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Selecting a routing strategy for your ad hoc network

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Abstract

In this paper we investigate the performance of routing strategies in ad hoc networks. An ad hoc network operates without a central entity or infrastructure, and is composed of highly mobile network hosts. In this environment, routes tend to be multihop and routing protocols are faced with host mobility and bandwidth constraints. In recent years, numerous routing protocols of different styles have been proposed. Traditional table-driven protocols (distance vector, link state), reactive on-demand protocols, and location-based protocols that use position information provided by GPS are the most commonly used strategies. Using PARSEC, we simulate protocols that represent these various routing strategies. The protocols are evaluated in different network scenarios. Relative strengths, weaknesses, and applicability to various situations of each routing protocol are studied and discussed.

Keywords: Ad hoc network; Demand routing protocol; PARSEC

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1. Introduction

With the advance of wireless communication technology, portable computers with radios are being increasingly deployed in common activities. Applications such as conferences, meetings, lectures, crowd control, search and rescue, disaster recovery, and automated battlefields typically do not have central administration or infrastructure available. In these situations, ad hoc networks, or packet radio networks [9,13] consisting of hosts equipped with portable radios must be deployed impromptu without any wired base stations. In ad hoc networks, each host must act as a router since routes are mostly 'multihop.' Nodes in such a network move arbitrarily, thus network topology changes frequently and unpredictably. Moreover, bandwidth and power are limited. These constraints, in combination with network topology dynamics make routing in ad hoc networks challenging.

Routing protocols for ad hoc networks have adopted a variety of approaches. These protocols can be generally classified as: (a) distance vector based; (b) link state based; (c) on-demand; and (d) location based. The first two categories modify a traditional table-driven scheme to adapt to ad hoc networks. On-demand, or reactive, routing protocols are proposed specifically for ad hoc networks. These protocols do not maintain permanent route tables. Instead, routes are built by the source on demand. With the advent of GPS (Global Positioning System) [14], protocols that utilize location information to establish routes have been proposed. In this paper, we conduct a performance study of routing protocols that represent each routing category. The distance vector based protocol WRP [17], the link state based protocol FSR [10], the on-demand routing protocol DSR [12], the location based reactive protocol LAR [15], and the location based proactive protocol DREAM [2] are simulated in a common wireless network simulation platform. In addition to routing protocols, we implemented a detailed and realistic model of the physical layer and medium access control protocols.

The five routing protocols were simulated in diverse network scenarios using two different movement patterns: the random waypoint model, [3,12] where the node movements are not correlated, and a group mobility model, [18] where nodes form groups and nodes in the same group move in a similar direction with similar speed. Node speeds were varied from 0 to 72 km/h in these models to investigate the impact of speed as well as mobility pattern on routing protocols. Various traffic loads were applied to study how traffic patterns influence routing protocol performance.

Related works [3,5,11] that performed comparative evaluation of ad hoc routing protocols can be found in the literature. However, these articles compared/ranked

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protocols that are similar in style (e.g. on-demand) and used only a single mobility model. These papers evaluate the single class of protocols using performance metrics such as throughput and pure control overhead that only show the 'effectiveness' of the protocol. In this paper, we investigate performance of protocols from different categories under various network scenarios (e.g. different mobility patterns, mobility rates, traffic patterns, etc.). We apply metrics that show the 'efficiency' in addition to the 'effectiveness' of the protocols. Understanding the protocol's efficiency gives us the ability to study and discuss relative strengths, weaknesses, and applicability to various situations of each routing protocol. The ultimate purpose is not to rank the protocols, but to find which routing strategy is best for which environment.

The rest of the paper is organized as follows. Section 2 presents an overview of the routing protocols we simulate. The simulation environment and methodology are described in Section 3, followed by simulation results in Section 4. Merits and shortcomings of each routing strategy are discussed in Section 5 and concluding remarks are made in Section 6

2. Routing protocols review

In this section, we introduce routing protocols from each category we chose to simulate. Basic operation descriptions with our implementation decisions are illustrated. There are many other routing protocols proposed, but their overview is beyond the scope of this paper. Readers are referred to Ref. [21] for a survey of ad hoc routing protocols.

2.1. Wireless routing protocol (WRP)

Wireless routing protocol (WRP) [17] is a distance vector based protocol designed for ad hoc networks. WRP modifies and enhances distance vector routing in the following three ways. First, when there are no link changes, WRP periodically exchanges a simple HELLO packet rather than exchanging the whole route table. If topology changes are perceived, only the 'path-vector tuples' that reflect the updates are sent. These path-vector tuples contain the destination, distance, and the predecessor (second-to-last-hop) node ID. Second, to improve reliability in delivering update messages, every neighbor is required to send acknowledgments for update packets received. Retransmissions are sent if no positive acknowledgments are received within the timeout period. Third, the predecessor node ID information allows the protocol to recursively calculate the entire path from source to destination. With this information, WRP substantially reduces looping situations, speeds up the convergence, and is less prone to the 'count-to-infinity' problem. Still, temporary loops do exist and update messages are triggered frequently in networks with highly mobile hosts.

Table 1
Parameter values for WRP

Periodic HELLO interval	1 s
Max allowed HELLO miss	4
Update acknowledgment timeout interval	1 s
Retransmission counter	4
Retransmission timer	1 s

Table 1 shows the WRP parameter values used in our experiments. Values suggested by the designers of WRP and specified in Ref. [17] were used for the most part. Only a couple of values were modified to maximize WRP performance in our simulation environment. We set the timer values so as to send more frequent connectivity updates, but less frequent retransmissions than suggested. The former modification was required by the high mobility speed on our experiments, and the latter is due to the fact that under the MAC protocol we implemented (to be described in detail in Section 3.2), retransmitting at twice the round trip time would flood the MAC buffer as well as cause unnecessary collisions with cross traffic in the channel.

