questions: 1) which links should be in the tree, and 2) what transmission rate and how many radios should be used at each link for each multicast group. Thus, the decision variable $x_{ijk(m)}^{nr}$ = 1, if link (i, j) is in the path for the multicast group k for its member m with n_{ij} radios at a rate r_{ij}. Otherwise, $x_{ijk(m)}^{nr}$ = 0.

Now, to obtain end_to_end transmission delay we consider the link transmission delay l_{ijk}^{nr} as defined in Equation (6). Note that the equation is from the MR2_ETT given in Equation (2).

$$l_{ijk}^{nr} = \frac{1}{p_{ij}} \times \frac{s_k}{n_{ij} \times r_{ij}} \tag{6}$$

Equation (6) is the link transmission delay when *link (i, j)* with n_{ij} radios at a data rate r_{ij} is in the path for multicast group k. The loss rate of forward links with a common transmitter has the same value as the loss rate p_{ij}, as mentioned in Section III. This loss rate is maintained at each node and periodically updated. Based on the transmission delay of each link, the path transmission delay is calculated as in (7).

$$End\_to\_End\ Transmission\ Delay = \sum_{(i,j)\in path} l_{ijk}^{nr}. \tag{7}$$

With the definition of the end-to-end transmission delay, our objective is to minimize the maximum path transmission delay as follows.

$$\begin{gathered} Minimize\ L \\ \sum_{n_{ij}\in N}\sum_{r_{ij}\in R}\sum_{(i,j)\in E_r} l_{ijk}^{nr} x_{ijk(m)}^{nr} \le L \\ \forall k(m)\in M_k \setminus \{k(s)\}\ and\ k\in K. \end{gathered} \tag{8}$$

Constraints are related to the path construction and transmission range. Flow conservation equations are used for each path from a source to a member. Equation (9) is for the source of each multicast group and (10) is for the member nodes. The relay nodes have to satisfy (11).

$$\begin{gathered} \sum_{n_{ij}\in N}\sum_{r\in R}\sum_{j\in N(i,r)} x_{ijk(m)}^{nr} - \sum_{n_{ij}\in N}\sum_{r\in R}\sum_{j\in N(i,r)} x_{jik(m)}^{nr} = 1 \\ \forall i = k(s), k(m)\in M_k \setminus \{k(s)\}\ and\ k\in K \end{gathered} \tag{9}$$

$$\begin{gathered} \sum_{n_{ij}\in N}\sum_{r\in R}\sum_{j\in N(i,r)} x_{ijk(m)}^{nr} - \sum_{n_{ij}\in N}\sum_{r\in R}\sum_{j\in N(i,r)} x_{jik(m)}^{nr} = -1 \\ \forall i = k(m)\in M_k \setminus \{k(s)\}\ and\ k\in K \end{gathered} \tag{10}$$

$$\begin{gathered} \sum_{n_{ij}\in N}\sum_{r\in R}\sum_{j\in N(i,r)} x_{ijk(m)}^{nr} - \sum_{n_{ij}\in N}\sum_{r\in R}\sum_{j\in N(i,r)} x_{jik(m)}^{nr} = 0 \\ \forall i = V \setminus \{k(s), k(m)\}, k(m)\in M_k \setminus \{k(s)\}\ and\ k\in K \end{gathered} \tag{11}$$

For the transmission range, a binary variable y_{ijk}^{r} = 1, if link (i, j) for a multicast group k is within the transmission range with a data rate $r \in R$. Otherwise, y_{ijk}^{r} = 0. According to the wireless multicast advantage all links within the transmission range of a particular transmitter use the same data rate for a group. Thus, the constraints for the transmission range are expressed as follows.

