MR^2RP: The Multi-Rate and Multi-Range Routing Protocol for Ad Hoc Wireless Networks

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***Abstract*— This paper will discuss the issue of routing packets over an IEEE 802.11 wireless *ad hoc* network with multiple data rates (1, 2, 5.5, and 11 Mb/s). With the characteristics of modulation schemes, the data rate of wireless network is inversely proportional with the transmission distance. The conventional shortest path of minimum-hops approach will be no longer suitable for the contemporary multi-rate/multi-range wireless networks (MR^2WN). In this paper, we will propose an efficient delay-oriented multi-rate/multi-range routing protocol (MR^2RP) for MR^2WN to maximize the channel resource utilization as well as to minimize the network end-to-end transfer delay. By analyzing the medium access delay of the IEEE 802.11 medium access control (MAC) protocol, the proposed MR^2RP is capable of predicting the end-to-end transfer delay of a routing path and find the best one. The proposed MR^2RP may choose a longer path but with less contention competitors and buffer queuing delay. Simulation results show that MR^2RP performs the load balancing and fast routing very well and its call blocking probability is obviously lower than that of conventional minimum-hops approach with fixed transmission rate.**

***Index Terms*—*ad hoc*, MAC, WLAN**

I. Introduction

As wireless services become ever more ubiquitous, there is an increasing demand for the provision of the multimedia services over wireless networks. Wireless applications are becoming popular for high-speed communications over small areas, where wiring for conventional networking is difficult or not economic. A *ad hoc* wireless network is a collection of mobile hosts (MHs), which forms a temporary network without the aid of any pre-established infrastructure or centralized administration. The IEEE 802.11 standard provides detailed medium access control (MAC) and physical (PHY) layer specifications for wireless local area networks (WLANs) [5]. This standard includes a basic Distributed Coordination Function (DCF) and an optional Point Coordination Function (PCF). The DCF uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the basic channel access protocol to transmit asynchronous data in the contention period. This contention-based MAC protocol cannot guarantee transfer delay for multimedia services. By employing the PCF, the service delay bound can be guaranteed. However, the PCF is a polling-based protocol, which is not designed for the distributed environment. Furthermore, in IEEE 802.11 ad hoc WLAN, the diameter of the Basic Service Area (BSA) of an Independent Basic Service Set (IBSS) is only considered on the order of 100 feet. This implies that all MHs in the ad hoc WLAN are able to communicate to each other directly. In fact, any movable MH may easily cross the transmission boundary of BSA and the packets from/for them must be relayed via some intermediate MHs [9], [11]. The incurred problem is how to find a reliable route with delay constrain from source to destination. Unfortunately, IEEE 802.11 standard does not provide any solution for this complicated multi-hop routing problem.

In [16], authors proposed the concept that throughput could be increased by permitting MHs, which near the central of the cell, to use the high-level modulation scheme. In contract, MHs near the fringes of the cell have to use the low-level (e.g., binary) modulation to cope with the lower signal to noise ratio (SNR). The same concept has also been proposed in [1], [2], [15]. Similarly, Harris and Lucent companies have proposed high data rate modulation scheme "Complementary Code Keying" (CCK) [2], [15], which was referred from the "Complementary Code" [4], [13], [14]. To provide the interoperability for existing networks, Harris proposed a baseband processor [3] that has the ability to provide four different modulation schemes: DBPSK, DQPSK, CCK, and MBOK. Based on these schemes, four different data rates (1, 2, 5.5, and 11 Mb/s) are supported in current WLANs.

In such multi-rate WLAN, the maximal data rate may not always be adopted due to the transmission distance between MHs 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 BER in respect to a lower level modulation scheme. That is, 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. In paper [1], the longest transmission distances of data rates 11 Mb/s, 5.5 Mb/s, 2/1 Mb/s are identified as 30 m, 60 m and 100 m respectively. For simplicity, we denote such multi-rate/multi-range wireless ad hoc network as MR^2WN in this paper.

In MR^2WN, two adjacent MHs may deliver packets to each other in several transmission rates. Therefore, the shortest path of minimal hops may not be the fast route from source to destination. The way of finding the reliable route from source to destination with minimal end-to-end transfer delay in MR^2WN becomes more difficult than conventional ad hoc WLAN. In this paper, we will propose a multi-rate and multi-range routing protocol (MR^2RP) for MR^2WN to maximize channel utilization as well as to minimize the end-to-end transfer delay.