2.2. Fisheye state routing (FSR)

Fisheye state routing (FSR) [10] is a link state type protocol which maintains a topology map at each node. To reduce the overhead incurred by control packets, FSR modifies the link state algorithm in the following three ways. First, link state packets are not flooded. Instead, only neighboring nodes exchange the link state information. Second, the link state exchange is only time-triggered, not event-triggered. Third, instead of transmitting the entire link state information at each iteration, FSR uses different exchange intervals for different entries in the table. To be precise, entries corresponding to nodes that are nearby (within a predefined scope) are propagated to the neighbors more frequently than entries of nodes that are far away. These modifications reduce the control packet size and the frequency of transmissions. As a result, FSR scales well to large network size since link state exchange overhead is kept low. As mobility increases, however, routes to remote destinations may become less accurate.

Simulation parameter values for FSR are shown in Table 2.

Table 2
Parameter values for FSR

Scope		1 hop
Periodic HELLO interval	Speed ≤ 3.5 km/h	5 s
	Speed > 3.5 km/h	1 s
Max allowed HELLO miss		3
Periodic INTRASCOPE UPDATE interval	Speed ≤ 3.5 km/h	5 s
	Speed > 3.5 km/h	1 s
Periodic INTERSCOPE UPDATE interval	Speed ≤ 3.5 km/h	15 s
	Speed > 3.5 km/h	3 s

Table 3
Parameter values for DSR

Time between retransmitted ROUTE REQUESTS (exponentially backed off)	500 ms
Max time where the same requests can be sent	10 s
Non-propagating ROUTE REQUEST timeout	30 ms

2.3. Dynamic source routing (DSR)

Dynamic source routing (DSR) [12] is an on-demand routing protocol that builds routes only when necessary. A source floods a ROUTE REQUEST if data to send exist but no route to its destination is known. The ROUTE REQUEST packet records in its header the IDs of the nodes it traverses. When the ROUTE REQUEST is received by the destination or a node that knows a route to the destination, a Route Reply is sent to the source via the recorded route. Each node in the network maintains a route cache storing routes it has learned over time. Aggressive caching helps minimizing the cost incurred by the route discovery process. DSR uses source routing instead of hop-by-hop routing; the source node appends the list of node IDs that comprise the route in the data header. When a node learns the route is obsolete due to topology changes, it builds and sends a Route Error to the source. The source then invokes a route discovery process to construct a new route. No periodic message of any kind are required in DSR.

Table 3 shows the DSR parameter values used in our implementation. We implemented some optimization features of DSR (explanations and details of DSR optimization can be found in Ref. [16]): non-propagating route requests, replying from cache, salvaging, tapping, and updating shorter routes.

2.4. Location-aided routing (LAR)

Location-aided routing (LAR) [15] is an on-demand routing protocol which exploits location information. In fact, LAR operates very similarly to DSR. The major difference between the two protocols is that LAR uses location information obtained from GPS to restrict the flooded area of ROUTE REQUEST packets. There are two schemes determine which nodes propagate ROUTE REQUESTs. In Scheme 1, the source defines a circular area in which the destination may be located. The position and size of the circle is decided with the following information: (a) the destination location known to the source; (b) the time instant when the destination was located at that position; and (c) the average moving speed of the destination. The smallest rectangular area that includes this circle and the source is the *request zone*. This information is attached to a ROUTE REQUEST by the source and only nodes inside the request zone propagate the packet. In Scheme 2, the source calculates the distance between the destination and itself. This distance, along with the destination location known to the source, is included in a ROUTE REQUEST and sent to neighbors. When nodes receive this packet, they compute their distance to the destination, and continue to relay the packet only if their distance to destination is less than or equal to the distance indicated by the packet. When forwarding the packet, the node updates the distance field with its distance to the destination. In both schemes, if no Route Reply is received within the timeout period, the source retransmits a ROUTE REQUEST via pure flooding.

Table 4
A parameter value for LAR

Timeout to send ordinary flooding request when no reply is received	2 s

A parameter setting for LAR is shown in Table 4. We implemented LAR as specified in Ref. [15] and no DSR optimization features were included in LAR. The results shown for LAR in this paper are those of Scheme 1. Both schemes were implemented and Scheme 1 gave a slight better performance in our simulations.

2.5. Distance routing effect algorithm for mobility (DREAM)

Distance routing effect algorithm for mobility (DREAM) [2] is another location based routing protocol. In contrast to LAR, DREAM is a proactive scheme (i.e. it maintains permanent routing tables). The scheme partially floods data to nodes in the direction of the destination. In the route table, *coordinates* of each node are recorded instead of route vectors. Each node in the network periodically exchanges control messages to inform all other nodes in the network of its location. *Distance effect* is achieved by assigning 'TTL (Time-To-Live)' value to location control messages. Location updates with low TTL value (*short-lived* updates) are sent more frequently to packets with high TTL value (*long-lived* updates). In addition, DREAM adjusts to network dynamics by controlling update frequency based on movement speed. When sending data, if the source has 'fresh enough' location information of the destination, it selects a set of one hop neighbors that are located in the direction from source to destination. If no such nodes are found, the data is flooded to the entire network. If such nodes exist, the list is enclosed in the data header and transmitted. Only nodes specified in the header are qualified to receive and process the packet. These nodes in turn select their own list of possible next hops and forward the packet with such updated list. If no neighbors are located in the direction of the destination, the packet is simply dropped. When the destination receives data, it sends ACKs back to the source in a similar fashion. However, ACKs are not transmitted when data was received via flooding. When the source sends data with designated

