Performance Evaluation of Topology Management in Multi-Rate Ad Hoc Networks

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Abstract— **Finite battery energy and limited bandwidth resources are two major constraints in ad hoc networks. Topology management and multi-rate adaptation mechanisms have been proposed to reduce the control overhead and to increase bandwidth utilization efficiency. However, topology management and multi-rate adaptation were handled separately in most cases so far. In this paper, we propose a novel approach that combines the multi-rate adaptation and topology management mechanisms so as to provide the highest network throughput under very low control overhead. Under topology management, a connected dominating set (CDS) of the network topology is elected and maintained for routing protocols as the backbone of the network. A MAC protocol using multi-rate transmission capability in the physical media is further applied to to provide high network throughput so that a low data-rate wireless link is substituted with a high data-rate two-hop wireless link by employing an intermediate node. The efficiency of the combined optimization algorithms is validated by network performance analysis and extensive simulations with DSR (Dynamic Source Routing) as the routing protocol. The analytical and simulation results demonstrate that our solution significantly reduces the routing control overhead, improves the network data forwarding performance.**

I. INTRODUCTION

Two major constraints in ad hoc networks are the finite battery energy and limited bandwidth resources. Therefore, most research on ad hoc networks has focused on optimization algorithms aimed at reducing control overhead and increasing the efficiency of bandwidth utilizations. For instance, topology management techniques [13] [3] try to provide the minimal network connectivity information to routing protocols so as to reduce the control overhead by cutting back the amount of topological information maintenance and the routing updates. In other occasions, automatic data transmission rate selection protocols [6] allow wireless devices to operate at high data rate when the channel conditions are sufficiently clear so as to improve the network throughput and to increase the bandwidth efficiency. To our knowledge, the topology management and multi-rate adaptation algorithms were optimized independently. In this paper, we propose a novel solution for efficient network operations in ad hoc networks by combining multi-rate adaptation algorithm with topology management to achieve high network throughput with low overhead.

Different from infrastructure networks, where base stations perform the control functionalities, there is hardly any centralized control in ad hoc networks. The topology management has been proposed as an effective way to performing some of the control functionalities, such as power management, routing control and data forwarding services [5] [11]. The main task of topology management consists of selecting a set of cluster-heads that covers every other node, and are connected with each other by means of gateways.

Different criteria and heuristics have been proposed in selecting cluster-heads and gateways. Some are proactive clustering algorithms, which require periodic broadcast of cluster-related information. SPAN [5] adaptively elects coordinators according to the remaining energy and the number of pairs of neighbors a node can connect. Topology Management by Priority Ordering (TMPO) [3] proposed to construct and maintain a network backbone based on MDS (Minimal Dominating Set) and CDS (Connected Dominating Set) using only two-hop neighbor information. Unlike SPAN and TMPO, On-Demand Cluster Formation (ODCF) [14] is a reactive, on-demand clustering algorithm. There is no periodic exchange of clustering information in the network. Instead, whenever there is data traffic, cluster-related information is piggybacked in outgoing data packets and extracted out of received packets.

Meanwhile, advances in wireless communication technologies presents another opportunity to communicate efficiently by allowing nodes to transmit data frames at different rates according to the channel conditions by changing the modulation/coding scheme. A great amount of research has focused on how to exploit this multi-rate capability in wireless ad hoc networks.

A rate adaptive MAC, called RBAR, is presented in [6] to adjust the data transmission rate based on the information obtained in the RTS/CTS exchange process. In RBAR, RTS/CTS carries the information such as frame size and the data rate, instead of the duration of the reservation. The sender proposes a data rate and stores the data rate and the frame size into the RTS frame. The proposed data rate can be based on the previous successful frame transmission. Other nodes overhearing the RTS frame calculate the duration of the requested reservation based on the frame size and the proposed data rate, and then update their own NAVs (Network Allocation Vector). When the receiver receives the RTS, it estimates the received SNR of the RTS, selects an appropriate data rate, and sends back a CTS frame with the frame size and a newly chosen data rate. Other nodes overhearing the RTS/CTS update their NAVs accordingly. After receiving the CTS, the sender transmits the data frame at the rate chosen by the receiver.