The remainder of this paper is organized as follows. Section II will briefly describe the operations of the DCF in the IEEE

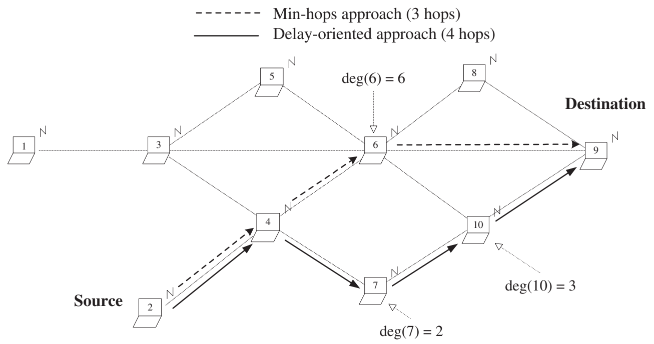


Fig. 1. An example of multi-hop routing in wireless ad hoc network.

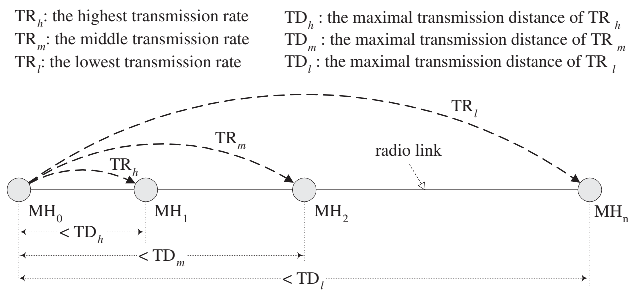


Fig. 2. Multi-rate transmissions in MR^{2}WN.

802.11 standard. In Section III, we will discuss the multi-hop routing in MR^{2}WN. The proposed MR^{2}RP is introduced in section IV and the MAC delay in IEEE 802.11 CSMA/CA protocol is also estimated in this section. Simulation models and results are shown in Section V. Finally, we present the conclusions and remarks in section VI.

II. THE IEEE 802.11 MAC PROTOCOL

When a MH desiring to transmit frames, it needs monitor the channel activity before its transmission. If the MH perceives channel is idle for a time period equal to a distributed interframe space (DIFS), it will trigger a random backoff delay before its transmission. Otherwise, the MH persists on monitoring the channel. The backoff time is measured in slot_time. For each frame transmission, the DCF defines an optionally handshaking scheme with request-to-send (RTS) and clear-to-send (CTS) control frames. To prevent the hand-shaking process from disturbing by other transmissions, the short interframe space (SIFS) is used to guarantee control frames to have a higher priority than data frames.

III. MULTI-HOP ROUTING IN WIRELESS AD HOC NETWORKS

When the network population is large, all MHs are often partitioned into clusters so that the bandwidth can be utilized efficiently. Generally, a cluster is defined as a number of MHs, which can directly transmit/receive packet to/from each other and content the bandwidth. A MH is allowed to belong to many clusters at any time. Since all members of a cluster share the channel resource, member in a larger cluster will have a higher probability of suffering a longer MAC delay.

The most important issue in an ad hoc WLAN is how a MH to communicate with another MH, which is not in its direct transmission range. The common approach is to consider the shortest-path routing. The well-known algorithm is the distributed Bellman-Ford (DBF) algorithm [8]. In DBF, every host maintains the length (cost) of the shortest path from each of its neighbor hosts to every destination. The most commonly used measurement of distance is the number of hops in the path. Even though this measure is easy to compute, it cannot reflect the influences on realistic access delay. This is because that a routing algorithm, which is based on such a distance measurement, may route packets over a few popular paths in network. This will result in serious congestion in network, especially in the wireless network with limited bandwidth capacity. Taking Fig. 1 for example, if MH_2 wants to send packets to MH_9, the shortest path of the minimum hops will be the path (MH_2, MH_4, MH_6, MH_9). Along this path, when MH6 relays packets, it needs to contend the air channel with the other six neighbors (MH_3, MH_4, MH_5, MH_8, MH_9, MH_{10}). This will spend a long time to solve the channel contention by any contention-based protocol. On the contrary, if we select the path (MH_2, MH_4, MH_7, MH_{10}, MH_9) with 4 hops, the relayed packets have a better chance to quickly reach destination. Therefore, it is desired to design a delay-oriented shortest path routing protocol for wireless ad hoc networks to perform load balancing to maximize channel utilization as well as to minimize end-to-end transfer delay.