Table 5
Parameter values for DREAM

Periodic 'short-lived' control update interval	
Speed < 10 km/h	45 s
10 km/h ≤ speed < 30 km/h	35 s
Speed ≥ 30 km/h	25 s
TTL of short-lived control updates	200 m
Ratio of short-lived and long-lived control updates sent	10:1
Min flooding angle towards the direction of destination	40°

next hops (i.e. not by pure flooding), it starts a timer. If no ACK is received before the timer expires, the data is retransmitted by ordinary flooding.

Table 5 shows the parameter values for DREAM used in our experiments. After a few experiments, we decided to remove the ACK procedure of DREAM. There were situations, where data packets reached destinations but ACKs for those packets failed to get back to sources, thus invoking unnecessary flooding. In addition, transmission of ACKs congested the network to a great degree, yielding poor performance.

2.6. Protocols summary

Table 6 summarizes key characteristics and properties of the protocols we simulated.

3. Simulation model and methodology

The simulator for evaluating routing protocols was implemented within the GloMoSim library [24]. The GloMoSim library is a scalable simulation environment for wireless network systems using the parallel discrete-event simulation capability provided by PARSEC [1]. Our simulation modeled a network of 50 mobile hosts placed randomly within a 750 × 750 m area. Radio propagation range for each node was 200 m and channel capacity was 2 Mbits/s. There were no network partitions throughout the simulation. Each simulation executed for 600 s of simulation time. Multiple runs with different seed numbers were conducted for each scenario and collected data was averaged over those runs.

3.1. Channel and radio model

A free space propagation model [19] with a threshold cutoff was used in our experiments. In the free space model, the power of a signal attenuates as $1/d^2$, where d is the distance between radios. In addition to the free space channel model, we also implemented SIRCIM (Simulation of indoor radio channel impulse-response models) [20] which considers multipath fading, shadowing, barriers, foliages, etc. SIRCIM is more accurate than the free space model, but we decided against using SIRCIM in our study because: (a) the complexity of SIRCIM increases simulation time by two orders of magnitude; (b) the accuracy of the channel model does not affect the relative ranking of the routing protocols evaluated in this study; and (c) SIRCIM must be 'tuned' to the characteristics of the physical environment (e.g. furniture, partitions, etc.), thus requiring a much more specific scenario than we are assuming in our experiments.

In the radio model, we assume the ability of a radio to lock onto a sufficiently strong signal in the presence of interfering signals, i.e. radio capture. If the capture ratio (the minimum ratio of an arriving packet's signal strength relative to those of other colliding packets) [19] is greater than the predefined threshold value, the arriving packet is received while other interfering packets are dropped.

3.2. Medium access control protocol

The IEEE 802.11 MAC protocol with distributed coordination function (DCF) [8] is used as the MAC layer in our experiments. DCF is the basic access method used by mobiles to share the wireless channel under independent ad hoc configuration. The access scheme is Carrier Sense multiple access/collision avoidance (CSMA/CA) with acknowledgments. Optionally, the nodes can make use of

Table 6
Summary of protocols

Protocols	WRP	FSR	DSR	LAR	DREAM
Routing strategy	Distance vector	Link state	On-demand	Location based (reactive)	Location based (proactive)
Route selection metric	Shortest path	Shortest path	Shortest path	Shortest path, location	Shortest path, location
Loop-free	No (temporary)	Yes	Yes	Yes	Yes
Periodic messages	HELLOS	HELLOS, ROUTE entries	None	None	Location Packets
Updates triggered by	Event, time	Time	Event	Event	Time
Flooding packets	None	None	RREQs	RREQs	Location packets, data (Partial)
Routes in data	No	No	Source route	Source route	Next hop nodes
Promiscuous mode	No	No	Yes	No	No
Need for GPS	No	No	No	Yes	Yes

Request To Send/Clear To Send(RTS/CTS) channel reservation control frames for unicast, virtual carrier sense, and fragmentation of packets larger than a given threshold. By setting timers based upon the reservations in RTS/CTS packets, the virtual carrier sense augments the physical carrier sense in determining when mobile nodes perceive that the medium is busy. Fragmentation is useful in the presence of high bit error and loss rates, as it reduces the size of the data units that need to be retransmitted.

In our experiments, we employed RTS/CTS and virtual carrier sense. We chose this configuration to minimize the frequency and deleterious effects of collisions over the wireless medium. We did not employ fragmentation because our data packets were small enough that the additional overhead would reduce overall network throughput.

3.3. Traffic pattern

A traffic generator was developed to simulate constant bit rate sources. The size of datapayload is 512 bytes. We have chosen this value because smaller payload sizes penalize protocols that append source routes to each data packet. Ten data sessions with randomly selected sources and destinations were simulated. Each source transmits data packets at a rate between 0.5 and 4 packet/s. In Section 4.6, we vary the traffic load by changing the number of data sessions and examine its effect on routing protocols.