Other researchers investigated the interactions between the routing layer and MAC layer when the multi-rate feature is considered [10] [9]. However, as pointed out by [8], such schemes can have undesirable consequences for the higher network layer. In particular when combined with minimum hop routing, they can lead to performance worse than the original system because minimum hop routing always chooses the longest hop path, which provides lowest data rate along the path.

A very common solution to this problem is to design special data-rate aware routing algorithms to take advantage of the multi-rate feature. For example, Yuen *et al.* considered using route selection criteria such as interference, throughput or delay [16] in the route selection process. A new metric called Medium Time Metric is also introduced in [2], which considers how different network components affect each other in a multi-rate environment.

The rest of the paper is organized as follows. Section II presents the Priority-based Adaptive Topology Management. Then we describe Relay-based MAC protocol in Section III. Section IV describes the combination of PATM with RMAC. Performance evaluations based on theoretical analysis and extensive simulations are presented in Sections V and VI, which show significant network performance improvements by combining PATM with RMAC. Section VII summarizes the paper.

II. PRIORITY-BASED ADAPTIVE TOPOLOGY MANAGEMENT

In Priority-based Adaptive Topology Management (PATM), we assume that each mobile node in the ad hoc network has a unique identifier and an omni-directional transceiver.

In order to elect cluster heads, every node computes its own priority value, which is a function of the node's ID, the remaining energy, the current speed and time. The function is designed in such a way that it is more likely to render high priority values in high-energy and low-speed scenarios. We use the node's ID and the current time as random elements of the priority computations for load balancing purpose. Then, each node compares its priority value with its neighbors' values, and chooses the node with the highest priority value as its cluster head.

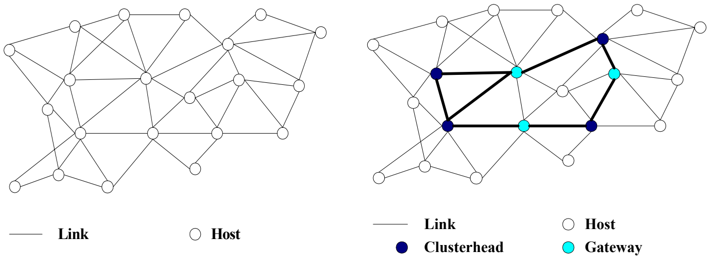
After cluster heads are elected, the doorways and gateways are added for network connectivity purposes.

1) Doorway election: If two cluster heads are separated by three hops and there are no other cluster heads between them, a node with the highest priority on the shortest paths between the two cluster heads is elected as a doorway.
2) Gateway election: If two cluster heads or one cluster head and one doorway are only two hops away, and there are no other cluster heads between them, one of the nodes between them with the highest priority becomes a gateway.

The construction of the backbone topology is completed by adding links between the elected cluster heads, doorways and gateways. As an example which is also used in all subsequent illustrations, Fig. 1 (a) shows the topology of an ad hoc network. Fig. 1 (b) demonstrates a possible result of applying topology management and forming the backbone.

For the nodes to get up-to-date topology information in a mobile environment, traditional topology management techniques, such as [3], broadcast *hello* messages periodically, which incurs a heavy traffic overhead and interference. Instead, two optimizations are made in PATM:

1) Every node adapts its update intervals according to the degree of mobility it feels during a certain time window, and the degree of mobility is measured by relative speed rather than absolute speed. We can understand that by the following example, in a scenario where a group of nodes move with the same speed in the same direction, no topology update is needed at all. Thus, if there are few neighborhood changes happening, a node can set the update intervals longer.
2) To reduce the interference more, we piggyback *hello* packets in outgoing data packets, if data packets can be found within the interval. Otherwise, the *hello* packets are sent separately.