IV. THE MULTI-RATE AND MULTI-RANGE ROUTING PROTOCOL (MR^{2}RP)

For simplicity, we assume the PHY in MR^{2}WN be able to support three transmission rates TR_h, TR_m and TR_l ($TR_h > TR_m > TR_l$), and the maximal transmission distances of them are denoted as TD_h, TD_m and TD_l ($TD_h < TD_m < TD_l$), respectively. Fig. 2 shows three possible transmissions from MH_0 in a MR^{2}WN. We note that MH_0 can transmit packets to MH_1 by any one of data rates since the transmission distance is less than TD_h. However, in the case of transmitting packets from MH_0 to MH_n, it can only use the lowest data rate TR_l. Therefore, in MR^{2}WN, a longer hopping will shorten the transmission distance in the next hop but scarifying the transmission speed. Instructively, one may choose the path of the maximal transmission rate to minimize the end-to-end transfer delay. Nevertheless, too many times of relaying a packet in MR^{2}WN is not a smart solution because of the increasing of contention delay and buffer delay. Besides, transmitting a packet several times in the network will degrade the network throughput significantly. As a result, it is a tradeoff between the channel utilization (hop count) and transmission speed in MR^{2}WN. Fig. 3 shows an example of routing packets from MH_0 to MH_5. By minimal-hops (Min-hops, for short) approach, path (MH_0, MH_3, MH_5) of two hops will be chose. However, path (MH_0, MH_6, MH_7, MH_5) of three hops may provide a faster route than the previous one.

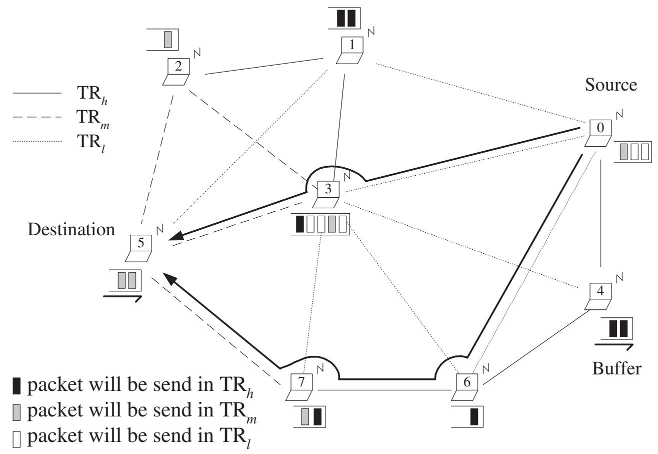


Fig. 3. Multi-rate transmissions in MR^{2}WN.

A. The MR^{2}RP Protocol

Before describing the MR^{2}RP protocol, three requirements must be satisfied: (1) The MR^{2}RP needs to collect all network information to find the best route with minimal end-to-end transfer delay. (2) The MR^{2}RP needs to predict the MAC delay of a MH in WLANs. (3) According to the estimated MAC delay and the information of the number of buffered packets of a node, the MR^{2}RP estimates the precise transmission cost for making the routing decision.

The first problem can be solved by employing the well-known *link-state* routing protocol to exchange network information between nodes. (In this paper, we ignore the overhead caused by such control messages.) The predictable MAC delay can be obtained by extending from our previous work in [12]. To derive the access delay and the available path, each MH needs to maintain a connectivity matrix (CM), which is defined as follows.

- $Connectivity\ Matrix : CM = \{cm(u,v)_{N\times N} \mid 1 \leq u,v \leq N\}$, where $cm(u,v) = k,\ k \in \{0,1,2,3\}$. Element $cm(u,v) = k$ $(k > 0)$ indicates that vertex u can transmit packets to vertex v at transmission rate TR$_x$ ($\forall$ TR$_x \leq$ TR$_k$) directly. Otherwise, vertices u and v cannot hear each other. Thus, we have

$$cm(u,v) = \begin{cases} 1, & \text{the lowest transmission rate TR}_l \\ 2, & \text{the medium transmission rate TR}_m \\ 3, & \text{the highest transmission rate TR}_h \\ 0, & \text{no connectivity} \end{cases}.$$

For illustration, we denote TR$_h$, TR$_m$ and TR$_l$ as TR$_3$, TR$_2$ and TR$_1$ respectively (where TR$_3$ >TR$_2$ >TR$_1$). Considering the example shown in Fig. 3 again, the corresponding CM matrix is shown as follows.