3.4. Mobility pattern

We implemented two different mobility patterns. The random waypoint model [3,12] was used in the results shown from Sections 4.1–4.6. In this model, a node selects a destination randomly within the terrain range and moves towards that destination at a predefined speed. Once the node arrives at the destination, it stays at its current position for a pause time of 10 s. After being stationary for the pause time, it selects another destination randomly and migrates towards it, staying there for 10 s, and so forth. Mobility speed varies from 0 to 72 km/h across the range of experiments. Note that the stationary period is not considered in computing node speed. The results presented in Section 4.7 are obtained by using a group mobility model [18]. The details of the model will be described in the corresponding subsection.

3.5. Metrics

We have used the following metrics in comparing protocol performance. Some of these metrics were suggested by the MANET working group for routing protocol evaluation [4].

- *Packet delivery ratio*. The ratio of data packets delivered to the destinations and data packets originated by the sources. This number presents the routing effectiveness of a protocol.
- *Hop count*. Average number of hops traveled by data packets that reached their destinations. One might argue that a low hop count indicates effectiveness of route selection. This argument is true when different routing protocols have the same packet delivery ratio. However, if routing protocols give different ratios (especially in networks with high mobility rates and link changes), hop count is closely related to the packet delivery ratio. Namely, the higher the delivery rate, the higher the hop-count. Since only data packets that survive all the way to destinations are reflected, low hop count means that most of the data packets delivered are destined for nearby nodes, and packets sent to remote hosts are likely dropped. Thus, the hop count measure provides us with information about the survivability of the protocols.
- *Number of data packets transmitted per data packet delivered:* One should not confuse this measure with average hop count. 'Data packets transmitted' is the count of every transmission of data by each node. This count includes transmissions of packets that are eventually dropped and retransmitted by intermediate nodes. Since we divide this figure by the number of packets delivered to the destinations, this measure can be viewed as the efficiency of delivering data [4].
- *Number of control bytes transmitted per data byte delivered*. In place of using a pure control overhead, we chose to use a ratio of control bytes transmitted to data byte delivered to investigate how efficiently control packets are utilized in delivering data. Note that not only bytes of control packets (i.e. route tables, route update vectors, hellos, location updates, etc.), but also bytes of data packet headers (including source routes) are included in the number of control bytes transmitted. Accordingly, only bytes of the data payload contribute to the data bytes delivered.
- *Number of control and data packets transmitted per data packet delivered*. This measure shows the efficiency in terms of channel access [4]. This efficiency is very important in ad hoc networks since link layer protocols are typically contention-based.

4. Simulation results

4.1. Packet delivery ratio

Fig. 1 highlights the packet delivery ratio of five protocols. All protocols perform well under low mobility rates, but they become less effective as the mobility speed increases. DREAM is the most robust to mobility. This robustness is due to the partial flooding of data. With this flooding, multiple packets can reach the destination via different paths. Utilizing location information, this flooded area is confined to reduce network congestion. However, flooding did induce increased congestion, contention, and

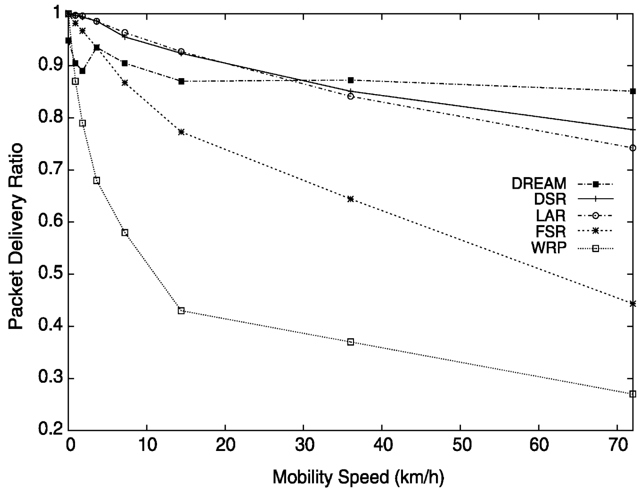

Fig. 1. Average packet delivery ratio as a function of mobility speed.

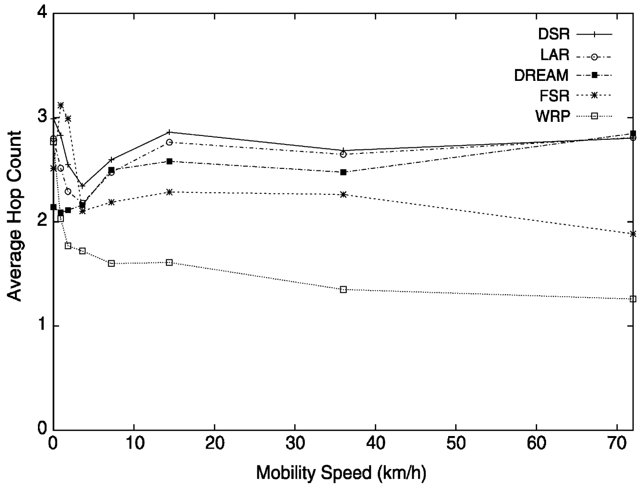

Fig. 2. Average hop count as a function of mobility speed.

collisions, causing DREAM to be the only protocol that did not successfully deliver all packets in the absence of mobility.

On-demand routing protocols (DSR and LAR) have very high packet delivery ratios overall, especially when subject to relatively low mobility. We observe only a slight performance degradation with mobility. In highly mobile situations, routes taken by ROUTE REQUESTs may already be broken when the source sends data or even when Route Replies are being returned back to the source. Thus, we find that the delay resulting from discovering routes plays an important role in the performance degradation at high mobility speed. Since LAR is an improvement of basic DSR, one might wonder why LAR does not perform much better than DSR. However, remember that DSR has several optimization features that are not implemented in LAR. In addition, the location information used by LAR may be out-of-date when nodes move at high speeds.