(a) A Sample Network Topology (b) Hierarchical Clustering

Fig. 1. Topology Management

PATM improves the performance of ad hoc network topology management by using the following features:

1) While some clustering algorithms require such assumptions as node position information, distance to neighbors, synchronization among nodes [3], PATM eliminates the assumptions that require expensive devices, and depends on assumptions that are easy to acquire in ad hoc networks, such as neighbor IDs, and the remaining energy of each node.
2) In ad hoc networks, collecting accurate and up-to-date topology information incurs a heavy traffic overhead. PATM reduces the control over-head through piggybacking the control information onto the data traffic as much as possible, while sufficiently keeping nodes informed of the topology updates for topology management purposes.
3) Proactive clustering algorithms require periodic topological information exchange, while on-demand algorithms reduce the overhead at the expenses of introducing cluster setup latency. PATM adopts an adaptive trade-off between topology management accuracy and control overhead efficiency. It is proactive without explicit periodic messages, thus maintaining clusters with a very low cost.

III. RELAY-BASED MAC

Different from other approaches which modify the routing metrics to support multi-rate communication with minimum-hop routing protocols in ad hoc networks [16] [2], the relay-based MAC (RMAC) affects the MAC layer alone by replacing a long low-rate data link with a high-rate multi-hop data link using a single RTS-CTS-DATA-ACK message sequence.

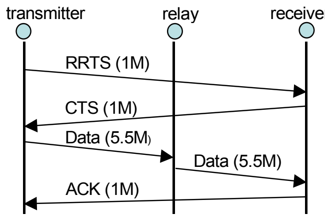


Fig. 2. Message Exchange Procedure

Fig. 2 shows a relay-assisted transmission between a pair of nodes. Because the data transmission from the transmitter to the receiver is able to occur at a high data rate, a relay is employed after the initial RTS/CTS channel reservation.

In order to determine whether a node should become a relay, the node listens to the RTS-CTS handshaking events between its neighbors. Based on the signal strength of RTS, CTS and DATA messages it overhears, the node calculates the data rate it can provide between itself and the transmitter, the receiver, respectively. If a node infers that its participation in the communication under the calculated data rate provide higher throughput than the original communicating pair, the node volunteers to be a relay by sending out an *RTR (Request To Relay)* packet to the transmitter during regular communication periods. The RTR packet contains the data rate that the node supports for transmitting packets from the transmitter to the relay, and the data rate from the relay to the receiver. A relay table is maintained at each node to keep track of the relay node's ID, data rates used by the relay node, and the corresponding neighbors supported under the data rates.

Afterward, depending on the sizes of the frames and achievable data rates, the data frame transmissions happen in one of two modes: direct transmission and relay-based transmission.

The transmission cycle for a data frame includes the time for transmitting RTS, CTS, DATA and ACK. For simplicity, we also ignore the propagation delay, SIFS, and DIFS. To determine whether a relay-based transmission is better than the direct transmission, we compute

TABLE I
THRESHOLD VALUES FOR TRANSMISSION MODE SELECTION

Relay Mode Direct Mode	1 Mbps	2 Mbps
2 Mbps + 5.5 Mbps	75 B	∞
2 Mbps + 11 Mbps	63 B	∞
5.5 Mbps + 5.5 Mbps	40 B	177 B
5.5 Mbps + 11 Mbps	35 B	106 B
11 Mbps + 11 Mbps	31 B	76 B

the transmission durations of a given frame for both direct and relay-based transmissions under different data rate. Symbols L_{data}, L_{rts}, L_{cts}, L_{ack} and L_{phyh} are used to represent the respective sizes of data, RTS, CTS, ACK frames and the physical header, and symbols R_{base}, R_{data} denote the base rate and the data transmission rate, respectively. To guarantee correct operation in the MAC protocols, the initial exchange sequence can only be set at the base rate even though the channel conditions are sufficiently good for high data rate transmission. In the IEEE 802.11 standard, the physical layer header, RTS, CTS, and ACK frames are always transmitted at the base rate. Accordingly, the transmission time in direct mode is expressed as

$$T_{direct} = \frac{L_{data}}{R_{data}} + \frac{L_{rts} + L_{cts} + L_{ack} + 4 \times L_{phyh}}{R_{base}} \ .$$

Similarly, denote R_{data1}, R_{data2} as the data rates of the first hop and the second hop, respectively in relay-mode transmissions. Then, the transmission time in the relay mode is:

$$T_{relay} = \frac{L_{data}}{R_{data1}} + \frac{L_{data}}{R_{data2}} + \frac{L_{rts} + L_{cts} + L_{ack} + 5 \times L_{phyh}}{R_{base}} \ .$$

If $T_{relay} > T_{direct}$, then relay-mode transmission is chosen in RMAC.