$$CM = \begin{pmatrix} 0 & 1 & 0 & 1 & 3 & 0 & 1 & 0 \\ 1 & 0 & 3 & 3 & 0 & 1 & 0 & 0 \\ 0 & 3 & 0 & 2 & 0 & 2 & 0 & 0 \\ 1 & 3 & 2 & 0 & 1 & 2 & 1 & 1 \\ 3 & 0 & 0 & 1 & 0 & 0 & 3 & 0 \\ 0 & 1 & 2 & 2 & 0 & 0 & 0 & 2 \\ 1 & 0 & 0 & 1 & 3 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 2 & 1 & 0 \end{pmatrix}_{N\times N}$$

According to the CM[1], every source can apply the Dijkstra algorithm to find the path of minimal hops. To do this every non-zero value and value 0 in CM matrix should be treated as value 1 and infinite positive value respectively. The routing algorithm adopted by MR^{2}RP protocol is similar to the Dijkstra algorithm excepting the cost function on edges. We modify the value of each element in the CM matrix as the desired cost value, which is the predicted access delay, to obtain the path of the minimal end-to-end transfer delay from source to destination. Recall the estimated access delay should include the MAC delay, the buffer queueing delay and transmission delay. Now we will describe how to estimate the delay cost $cm(u,v)$ of node u transmitting packet to node v.

B. The MAC Delay Estimation

Let W denote the specified contention window size. In this paper, we assume W=32 time slots and the maximum window size for retransmission is 1024 time slots. Based on the analytical results in paper [12], we further calculate the precise MAC delay, denoted as $D_r^{i,j}$, of routing a packet from MH$_i$ to MH$_j$ with transmission rate TR$_r$. We consider the handshaking between MH$_i$ and MH$_j$ may fail by collisions occurring either when MH$_i$ issues RTS or when MH$_j$ replies CTS (i.e., the hidden node situation). Let $\widehat{\lambda}$ be the total packet arrival rate of other neighbors of either MH$_i$ or MH$_j$. Thus, we have

$$\begin{aligned} D_r^{i,j} &= P_{\text{idle}}^{i,j}(\text{DIFS})(\text{DIFS} + \widetilde{b} + EA(i,j)) \\ &\quad + (1 - P_{\text{idle}}^{i,j}(\text{DIFS}))(\text{SIFS} + EB(i,j)) \\ &\quad + (\text{packet\_len}/\text{TR}_r) \end{aligned}$$

where $P_{\text{idle}}^{i,j}(t) = e^{-\widehat{\lambda}t}$,

$$\begin{aligned} \widetilde{b} = &\sum_{n=0}^{4} \left[P_{\text{idle}}^{i,j}(\text{slot})\big(1 - P_{\text{idle}}^{i,j}(\text{slot})\big)^n 2^{n-1} W \right] \\ &+ (1 - P_{\text{idle}}^{i,j}(\text{slot}))^5 2^4 W, \end{aligned}$$

$$\begin{aligned} EA(i,j) =& P_{\text{idle}}^{i,j}(\text{slot})(\text{RTS} + 2\text{SIFS} + \text{CTS}) \\ &+ \big(1 - P_{\text{idle}}^{i,j}(\text{slot})\big)\big(\text{RTS} + 2\text{SIFS} + EB(i,j)\big), \end{aligned}$$

$$\begin{aligned} EB(i,j) =& P_{\text{idle}}^{i,j}(\text{DIFS})\big(\text{DIFS} + \widetilde{b} + EA(i,j)\big) \\ &+ \big(1 - P_{\text{idle}}^{i,j}(\text{DIFS})\big)\big(\overline{B} + EB(i,j)\big), \end{aligned}$$

and $\overline{B} = \text{RTS} + 3\text{SIFS} + \text{CTS} + \text{packet\_len} + \text{ACK}$.

C. The Buffer Queuing Delay Estimation

Even though the estimation of the MAC delay can help finding the path of minimal MAC access delay, this path may not be the best one with the minimal end-to-end transfer delay. This mainly results from the buffer queuing delay occurring in intermediate host. Actually, in multi-hop routing, the buffer delay may dominate the end-to-end transfer delay of a transmission. Here, we assume the buffer information of each MH can be also collected when exchanging network information. In

[1] The matrix in this example is symmetry. We note that, in real case, the transmission condition between two MHs may not be the same in both directions.