FSR was sensitive to mobility. Update messages in FSR are time-triggered only, i.e. there are no event-triggered updates. Additionally, routes to remote destinations become less accurate as mobility increases. As a result, some of the link-state information maintained in route tables is imprecise. Shortening the periodic update interval may resolve this problem, but at the cost of excessive routing overhead.

WRP showed less effectiveness when compared to other protocols, especially at high mobility rates. As nodes move faster, link connectivity changes more often and more update messages are triggered. For each triggered update, neighboring nodes are required to send back an acknowledgment, and this adds to control overhead. Moreover, temporary loops were being formed because the network view converged slowly, with many changes needing to be absorbed and propagated. Loops, triggered updates, and ACKs created an enormous amount of packets, contributing further to collisions, congestion, contention, and packet drops.

4.2. Hop count

As mentioned in Section 3.5, average hop count only accounts for data packets that ‘survive’ to destinations. As expected, Fig. 2 reveals that protocols that delivered more data packets (as was shown in Fig. 1) have higher average hop count. If the distance between source and destination is greater, the number of intermediate nodes that data packets need to visit increases. The likelihood of a packet being dropped becomes greater as packets are required to traverse many links, particularly if network topology changes often. Thus, if a routing protocol cannot handle connectivity changes rapidly, more data packets get dropped.

4.3. Number of data packets transmitted per data packet delivered

The average number of data transmissions per data packet delivery for each protocol is shown in Fig. 3. As

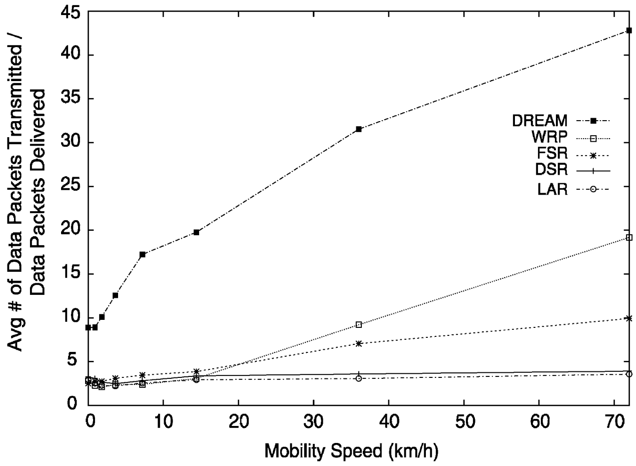

Fig. 3. Average number of data packets transmitted per data packet delivered as a function of mobility speed.

expected, DREAM has the highest measure since it partially floods data while other protocols unicast data. The value increases with mobility because sources are more likely to send data by pure flooding. The values of WRP and FSR increase with mobility as well and these increases stem from packet drops by intermediate nodes.

It is interesting to compare Figs. 2 and 3. With the exception of DREAM, the difference between the two measures indicates the number of packet drops and retransmissions per single data delivery. We can observe that there are only minor differences between the two measures for on-demand protocols. On-demand protocols were able to deliver data packets without much wasted data transmissions. DSR, in particular, has an optimization feature called salvaging, where the node detecting a route break salvages the data by sending it through another route to the destination, via a path it already knows (i.e. stored in route cache). Hence, data packets are dropped much less frequently when compared to proactive schemes. Proactive schemes (WRP and FSR) suffer from a large difference that grows with mobility speed. This observation confirms that WRP and FSR have numerous packet drops in highly dynamic networks.

4.4. Number of control bytes transmitted per data byte delivered

Fig. 4 shows the efficiency of control overhead utilized in data delivery. The graph demonstrates that proactive protocols with periodic messages (e.g. HELLOS, route entries) have high comparative overhead. In WRP, each node sends acknowledgments for each HELLO it receives. Additionally, route update entries are produced more frequently in high mobility, where there are many link changes. As the WRP path vector has an extra field (next-to-last-hop node), control byte overhead actually becomes larger than that of a basic distance vector algorithm when the mobility rate is high. In FSR, route update messages are sent periodically only, thus the pure control overhead value does not increase. However, recall that in our measure, control byte overhead is divided by data bytes delivered. FSR delivered less data in high mobility cases. We can also observe a sudden jump in the FSR plot. The point of sharp increase represents the point when the update interval is adjusted to node movement speed. DREAM shows a very low control overhead in the figure because the size of location information packets is small. If our implementation used ACK procedure, where ACKs are partially flooded in a similar manner to data, the value would be much higher. DSR and LAR have the least control traffic because they have no periodic messages and send control packets only when necessary. Link changes that are not part of existing data session routes are not updated in DSR and LAR while proactive protocols still send this information. In other words, control packets in on-demand protocols are used efficiently. The two on-demand protocols have almost equal overhead. Although LAR sends ROUTE REQUESTs to a limited area, extra overhead is produced by attaching location information in ROUTE REQUESTs and Route Replies and that evens out the difference.