$$\begin{gathered} y_{ijk}^{r} = y_{ij'k}^{r}, \\ \forall (i,j),(i,j') \in E_r, k \in K \ and \ r \in R \end{gathered} \tag{12}$$

$$\begin{gathered} \sum_{r \in R} y_{ijk}^{r} \le 1, \\ \forall (i,j) \in E_r \ and \ k \in K \end{gathered} \tag{13}$$

$$\begin{gathered} x_{ijk(m)}^{nr} \le y_{ijk}^{r}, \\ \forall (i,j) \in E_r, k(m) \in M_k, k \in K, n \in N \ and \ r \in R \end{gathered} \tag{14}$$

6. Performance Analysis

This section presents the performance of the proposed MR2_ODMRP. A C++ simulator is created to implement and compute the end-to-end delay of the MR2_ODMRP proposed in Section 4. Computational results of the ILP formulation solved by CPLEX are also provided to illustrate the superiority of the proposed MR2_ODMRP to the ODMRP. WMNs are implemented with IEEE 802.11 carrier sense multiple accesses with collision avoidance (CSMA/CA) medium access control (MAC). In particular, simulation results are based on IEEE 802.11b and IEEE 802.11 a/g networks. [4] is used as a reference of the transmission rate vs. the transmission range relationship for IEEE 802.11b/a. The received signal strength is assumed to be dependent on the distance between two nodes according to the two-ray ground propagation model.

To examine the transmission delay, 100-byte packets are generated. The average loss rate at each node is normally distributed with a mean of 0.5 and a variation of one. Normalized probability over a loss rate greater than or equal to zero is applied. Twenty different random topologies are generated with various numbers of nodes uniformly distributed over (25, 105) in a 1 km^2 area. Each multicast path has a maximum of five hops at the highest transmission rates. For the channel assignment, two schemes are used: one for the background traffic and another for the multicast flows. For the background traffic, the *Varying Channel Approach* (VCA) [20] is applied independently of the routing protocol. One radio is allocated to all nodes to ensure network connectivity. For the multicast flows, the channel is selected by a transmitter node. The transmitter scans a list of channels assigned to its cell. An idle channel or the best channel with the lowest interference level is selected. The transmitter associates with receivers to coordinate the selected channel through the default background channel assigned for the network connectivity.

Fig. 2 shows the tradeoff between range and rate for the end-to-end transmission delay. Higher rate transmission in a short range lowers the delay compared to lower rate transmission in a long range. In the simulation, the data rate set is divided into two subsets: one for the higher rates and another for the lower rates. In the figure, HIGH2 (HIGH3) and LOW2 (LOW3) respectively show the use of the highest two (three) transmission rates and the lowest two (three) rates in IEEE 802.11b networks (IEEE 802.11a/g). From Fig. 2, it is clear that better delay performance is obtained with higher rates. The performance of HIGH2 provides a near optimal solution as the number of nodes increases.

Fig. 3 compares the performance of the proposed MR2_ODMRP and the ODMRP. The results are from 20 topologies with nodes ranging from 35 to 75 and with five members in one multicast group. Better performance by the proposed method is illustrated with the optimal solutions obtained by the CPLEX. The gap between two methods is consistent regardless of the node density of the network.

Fig. 4 shows the results from the ILP optimization model. The transmission rates employed in the MR2_ODMRP and the ODMRP are compared. Higher performance by the MR2_ODMRP is shown in the figure. The transmission rate in the ODMRP is obtained by applying the hop count H to the objective function given in Equation (8). This result is consistent with the rate and range tradeoff explained in Fig. 2.

The effect of the number of multicast groups on the end-to-end transmission delay is shown in Fig. 5. The simulations are with two radios at each node and five members in each multicast group in IEEE 802.11b networks. The transmission delay clearly increases with an increasing number of multicast groups. This is because more links are shared with multiple groups.

7. Conclusions

A new multicast routing protocol MR2_ODMRP is developed based on the ODMRP. The proposed protocol considers multi-rate and multi-radio characteristics in wireless mesh networks. The *Maximum Potential Rate* (*MPR*) is considered to select the proper rate at each node to reduce the transmission delay. *Rate based Transmission Delay* (*RTD*) is also considered to reflect the number of radios employed in the transmission. Based on the *MPR* and *RTD*, route construction and radio allocation are implemented simultaneously during the route discovery process.