MR^2WN, the buffer information includes the individual queue length (in packets) of each transmission rate. We also assume the packet size is fixed for simplicity. Let B_r^i denote the number of buffered packets with transmission rates TR_r in MH_i ($1 \leq r \leq 3$). If we want to route a packet from MH_i to MH_j with transmission rate TR_r, the estimated end-to-end transfer delay (denoted as $E_r^{i,j}$) will be

$$E_r^{i,j} = \sum_{k=1}^{3} (B_k^i \cdot D_k^{i,j}) + D_k^{i,j}. \quad (1)$$

TABLE I

SUMMARY OF SYSTEM PARAMETERS IN SIMULATIONS

Parameter	Value
Channel bit rate	2, 5.5, 11 Mb/s
Transmission Range (2/5.5/11 Mb/s)	30/60/100 m
RTS frame length	160 bits
CTS frame length	112 bits
ACK frame length	112 bits
Slot Time (slot)	20 μs
SIFS	10 μs
DIFS	50 μs
PHY and MAC header	400 bits
CW_{min}	31 slots
CW_{max}	1023 slots
Propagation delay (δ)	1 μs

D. The Routing Protocol

Based on the end-to-end transfer delay, we replace every non-zero element in CM by the estimated minimal delay $E_r^{i,j}$. (That is, $cm(i,j) = E_{cm(i,j)}^{i,j}, \forall\, 1 \leq i,j \leq N$.) Now, the shortest path with the minimal delay can be found by also employing the Dijkstra algorithm. (We also note that each element of zero indicates infinite delay cost in Dijkstra algorithm). Take the example shown in Fig. 3 again. With the system parameters shown in Table I and queue lengths shown in Fig. 3, the final CM (measured in ms) for our MR^2RP will become

$$CM = \begin{pmatrix} 0 & 2.89 & 0 & 2.89 & 2.81 & 0 & 2.89 & 0 \\ 2.08 & 0 & 2.05 & 2.05 & 0 & 2.08 & 0 & 0 \\ 0 & 1.36 & 0 & 1.38 & 0 & 1.38 & 0 & 0 \\ 4.55 & 4.44 & 4.48 & 0 & 4.55 & 4.48 & 4.55 & 4.55 \\ 2.05 & 0 & 0 & 2.08 & 0 & 0 & 2.05 & 0 \\ 0 & 2.11 & 2.06 & 2.06 & 0 & 0 & 0 & 2.06 \\ 1.42 & 0 & 0 & 1.42 & 1.36 & 0 & 0 & 1.36 \\ 0 & 0 & 0 & 2.07 & 0 & 2.04 & 2.02 & 0 \end{pmatrix}_{8\times 8}$$

The final CM may not be symmetric since the incurred buffer delay from MH_i to MH_j may different from MH_j to MH_i. According to the conventional shortest path of minimal hop counts, the path (MH_0, MH_3, MH_5) will take $2.89+4.48 = 7.37$ ms for every packet to reach destination. On the contrary, using the path (MH_0, MH_6, MH_7, MH_5) for route will lead a lower delay $2.89 + 1.36 + 2.04 = 6.29$ ms. It is apparent that the second path with more hops will gain 1.1 ms for every packet. Let's consider another case in this example where source is MH_0 and the destination is MH_7. The shortest path of Min-hops approach can be either the path (MH_0, MH_3, MH_7) or path (MH_0, MH_6, MH_7). We can see that these two paths have the same hop counts but they will lead to quite different delays. The path (MH_0, MH_6, MH_7) with end-to-end transfer delay 4.25 ms is much better than the path (MH_0, MH_3, MH_7) with total delay 7.44 ms by 3.19 ms. This is because MH_3 is the bottleneck for relaying packets and is often chose as the intermediate host by traditional Min-hops approach.