4.5. Number of total packets transmitted per data packet delivered

The average number of data and control packets transmitted per data packet delivered is shown in Fig. 5. We believe this measure is particularly significant in ad hoc networks since most link layer protocols are contention-based. The graph is nearly identical to Fig. 4 except for the vertical scale and higher values of DREAM. Remember that Fig. 4 accounts for transmitted *bytes* of control packets only while Fig. 5 accounts for the *number* of all packets transmitted. As mentioned above, data flooding accounts for higher values of DREAM. As expected, on-demand routing protocols show much lower values compared to those of other protocols. Although the difference is very

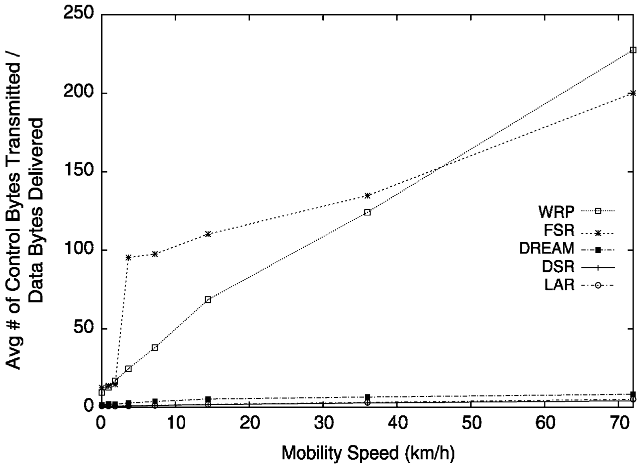

Fig. 4. Average number of control bytes transmitted per data byte delivered as a function of mobility speed.

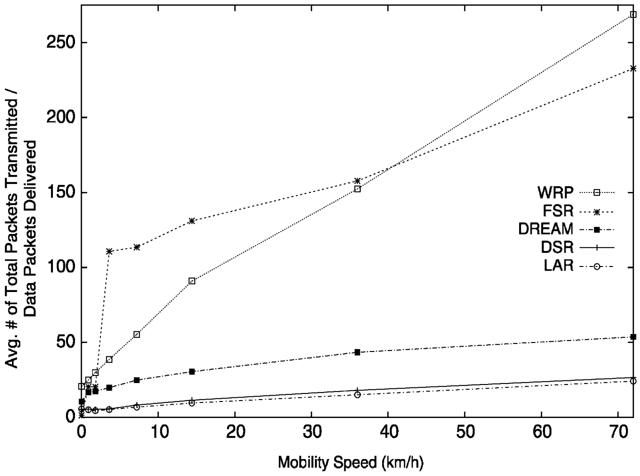

Fig. 5. Average number of total packets transmitted per data packet delivered as a function of mobility speed.

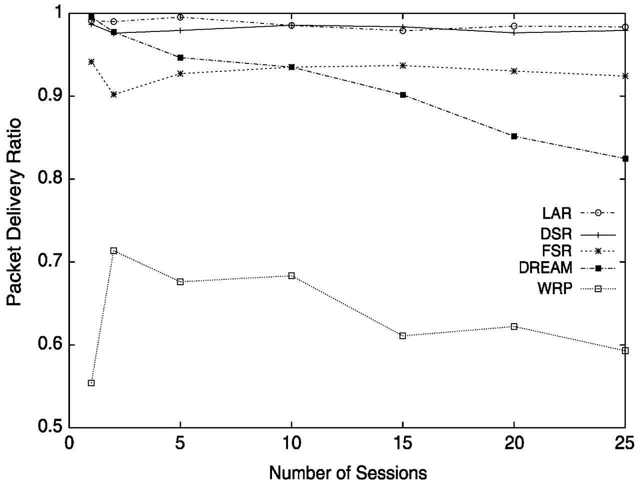

Fig. 6. Average packet delivered ratio as a function of number of sessions.

small, LAR has less packets transmitted than DSR. Restricting the propagation of ROUTE REQUESTs using location information accounts for the difference.

4.6. Effect of traffic load

In this subsection, we vary the number of data sessions while keeping the packet rate for each session constant. The mobility rate was set constant at 1 m/s. Figs. 6 and 7 reveal the packet delivery ratio and the average number of total packets transmitted per data packet delivered, respectively. Only DREAM and WRP suffer a packet delivery ratio drop with increase in the number of data sessions. Since data packets of DREAM are partially flooded, having many sessions increases the amount of flooded packets resulting in contention, collisions, and congestion. As for WRP, due to the random waypoint mobility, the routing algorithm is in a constant state of reconciling its tables to the perceived link changes, and propagating those changes across the network. Because of the method by which WRP reduces loops and invalid paths, there is a significant percentage of destinations that are temporarily unreachable from a given node while these link updates are being propagated. The effect of these temporarily unreachable destinations becomes increasingly noticeable with a larger number of sessions, as packets are dropped by the source or intermediate nodes with invalid routing table entries to a given destination.

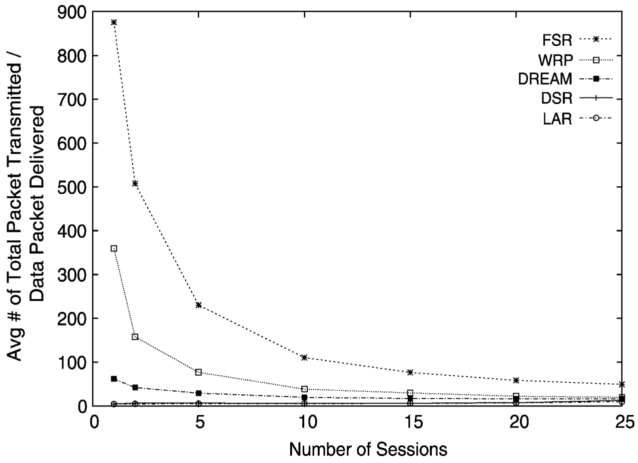

Fig. 7. Average number of total packets transmitted per data packet delivered as a function of number of sessions.