An Integer Linear Programming (ILP) model is provided to minimize the maximum transmission delay for multiple multicast groups. For each group, a multicast tree as well as rate and radios at each node of the tree are determined in the model.

The performance of the proposed MR2_ODMRP is investigated. Simulation results show that the proposed protocol improves the end-to-end transmission delay by a factor of four compared to the ODMRP. This is mainly due to the rates selected by the MR2_ODMRP. Computational results also indicate that a higher rate transmission in a short range lowers the delay compared to a lower rate transmission in a long range.

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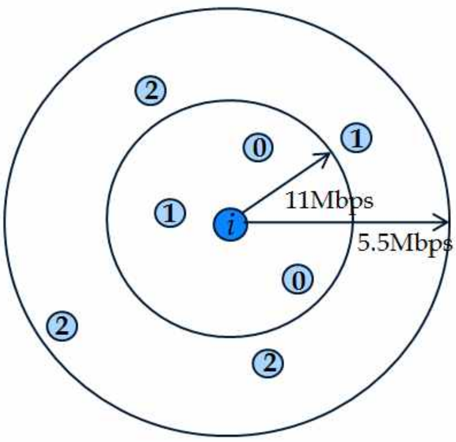

Fig. 1. Max Potential Rate

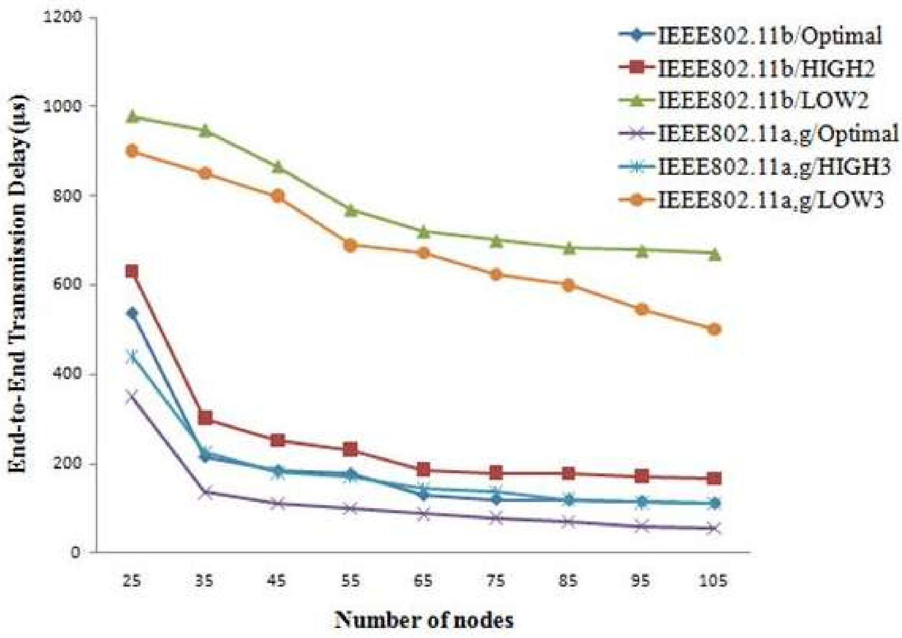

Fig. 2. Rate vs. Range.