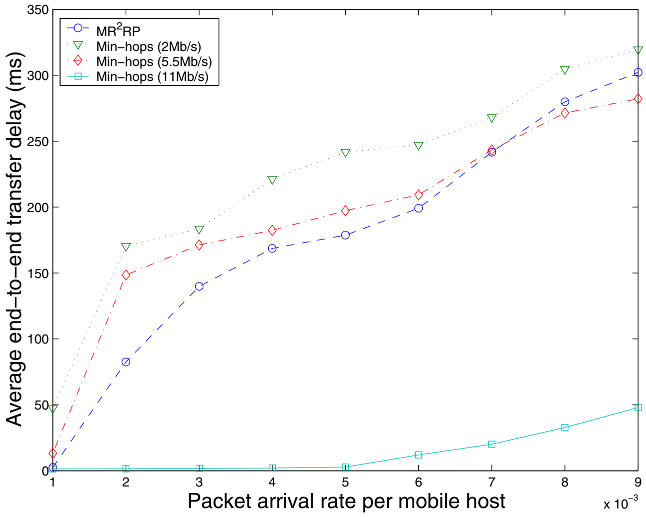
V. SIMULATION MODEL AND RESULTS

To evaluate the effectiveness of the proposed MR^2RP protocol, some simulations were done. In simulations, we considered the realistic system parameters in IEEE 802.11 MAC Protocol, which are shown in Table I.

In our simulations, we simulated a scenario of 16 mobile hosts active in a square area of 200 m x 200 m. The initial location of each mobile host is assigned randomly. Each mobile host has three possible transmission ranges of 100 m (2 Mb/s), 60 m (5.5 Mb/s) and 30 m (11 Mb/s) as shown in Fig. 2. The packet arrival rate of each mobile host follows the Poisson distribution with a mean λ, and the packet length is an exponential distribution with a mean of L slots. The packet mean length is according to the analyzed average network packets on ordinary LAN [7], which is about 50 $\sim$ 150 Bytes (i.e., about 10 $\sim$ 30 slots in 2 Mb/s transmission rate). These popular TCP/UDP packets occupy overall traffic loading over 74%. Thus, we assume $L = 20$ slots in our simulations. For evaluating the affect of the buffer queuing delay, every mobile host is assumed to equip with infinite buffer space. Each simulation run is last 200 seconds ($\approx 10^7$ slot times) and each simulation result is obtained by averaging the results from ten independent simulation runs.

In our simulations, we considered two different models. In the first simulation model (model I), hosts are static during whole simulation period. The packet arrival rate of each MH varies from 0.001 to 0.009 in a step of 0.001. In the second simulation model (model II), every host is movable and the packet arrival rate of each MH is 0.001. The moving probability is considered from 0.1 to 1.0 in a step of 0.1. Moving probability 0.1 means one movement will occur in every 10 slots in average. With this simulation model, we investigated three possible moving speeds of a mobile host: 20 m/s (car speed), 10 m/s (race speed) and 6 m/s (jog speed). For simplicity, we assume a mobile host will stay at the new position for a while before its next move. The pause time periods for moving speeds 20 m/s, 10 m/s and 6 m/s are 800 ms, 1600 ms and 2667 ms, respectively. The distance of each movement is 17 m and the moving direction is randomly selected from 8 directions.

In order to evaluate the efficiency of proposed MR^2RP protocol, we investigated four parameters: the average end-to-end transfer delay (in ms), the average MAC access delay (in ms), the call blocking probability and packet loss ratio. The average end-to-end transfer delay is defined as the average delay, which includes the MAC delay, buffer queuing delay and transmission delay, of a packet travelling from source to destination. In our simulations, we only measure the access delays of successful packets during simulation. The call blocking probability is defined as the ratio of the number of discarded request and the total arrival requests in simulation. A request/packet will be discarded only when no available path from source to destination



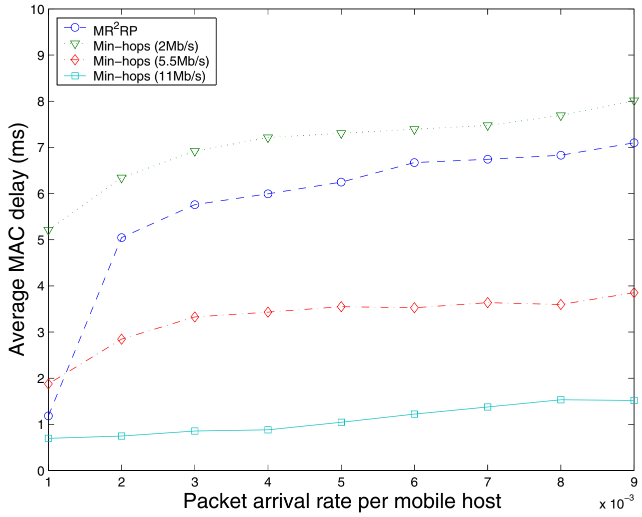


Fig. 4. Comparisons of the average end-to-end transfer delays derived by MR^{2}RP and Min-hops approach under different packet arrival rates in model I.