To illustrate the effects, we compute the transmission time differences under different data rates provided by IEEE 802.11b as shown in Table I. Table I shows the lower threshold when relay-based transmission under high data rates is preferred over a direct transmission under low data rate.

IV. COMBINATION OF PATM AND RMAC

Traditionally, a network architecture based on IEEE 802.11 [1] is organized as shown in Fig. 3 (a). The physical layer and the MAC layer provides the control information such as signal-to-noise ratio (SNR) and topology information to the network layer, and the network layer makes routing decisions based on the information provided by the lower layers. The upward arrows represent control information flows, and the downward arrows denote routing decisions for data forwarding.

Our architecture for topology management and multi-rate transmission is implemented as shown in Fig. 3 (b). The topology management based on PATM is inserted between the routing control layer and the MAC layer to provide a succinct presentation of the network topology to the network layer, and to reduce the control overhead in routing updates [3]. RMAC replaces IEEE 802.11 DCF to optimize the routing decisions made by the network layer to increase the network throughput. RMAC is seamlessly combined with PATM.

Multi-rate adaption is indispensable from topology management. The main purpose of topology management is to reduce the routing complexity and energy consumption, while keeping the network connectivity at the same time. However, using topology management, the capacity and throughput of the network usually degrade slightly because of longer communication paths and longer data links. Using multi-rate aware MAC protocols, such as RMAC, the communication between the cluster heads can still be achieved at the high data rate.

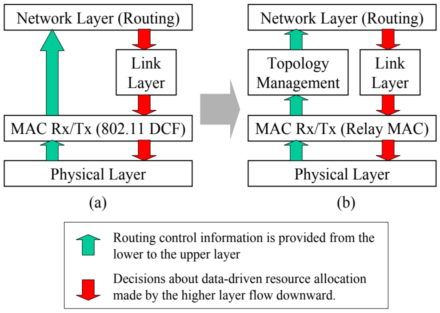
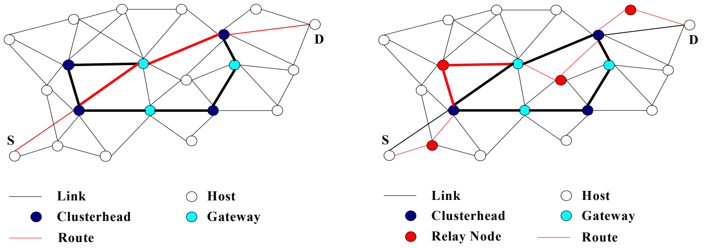


Fig. 3. Architectural Changes for Topology Management and RMAC



(a) A Routing Example (b) Route Optimization by RMAC

Fig. 4. Combination of PATM and RMAC

Fig. 4 gives an example of how topology management and routing protocols work together in a multi-rate ad hoc network. Fig. 4 (a) shows the result of topology management and routing protocol at the lowest data rate. Fig. 4 (b) shows the actual path the frames take from the source to the destination after applying RMAC to the data transmission process, where additional relay nodes are added to achieve high data transmission rates.

V. PERFORMANCE ANALYSIS

In this section, we analyze the performance of topology management theoretically. Section V-A demonstrates how PATM improves the probability of successful frame transmission, and Section V-B shows that PATM can reduce routing overhead effectively.