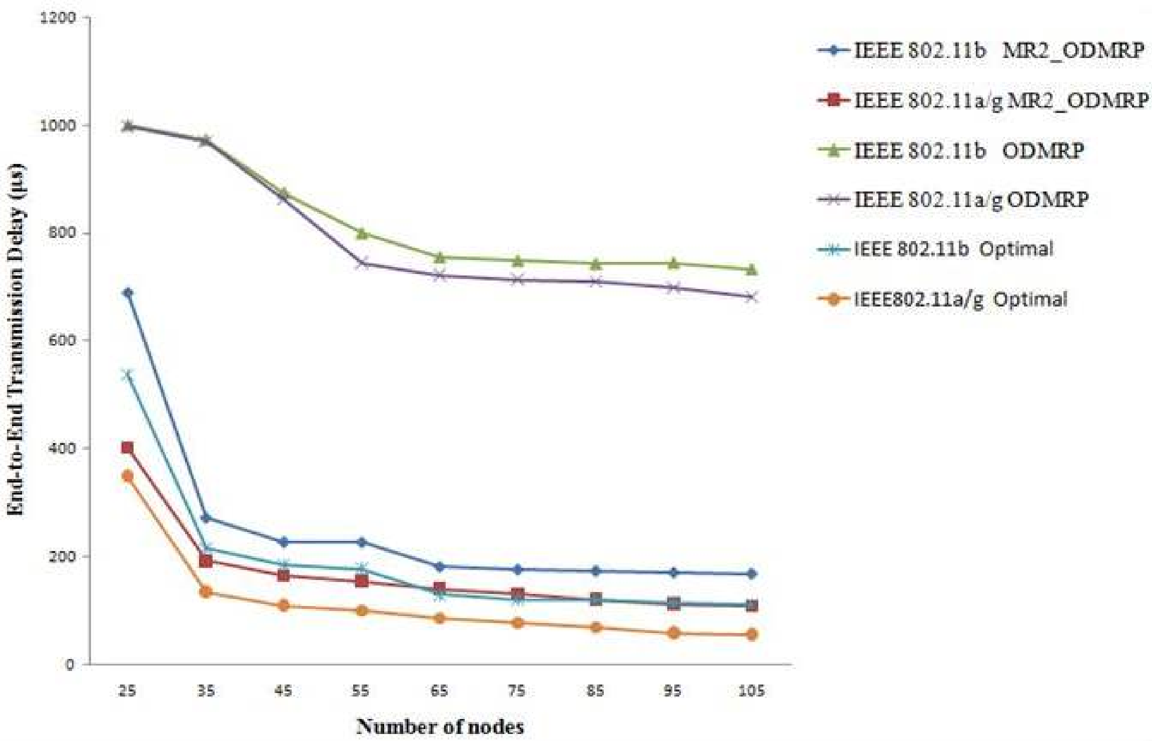

Fig. 3. Transmission delay by MR2_ODMRP and ODMRP.