Fig. 5. Comparisons of the average MAC delays derived by MR^{2}RP and Min-hops approach under different packet arrival rates in model I.

can be found in network. The packet loss ratio is the percentage of total arrival packets that packets fail in reaching destination by mobility. For comparisons, the conventional shortest path of Min-hops approach is considered. For a transmission rate, the Min-hops approach will route the packets from source to destination by the fixed transmission rate.

Fig. 4 shows the average end-to-end transfer delays derived by MR^{2}RP and Min-hops approach in model I under different packet arrival rates. A higher packet arrival rate indicates a higher network load. In Fig. 4, we can see that the average end-to-end transfer delay is proportional with packet arrival rate for both MR^{2}RP and Min-hops approaches. The Min-hops (11 Mb/s) and Min-hops (2 Mb/s) approaches always derive the smallest and the largest end-to-end transfer delays respectively. This is because that all packets transmitted in Min-hops (11 Mb/s) and Min-hops (2 Mb/s) are respectively fixed at 11 Mb/s and 2 Mb/s. One can imagine that the Min-hops (11 Mb/s), which has the shortest transmission distance, will have a less chance to find the highway from source to destination in network. On the other hands, the Min-hops (2 Mb/s) will have the highest possibility to establish the path for every request. Since we only measure the access delay of successful packets in simulation, the inevitable bias with affect the simulation results. That is, a more packets have been serviced, a longer average delay will be derived in our simulation. To compensate the bias, we need to observe the cell blocking probability as shown in Fig. 6. Fig. 4 also demonstrates the proposed MR^{2}RP always derives a lower average end-to-end transfer delay than that of Min-hops (2 Mb/s). We can see that the performance of MR^{2}RP is very close to the Min-hops (5.5 Mb/s). This indicates that the MR^{2}RP has the ability to find the path of supporting data rate up to 5.5 Mb/s in average.

We also emphasize that the incurred buffer delay along the path may dominate the average end-to-end transfer delay when the network load becomes heavy. This can be seen from the average end-to-end transfer delay of MR^{2}RP is larger than that of Min-hops (5.5 Mb/s) when the packet arrival rate is larger than 0.007. This phenomena is caused by the MR^{2}RP serving more packets than Min-hops (5.5 Mb/s) approach and the simulation only measures the access delays of successful packets. Recall that MR^{2}RP always selects the best path of the minimal end-to-end transfer delay for a request at that moment. Once these routes of the minimal end-to-end transfer delay are occupied, the increasing queue length along the path will make the following routing decision to select the second best route, which may take more hops or select a lower transmission rate but with less buffer delay or less contention. However, the increasing of the number of survived packets will raise the measured end-to-end transfer delay in our simulation.

Fig. 5 illustrates the average MAC delays derived by MR^{2}RP and Min-hops approach in model I under different packet arrival rates. The average MAC delay is also proportional with the network load. We can easily see that the MR^{2}RP will obtain a lower average MAC delay than Min-hops (2 Mb/s) but higher than Min-hops (5.5 Mb/s) and Min-hops (11 Mb/s). We note that the Min-hops (2 Mb/s), whose transmission distance is the longest, has the best chance in finding a path for request. In MR^{2}RP, the worse case for serving a request is to select the path with the lowest transmission rate as Min-hops (2 Mb/s) approach does. Therefore, in the case of no packet lost, the numbers of transmitted packets in MR^{2}RP and in the Min-hops (2 Mb/s) will be the same. Since the MAC delay is relying on the number of competitors, a lower MAC delay means there are less contentions occurring on each transmission attempt. Thus, simulations demonstrate that the proposed delay-oriented MR^{2}RP can distribute packets among entire network when the network load becomes heavy. Consequently, the queue length of each MH will grow up and each transmission will suffer a longer contention resolving. However, due to fewer packets will be serviced by both Min-hops (5.5 Mb/s) and Min-hops (11 Mb/s) (this conclusion will be explained later), the contention on each transmission will be reduced accordingly. This is why the average MAC and end-to-end transfer delays of MR^{2}RP and Min-hops (2 Mb/s) are obvious higher than that of Min-hops (11 Mb/s) and Min-hops (5.5 Mb/s) with higher data rates.