When increasing the number of sessions, the number of total packets transmitted per data packet delivered decreases for proactive schemes while they remain nearly constant for on-demand schemes. FSR and DREAM send periodic updates and the number of update transmissions remain the same regardless of number of data sessions. WRP sends event-triggered updates, but since the mobility rate is constant, having a different number of sessions does not affect the number of update transmissions. Meanwhile, the number of data packets received by destinations increases linearly with number of data sessions, resulting in the decrease of values. On-demand protocols, however, send more control packets when there are more data sessions. As the number of sessions increase, more route discovery and route maintenance procedures are executed. The increase of these control packets are in the same rate of that of data packets, and the measure remains almost constant.

4.7. Group mobility model

In certain ad hoc networking situations (e.g. troops moving in military situations, a number of students moving to the seminar room, etc.), network hosts form groups and nodes within the group move in a similar fashion. In this subsection, we model this *group mobility* in evaluating routing performances.

4.7.1. Mobility description

In the model we implemented, nodes in a network form groups, and nodes in the same group are placed close to one another. Nodes within a group move in a similar direction and speed while each group may move differently from the others. Movement of each group and each node in a group can be characterized as Exponentially correlated random mobility (ECRM) [18]. The model can be best described by the following equation:

$$b(t+1) = b(t)e^{1/\tau} + s\sigma\sqrt{1-e^{2/\tau}}r,$$

where $b(t)$ is the position (r, θ) of a group or a node at time t, τ is a time constant that regulates the rate of change, σ is the variance that regulates the variance of change, s is the speed of the node, and r is a Gaussian random variable.

Variables τ and σ control the movement. We chose to use the same values for nodes within the group but different value for each group. There are five groups in our simulation, each with 10 nodes. One group is stationary and other four groups move in different directions. If nodes hit the boundary of our simulation terrain range, they are

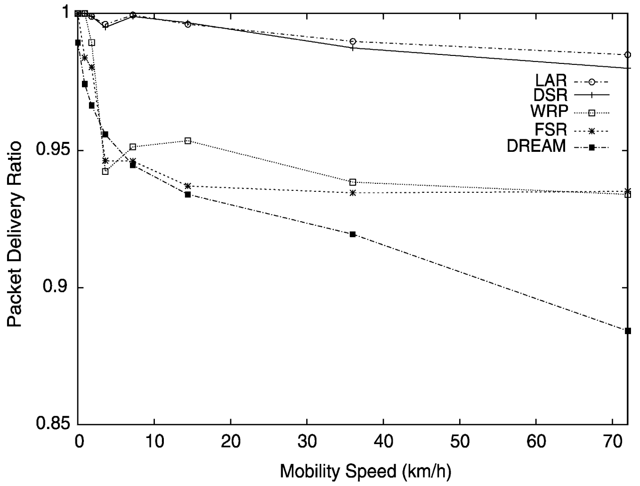

Fig. 8. Average packet delivery ratio as a function of group mobility speed.

bounced back in the reverse direction (i.e. west to east, northeast to southwest, etc.). Mobile nodes move constantly; there is no pause time. The average node degree in the group mobility model was 10:52 while it was 10:24 in the random waypoint model.

4.7.2. Results

Fig. 8 shows the packet delivery ratio of each protocol in the group ECRM model. All protocols are able to deliver more data packets successfully than in the random waypoint model. Notice the difference in the vertical scales between Figs. 1 and 8. WRP is the most improved protocol under the group mobility model. In the group ECRM model, nodes in the same group (i.e. immediate neighbors) move similarly and there are relatively few link changes. Even in highly mobile situations, route breaks occur much less frequently than in the random waypoint model. Few update packets are sent and the network view converges more quickly, thus improving WRP performance dramatically.

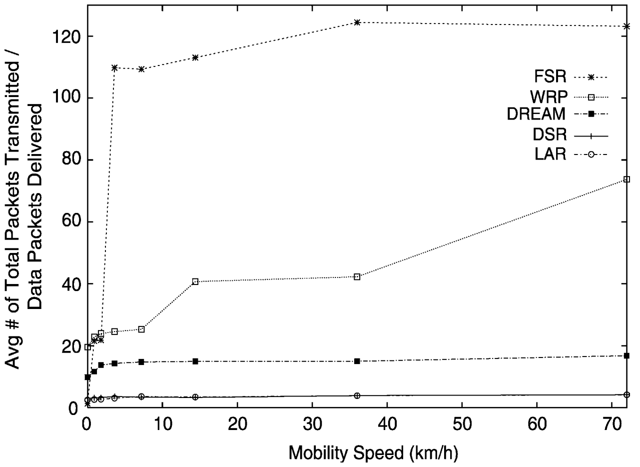

Fig. 9. Average number of total packets transmitted per data packet delivered as a function of group mobility speed.

Although the packet delivery ratio improved, DREAM is the protocol which benefited the least from this model. The number of link changes and route breaks does not affect the number of control packet transmissions in DREAM and it has no performance influence in delivering partially flooded data. In other words, DREAM is not only robust to mobility speed, it is also robust to movement pattern.

The average number of total packets transmitted per data packet delivered as a function of group mobility speed is shown in Fig. 9. The measures also improved (i.e. decreased) when compared with those in the random waypoint model. Because protocols delivered more data, the efficiencies are enhanced accordingly.