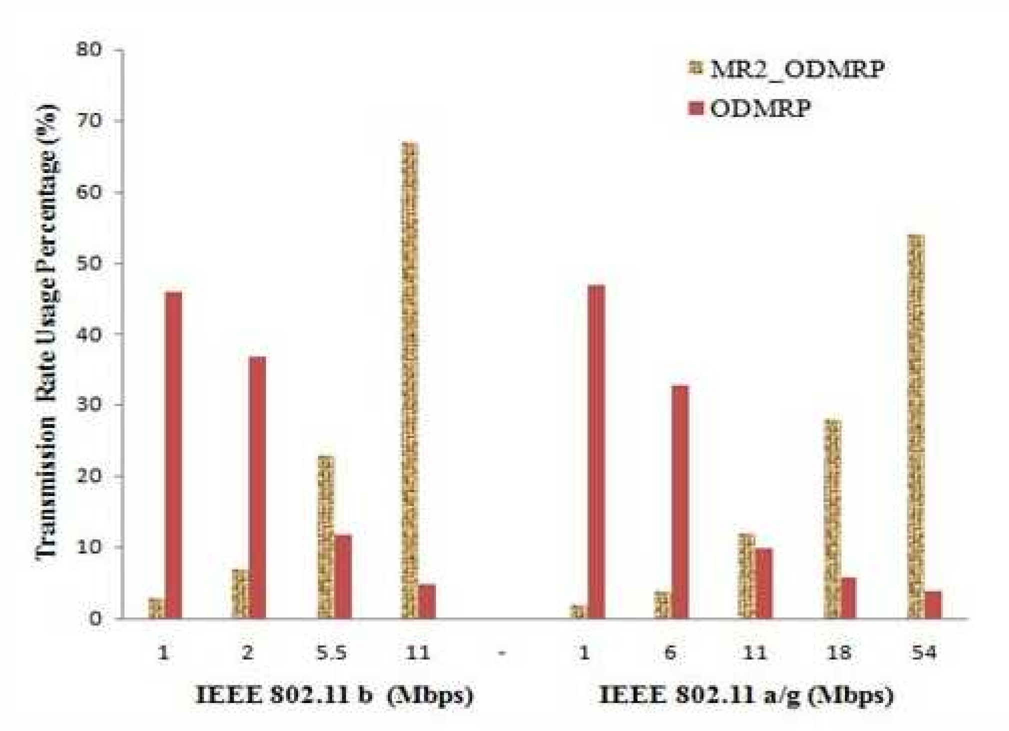

Fig. 4. Transmission rates employed by MR2_ODMRP and ODMRP.

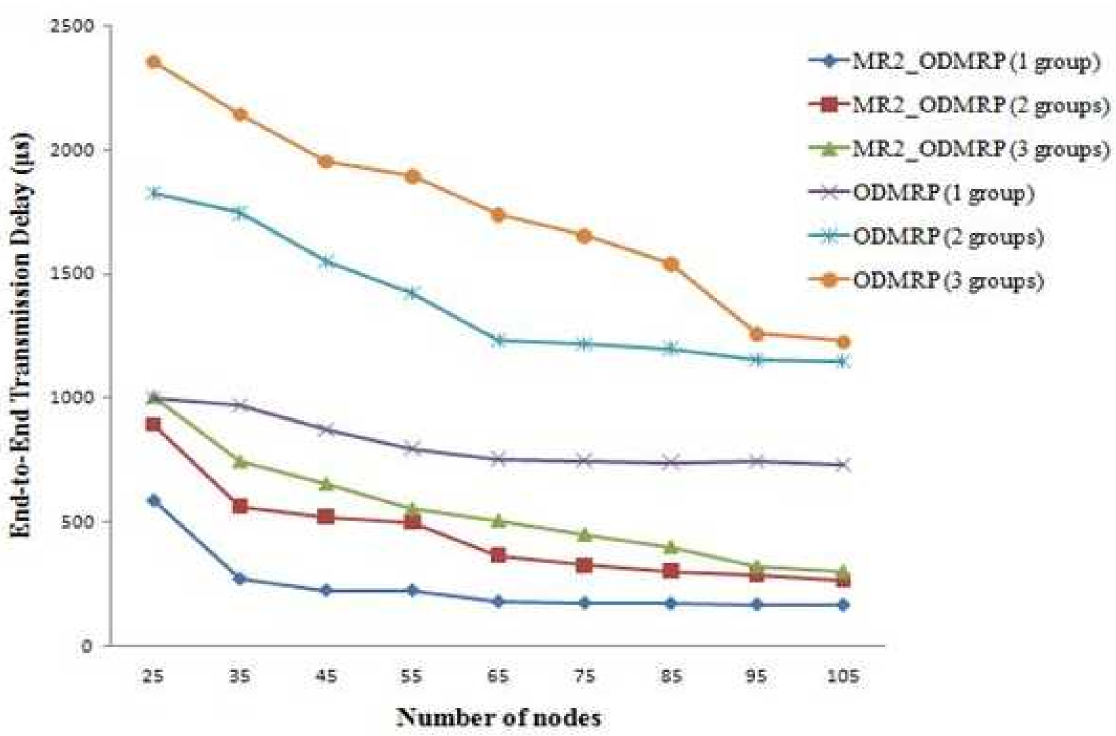

Fig. 5. Transmission delay vs. Number of multicast groups.