Fig. 6 illustrates the call blocking probabilities derived by

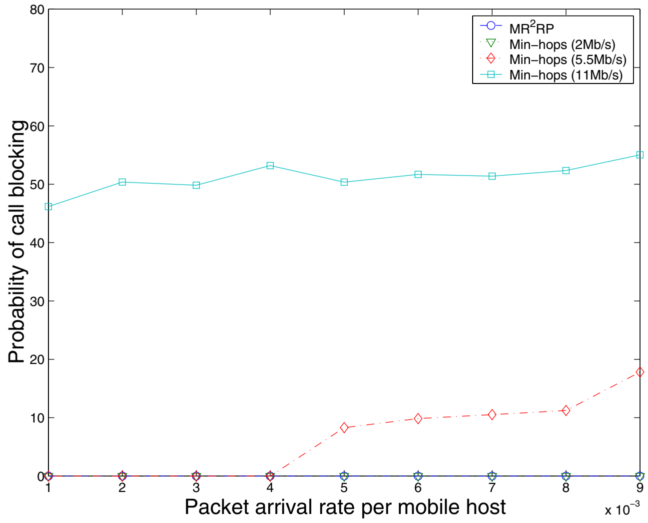


Fig. 6. Comparisons of the call blocking probabilities derived by MR^{2}RP and Min-hops approach under different packet arrival rates in model II.

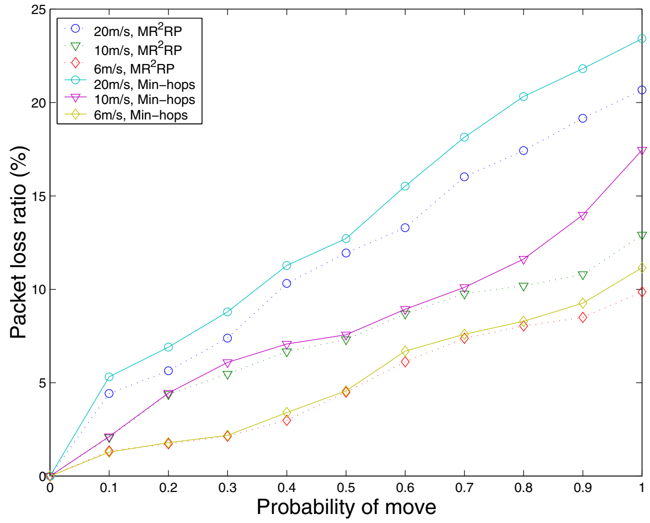


Fig. 7. Comparisons of the packet loss ratio derived by MR^{2}RP and Min-hops approach under different moving probabilities in model II.

MR^{2}RP and Min-hops approach. As mentioned before, both MR^{2}RP and Min-hops (2 Mb/s) have the same call blocking probability. In this figure, we can see that the call blocking probabilities of them are zero. The reason is the considered square area in simulation is only 200m x 200m and the 100m transmission distance can easily find the path for a pair of MHs. We also can find the call blocking probability of Min-hops (11 Mb/s) is about 50% for all kinds of network load. Also, when the packet arrival rate is larger than 0.005, approach Min-hops (5.5 Mb/s) will block about 10% packet requests. Based on these results shown in Figures 4, 5 and 6, we conclude that the total amount of packets serviced by MR^{2}RP is much more than the Min-hops approach.

Fig. 7 shows the derived packet loss ratios of proposed MR^{2}RP and Min-hops (2 Mb/s) approach under different moving probabilities and different moving speeds in model II. In this simulation, packets will be lost when the selected route cannot reach the destination any longer. Obviously, given a higher moving probability or a faster moving speed, a higher packet loss ratio will be obtained. When the MH moves in a speed of 20 m/s (about 72 km/hr), the packet loss ratio will increase sharply as the increasing of moving probability. From Fig. 7, we can see that the curves of the MR^{2}RP are still always lower than that of Min-hops (2 Mb/s). This encourages us the proposed MR^{2}RP can provide not only the fastest routing path but also the more reliable routing path for packets in MR^{2}WN.

VI. Conclusion

In this paper, we presented a new routing protocol, named as the multi-rate and multi-range routing protocol (MR^{2}RP), which can provide an efficient and scalable routing for multi-rate IEEE 802.11 wireless ad hoc networks. Referring from the predicted MAC delay, transmission delay and buffer queuing delay, the MR^{2}RP can find the fast routing path for packets. Simulation results demonstrated that the total end-to-end transfer delay from source to destination of each packet and the total amount of serviced packets can be significantly reduced and increased respectively by comparing with the conventional shortest path of minimal hops approach. Furthermore, the packet loss ratio, which is caused by mobility, can be also improved by MR^{2}RP.

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