A. Transmission Probabilities

1) Probabilities of Node States: In PATM, the role of a node can be either one of the four: cluster head, gateway, doorway, and host. The probabilities of a node becoming a cluster head, a gateway, a doorway and a host are denoted by p_{ch}, p_g, p_d and p_h, respectively. Thus

$$p_{ch} + p_g + p_d + p_h = 1 \ .$$

Bao *et al.* computed p_{ch} and derived the expected size of the MDS in an area with N nodes in the uniform distribution [3]:

$$|MDS_N| = N \cdot p_{ch} \ . \qquad (1)$$

Similarly, the expected size of the CDS is:

$$|CDS_N| = N \cdot (p_{ch} + p_g + p_d) = N \cdot (1 - p_h) \ . \qquad (2)$$

Although p_{ch} was easily derived assuming the Poisson distribution for the number of nodes located in unit area, the theoretical computations of p_g, p_d, and p_h are very complicated because of the relative geographic location estimation between two-hop neighbors. Instead, we use extensive simulations to estimate the probabilities.

Assuming a uniform distribution of nodes on an infinite plane, the various probabilities of nodes in cluster head, gateway, doorway and host states is directly related with the average number of one-hop neighbors, which is the node distribution density times the area covered under the transmission range. To find out the relationship between the average number of one-hop neighbors and p_h, we did a set of simulations by randomly placing 500 nodes in a 4000×4000 square feet area, and varying the antenna transmission range from 100 feet to 1100 feet. In each simulation scenario, the numbers of nodes in various states are periodically collected, and the average number of one-hop neighbors and the average number of hosts are printed out after long period of time. Fig. 5 shows the relationship between the average number of one-hop neighbors of each node and the probability of nodes in the host state, p_h.

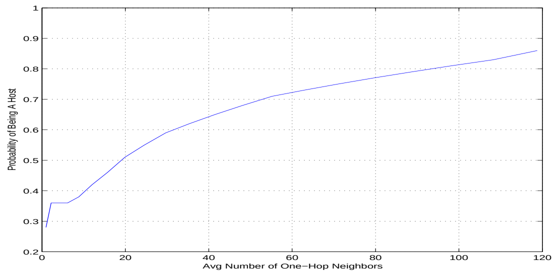


Fig. 5. Probability of Being a Host

2) Collision Probabilities: In order to compute the successful transmission probabilities under flat topology scenarios and topology-managed scenarios, we follow the analytical methods used in [4]. [4] assumed ideal channel conditions without hidden terminals, and a fixed number n of contending stations to each node, which always has backlogged packets for transmission. Our computations are based on some conclusions of [4].

In CSMA/CA channel access scheme, suppose that the minimum contention window size is $W = CW_{min}$, and the maximum contention window size is $2^m W = CW_{max}$, where m is a predefined parameter of the CSMA/CA protocol. In addition, denote p as the constant and independent probability that a transmitted packet encounters collision, regardless of the number of retransmissions that the packet has already suffered. Then the probability τ that a station transmits in a randomly chosen slot time is expressed as:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \ . \tag{3}$$

Because hidden terminal problems are not considered, under flat topology organizations, the aforementioned collision probability p of a node is equal to the probability that at least one of the node's one-hop neighbors transmits [4], which is:

$$p = 1 - (1-\tau)^{n-1} \tag{4}$$

where n is the average number of one-hop neighbors because all nodes are in active states under the flat topology organizations.

Under the network topology management by PATM, the number of contending nodes dramatically decreases because more nodes are in dormant host state. Therefore, the average number of contending nodes, denoted by n', becomes $n' = n(1-p_h)$, and the collision probability p' of a node is:

$$p' = 1 - (1-\tau')^{n'-1} = 1 - (1-\tau')^{n(1-p_h)-1} \tag{5}$$

where τ' is derived by replacing the p with p' in Eq. 3.

As an example for comparison purposes, when the average number of one-hop neighbors is $n = 40$, $n' = n(1-p_h) = 40(1-0.65) = 14$. Accordingly, Eq. 3 and Eq. 4 have a unique solution: $\tau = 0.018$, and $p = 0.50$. Similarly, Eq. 3 and Eq. 5 have a unique solution: $\tau' = 0.032$, and $p' = 0.34$. As we can see, with topology management, the collision probability decreases by $p - p' = 0.50 - 0.34 = 16\%$, which demonstrates that topology management can reduce collision probability.