5. Discussion

In Section 4 we have studied the effectiveness and efficiency of each routing protocol. Although we applied various network scenarios, those scenarios cannot cover every possible situation. Moreover, there are other considerations which cannot be or are difficult to measure in simulation, that must be considered when selecting a routing strategy for specific applications and networks. In this section, we discuss some of the merits and shortcomings of each routing protocol and strategy.

Distance vector protocols work well in static networks. Since they maintain the full topology view all the time, distance vector type protocols are good choices when delivering real-time and heavy traffic. However, they do not scale well to large and highly mobile networks because they suffer from the ‘count-to-infinity’ problem, slow convergence, and excessive control overhead. WRP, which improves the basic distance vector algorithm, did not perform well under dynamic situations, but performed very well when nodes form and move in groups. Control overhead efficiency was competitive in low mobility cases, but as the mobility increased, update packets were triggered more frequently and the network was clogged with control packets. Still, WRP enhances the pure distance vector protocol greatly; it reduces control overhead by sending route entries instead of route tables and diminishes situations, where loops may occur by utilizing next-to-last-hop information.

Link state algorithms are best suited for networks that require QoS (Quality of service) guarantees because they provide link costs and capacities. Similar to distance vector protocols, however, link state protocols do not scale well to large networks and suffer from enormous amount of control overhead. A link state type protocol, FSR, did not show routing effectiveness in highly dynamic situations. Up-to-date routing information was not maintained when hosts moved quickly and randomly. Route update messages can be exchanged more frequently to obtain fresh information, but that will incur additional control traffic. Applying distance effect and adjusting update rates to movement speed reduces the amount of control overhead and allows prompt adaptation to network changes. Even though nodes may keep inaccurate routes to remote destinations as mobility increases, when a packet approaches its destination, it finds more precise routing instructions as it enters an area with a higher refresh rate.

On-demand routing protocols produce less control traffic overhead than the above mentioned proactive schemes since no route tables are periodically exchanged. Control packets are generated only as needed, i.e. there are no control messages which are not utilized. Due to less overhead, they performed well in most of our simulation scenarios, even in highly mobile situations. However, extra delay (route acquisition latency) is required to obtain a route and this delay does not favor on-demand protocols when traffic needs to be delivered quickly (e.g. real-time traffic). Additionally, if the network has a large number of data sessions, the amount of control overhead grows to be comparable to those of proactive schemes. DSR, a typical on-demand scheme, has even less control overhead than other on-demand schemes (e.g. ABR [23], SSA [6]) since it does not exchange any ‘hello’ or ‘beacon’ messages. However, the drawback is that route breaks and link changes are detected only after data packets fail to go through the broken link, thus yielding longer delays. Intermediate nodes of a route in DSR need not maintain up-to-date route information since source routing is used, but additional overhead is introduced by listing the route in the data header.

With the appearance of GPS, protocols that utilize node location information in building routes have been recently proposed. With the knowledge of node position, routing can be more effective at the cost of overhead incurred by exchanging coordinates. In addition, location information recorded can be out-of-date and these protocols cannot be applied to networks, where nodes are not equipped with GPS. We studied two distinctive location-based protocols. LAR, a reactive approach, further reduces control traffic of DSR by restricting the propagation of flood packets. However, no route can be obtained by the protocol in situations where no link is available in the limited flooded areas or when location information is obsolete. More delays are expected when constructing routes in those circumstances. Even though LAR can diminish the number of control packet transmissions, more byte overhead is generated to exchange additional location information.

DREAM is another location-based protocol, but in contrast to LAR, it is a proactive scheme. The key characteristic of DREAM is its partial flooding of data packets to nodes that are in the direction of the destination. Because of this partial flooding, multiple packets travel to destinations via different paths. The probability of reaching destinations is higher than protocols that unicast the data. The performance of DREAM was not greatly affected by the speed or movement pattern of network hosts. In other words, it was robust to mobility speed and mobility model. However, we saw performance degradation when the number of sessions in the network increased. Even though flooding is resilient to mobility, it creates a lot of (duplicate) packets and increases the number of packets in the network as the number of sessions become larger. Congestion, collisions, and channel contention occur more frequently in those situations.

Besides the measures we obtained from simulations, there are other factors that characterize routing protocols. In ad hoc networks, hosts are more prone to security invasions. Provision of network security, and probability of detection/interception are important considerations, especially in tactical networks [7]. Power usage of the protocol [22] needs to be addressed since most network hosts operate with batteries that will eventually be exhausted. Other issues such as storage overhead, protocol complexity, computation overhead should all be considered when choosing the best routing strategy for your network environment.

6. Conclusions

We have conducted a performance study of five protocols that represent various routing categories. Simulations were run under many diverse scenarios and each protocol showed competence in different situations. Overall, all protocols performed much better with the group mobility model than with the random way point model. WRP and FSR, especially, were the main beneficiaries of the group movement model. Each protocol’s performance degraded as mobility rates increased, but DREAM was the most robust to the speed of network hosts. However, because of the data flooding, DREAM became less effective under heavy traffic scenarios. On-demand protocols were highly effective and efficient in most of our scenarios. Extra delay in acquiring routes, though, make them less attractive in delivering real-time traffic. LAR further improved an on-demand protocol by using location information, but produced more overhead to exchange location information.

In summary, there is no single routing strategy that is best for all network situations. Every protocol has its advantages and disadvantages in different scenarios. The choice of a routing protocol should be made carefully after considering every aspect we provided in this paper (and possibly more).

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