3) Successful Transmission Probabilities: We compute transmission probabilities under flat topology organization and under topology management. Denote P_{tr} as the probability that there is at least one transmission in a considered slot time under flat topology, and denote P'_{tr} as the probability under topology management. Then,

$$P_{tr} = 1 - (1-\tau)^n \tag{6}$$

$$P'_{tr} = 1 - (1-\tau')^{n'} \ . \tag{7}$$

Furthermore, denote P_s as the probability that a transmission over the channel is successful under flat topology organization, and denote P'_s as the probability under topology management:

$$P_s = \frac{n\tau(1-\tau)^n}{P_{tr}} = \frac{n\tau(1-\tau)^n}{1-(1-\tau)^n} \tag{8}$$

$$P'_s = \frac{n'\tau'(1-\tau')^{n'}}{P'_{tr}} = \frac{n'\tau'(1-\tau')^{n'}}{1-(1-\tau')^{n'}} \ . \tag{9}$$

As an example, taking the same parameters as in Section V-A.2 into Eq. 8 and Eq. 9, we have $P_s = 0.69$, and $P'_s = 0.80$, which demonstrates that topology management can increase delivery ratio effectively.

B. Routing Overhead

In our simulations, we apply PATM to the Dynamic Source Routing (DSR) protocol [7]. DSR consists of two mechanisms that work together to allow the discovery and maintenance of source routes in ad hoc networks: Route Discovery and Route Maintenance. Route Discovery includes two phases: Route Request and Route Reply. The major control overhead of DSR is caused by Route Request (RREQ) packets which are flooded in the network in search of paths to the destinations. Therefore, we modify the Route Request phase such that every node rebroadcasts an RREQ packet if the node is not a host. As a result, ordinary hosts are excluded from intermediate nodes for a routing path.

In the rest part of this section, we'll compute the numbers of Route Request (RREQ) packets, Route Reply (RREP) packets, and Route Error (RERR) packets for DSR and DSR-PATM, respectively.

1) Assumptions: Several important parameters that affect the performance of routing algorithms are network size, traffic load, network topology, and mobility model. Due to the random movements of mobile nodes in ad hoc networks, modeling of mobility was a challenging task. However, the study in [15] shows that only the topology change affects the operation of a routing algorithm. Therefore, we can simplify the influence of mobility into link failure ratio. In our analysis, p_f denotes the link failure probability between two neighbor nodes, and the probability that a route of h hops long fails is $P_f(h) = 1 - (1-p_f)^h$.

[15] only analyzed the routing performance for a specific network topology, while our analysis deals with a general case. In Section V-B, we assume a two-dimensional Poisson distribution with the average number of nodes per unit area λ. Communication bandwidth

is unlimited, and all the packets are correctly delivered since no collisions occur. All transmissions are omni-directional with the same transmission range R.

2) Number of Transmissions: First, we estimate the number of RREQ packets. We suppose that the straight line distance between a pair of source and destination nodes is L. For the source node to discover the destination, it should send out a RREQ packet, and the RREQ packet has to be flooded to all the nodes that no more than L far from the source node. Therefore, for DSR, the number of RREQ packets for route discovery should be the number of nodes that are less than L far from the source node, i.e. $\pi L^2\lambda$. For DSR-PATM, the number of RREQ packets is $\pi L^2\lambda(1-p_h)$. We list the final results in Table II.

Second, the number of RREP packets is estimated as follows. In DSR, for each of the received RREQ packet, the destination node should reply with an RREP packet, which results in multiple RREP received by the source node. In Table II, h is the number of hops on the shortest paths, and m is the number of RREP packets returned by the destination node. m' and h' are the corresponding parameters for DSR-PATM. Then we need to estimate the 4 parameters. [12] computed the expected progress of a packet in the direction of its final destination per hop. Let E denote this expected progress in DSR and E' in DSR-PATM:

$$E = R[1 + e^{-\lambda\pi R^2} - \int_{-1}^{1} e^{-\lambda R^2 q(t)} dt] \tag{10}$$

$$E' = R[1 + e^{-\lambda(1-p_h)\pi R^2} - \int_{-1}^{1} e^{-\lambda(1-p_h) R^2 q(t)} dt] \tag{11}$$

where

$$q(t) = \cos^{-1}(t) - t\sqrt{1-t^2}\ . \tag{12}$$

Thus h and h' can be estimated as:

$$h = \frac{L}{E} \tag{13}$$

$$h' = \frac{L}{E'}\ . \tag{14}$$

Then we try to estimate m, the number of RREP packets returned by the destination in DSR. The node "S" in Fig. 6 denotes the source node, and "D" denotes the destination node. Hopefully, the destination receives the RREQ packets from the nodes within the shadow area, so the expected number of possibilities is $\pi R^2\lambda/2$. In the extreme case, all these RREQ packets indicate the same hop number. Therefore, m is at most $\pi R^2\lambda/2$. Similarly, m' is estimated as $\pi R^2\lambda(1-p_h)/2$.

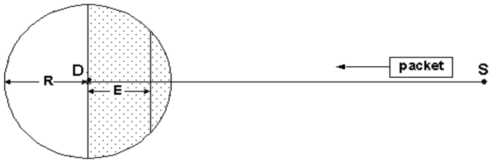


Fig. 6. Estimation of m

Third, we estimate the number of RERR packets. For DSR, during the Route Maintenance, once one route fails, the source node may try another backup route it found in the Route Discovery. If there are m routes discovered, the number of RERR packets can vary from 0 to $m(h-1)$. For DSR-PATM, the number of RERR packets can be estimated as $m'(h'-1)$.

As an example for the comparison, we use the same parameters as in Section V-A.2. Thus $\pi R^2\lambda = 40$, and $\pi R^2\lambda(1-p_h) = 14$. m is estimated as 20, and $m' = 7$. We suppose $L = 1000$ meters and $R = 250$ meters. Then based on Eq. 10, Eq. 11, Eq. 13, and Eq. 14, we can get $E = 222.43$, $E' = 193.38$, $h = 4.50$, and $h' = 5.17$. Our final results are shown in Table III. It is apparent that DSR-PATM can reduce the routing overhead by about 65% in this scenario.

TABLE II
NUMBER OF TRANSMISSIONS

	DSR	DSR-PATM
N_{RREQ}	$\pi L^2\lambda$	$\pi L^2\lambda(1-p_h)$
N_{RREP}	mh	$m'h'$
N_{RERR}	from 0 to $m(h-1)$	from 0 to $m'(h'-1)$

TABLE III
AN EXAMPLE

	DSR	DSR-PATM
N_{RREQ}	640	224
N_{RREP}	90	36
N_{RERR}	from 0 to 70	from 0 to 29

3) Expectation Values: The expectation values of the parameters estimated in Section V-B.2 will be computed.

$$\begin{cases} E[N_{RREQ}] = N_{RREQ} \cdot P(all\ routes\ fail) \\ E[N_{RREP}] = N_{RREP} \cdot P(all\ routes\ fail) \\ E[N_{RERR}] = \Sigma k \cdot N_{RERR} \cdot P(first\ k\ routes\ fail) \end{cases} \tag{15}$$

For DSR:

$$\begin{cases} E[N_{RREQ}] = \pi L^2\lambda[P_f(h)]^m \\ E[N_{RREP}] = mh[P_f(h)]^m \\ E[N_{RERR}] = \Sigma k\frac{m(h-1)}{2}[P_f(h)]^k \end{cases}$$

Similarly, for DSR-PATM:

$$\begin{cases} E[N_{RREQ}] = \pi L^2\lambda(1-p_h)[P_f(h')]^{m'} \\ E[N_{RREP}] = m'h'[P_f(h')]^{m'} \\ E[N_{RERR}] = \Sigma k\frac{m'(h'-1)}{2}[P_f(h')]^k \end{cases}$$

In Eq. 15, since DSR-PATM has much smaller N_{RREQ}, N_{RREP}, and N_{RERR}, which are common factors for every term, we can expect that DSR-PATM also has smaller expectation values.

VI. PERFORMANCE EVALUATION BY SIMULATIONS

A. Simulation Environments

We simulate our algorithms using NS-2 simulator. In the simulations, we apply PATM and combinations of PATM and other multi-rate algorithms with DSR. Under topology management scheme, we modify the Route Request phase such that every node re-broadcasts an RREQ packet if the node is not a host. As a result, hosts are excluded from serving as intermediate nodes on a routing path. However, since the nodal type is initialized to host, we allow hosts to forward RREQ packets when the hosts do not have a cluster head in its one-hop neighborhood. After the initialization phase, only non-host nodes can broadcast and forward RREQ packets.

To see the differences between various optimizations in ad hoc networks, we compare the performance of the following different combinations of routing protocols and MAC protocols.

1) DSR: DSR combined with the plain IEEE 802.11 MAC;
2) DSR-PATM: DSR with PATM combined with the plain IEEE 802.11 MAC;
3) DSR-SPAN: DSR with SPAN [5] combined with the plain IEEE 802.11 MAC;
4) DSR-PATM-RBAR: DSR with PATM combined with RBAR (Receiver-Based AutoRate);

5) DSR-PATM-RMAC: DSR with PATM combine with RMAC (Relay-Based MAC).

The simulations are carried out in ad hoc networks generated over a 1000 × 400 square meter area with 70 nodes moving in random directions at random speeds. The simulation range is fixed to 250 meters. Each simulation runs for 890 seconds.

We use the following metrics to show the performance of each protocol.

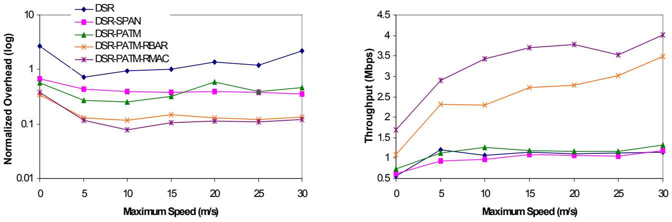
1) *Normalized Control Overhead*: the total number of control packets divided by the total number of data packets delivered to destinations.
2) *Average Delay*: the average delay of all the data packets delivered to destinations.
3) *Throughput*: the amount of data delivered to destinations during a simulation divided by the time span of the simulation.
4) *Combined Metric*: the product of Normalized Overhead and Average Delay divided by the Delivery Ratio or the Throughput. Although it is meaningless to simply combine several independent metrics, the combination fairly compares the overall performance if the individual metrics are equally important. The lower the Combined Metric of a protocol, the better the protocol performs.

B. Simulation Results

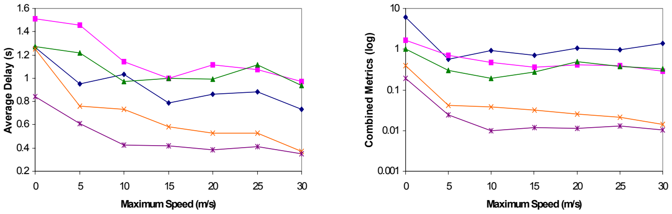
We use TCP flows to simulate data traffic, and each source starts a session randomly with data rate 4 packets/second and 1460 bytes payload size.

Scenarios with different degrees of mobility are simulated where the maximum speed of the nodes varies from 0 to 30 meters/second. The number of TCP flows is fixed to 20. Fig. 7 shows the performance comparison under different metrics between the five protocols. It is apparent that our PATM+RMAC combination solution improves the throughput, and reduces the routing overhead and average delay dramatically. The combined metrics in the last figure demonstrate that the combination algorithm always performs the best among all the protocols, in both low mobility and high mobility scenarios.

We also observe that in the static scenario, DSR-PATM reduces the routing overhead by about 70% over DSR, which closely matches our analytical result in Section V-B.2, 65%.



(a) Normalized Overhead (log) (b) Throughput



(c) End-to-End Delay (d) Combined Metric (log)

Fig. 7. Performance Under Various Speeds

VII. CONCLUSIONS

We have presented a novel approach to provide a high throughput yet low control-overhead solution for ad hoc networks, by integrating the topology management mechanisms with the multi-rate adaptation. It is different from most papers focusing either only on reducing control overhead and energy consumption, or only on increasing network capacity. Performance analysis and simulation studies demonstrate that the integrated approach is promising in improving network efficiency and capacity.

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