Study of Distance Vector Routing Protocols for Mobile Ad Hoc Networks [*]

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Abstract

We investigate the performance issues of destination-sequenced distance vector (DSDV) and ad-hoc on-demand distance vector (AODV) routing protocols for mobile ad hoc networks. Four performance metrics are measured by varying the maximum speed of mobile hosts, the number of connections, and the network size. The correlation between network topology change and mobility is investigated by using linear regression analysis. The simulation results indicate that AODV outperforms DSDV in less stressful situations, while DSDV is more scalable with respect to the network size. It is observed that network congestion is the dominant reason for packet drop for both protocols. We propose a new routing protocol, congestion-aware distance vector (CADV), to address the congestion issues. CADV outperforms AODV in delivery ratio by about 5%, while introduces less protocol load. The result demonstrates that integrating congestion avoidance mechanisms with proactive routing protocols is a promising way to improve performance.

1. Introduction

1.1. Problem statement

The high mobility, low bandwidth, and limited computing capability characteristics of mobile hosts make the design of routing protocols challenging. The protocols must be able to keep up with the drastically and unpredictably changing network topology, with minimized message exchanges, in a computation efficient way.

The routing protocols may be categorized as *proactive*, *on-demand*, and *hybrid*, according to the way the mobile hosts exchange routing information. The proactive protocols, such as DSDV [17] and source tree adaptive routing (STAR) [8], periodically disseminate routing information among all the hosts in the network, so that every host has the up-to-date information for all possible routes. On-demand routing protocols, such as AODV [16] and dynamic source routing (DSR) [12], operate on a need basis, discover and maintain only active routes that are currently used for delivering data packets. Hybrid routing protocols, such as zone routing protocol (ZRP) [9], maintain a virtual routing infrastructure, apply proactive routing mechanisms in certain regions of a network and on-demand routing in the rest of the network.

An ad hoc routing protocol tends to be well-suited for some network contexts, yet less suited for the others [5]. A better understanding of the advantages and disadvantages of different routing approaches in various network contexts will serve as a cornerstone for the development of new adaptive routing protocols. However, ad hoc networks are too complex to allow analytical study for explicit performance expressions. We use the means of simulation to evaluate the routing approaches numerically and gather data to estimate their characteristics.

We study the performance of DSDV and AODV in a wide range of network contexts with varied network size, mobility, and traffic load. Both protocols utilize distance vector coupled with destination sequence number, and choose routes in the same manner. They are differentiated by the way in which they operate (i.e., proactive versus on-demand). Studying these two protocols gives insights into the differences between proactive and on-demand approaches. This analysis provides guidelines to improve these two specific protocols as well.

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1.2. Our contributions

The linear dependence between network topology change and host mobility is investigated by using statistical analysis. The suitable network contexts for DSDV and AODV are identified. We discover that AODV introduces 1.5 to 5 times protocol load as DSDV does, which contradicts the motivation for the on-demand approach. The major causes for packet drop are investigated by exploring packet traces. We argue that DSDV is plagued by network congestion. Based upon the idea of integrating congestion avoidance mechanisms with proactive routing protocols to improve routing performance, we propose congestion-aware distance vector (CADV) routing protocol. The preliminary study of CADV shows positive results. To our knowledge, it is the first research effort to take the power consumption as a routing performance metric.

1.3. Related work

Several simulation-based performance comparisons have been done for ad hoc routing protocols in the recent years. Das et al. [6] evaluate performance of ad hoc routing protocols based on the number of conversations per mobile node using Maryland Routing Simulator (MaRS). The performance comparison of two on-demand routing protocols: DSR and AODV is presented in [18], using ns2 (network simulator) [1] for the simulation. The pause time and the offered traffic load are taken as parameters. In [10], GloMoSim [20] is used for the performance study of the STAR, AODV, and DSR routing protocols, taking the pause time as the parameter. The authors point out that simulating the same protocol in different simulators may produce differences in the results. The performance of two location-based routing protocols for ad hoc networks is investigated by using ns2 and the effect of average moving speed in different scenarios is presented in [4]. An adaptive distance vector routing algorithm is proposed in [2], and its performance, compared with AODV and DSR, is studied. The offered traffic load and the simulation time are the input parameters.

Our work is to comprehensively investigate the characteristics of proactive and on-demand approaches by studying DSDV and AODV. In addition to identifying the suitable network contexts for each approach, we explore the causes for performance degradation. Based on the investigation, a new distance vector based routing protocol is proposed.

The rest of the paper is organized as follows. Section 2 briefly introduces DSDV and AODV protocols. Section 3 describes the simulation environment, including the mobility, traffic, energy models, and performance metrics. In section 4, the correlation between topology change and mobility is investigated. The experiment results and analysis are presented in section 5. Section 6 introduces the proposed CADV routing protocol and presents preliminary results of performance comparison of CADV, DSDV, and AODV. Section 7 concludes this paper.

2. Distance vector routing protocols for ad hoc networks

In a *distance vector* routing protocol, every host maintains a routing table containing the distances from itself to possible destinations. Each routing table entry contains two parts: the next hop to the destination, and the distance to the destination. The distance metric might be the number of hops, the delay, the quality of links along the path, etc. The chosen next hops lead to the shortest path to the destination.

DSDV extends the basic Bellman-Ford mechanism by attaching a sequence number that is originated by the destination to each distance. This destination sequence number is used to determine the “freshness” of a route. Routes with more recent sequence numbers are preferred for making packet forwarding decisions by a host, but not necessarily advertised to other hosts. For routes with the equal sequence number, the one with the smallest distance metric is chosen. Each time a host sends an update to its neighbors, its current sequence number is incremented and included in the update. The sequence number is disseminated throughout a network via update messages. DSDV requires each host to periodically advertise its own routing table to its neighbors. Updates are triggered when significant new routing information is available. Routes received in broadcasts are used to update the routing table. The receiver adds an increment to the metric of each received route before updating.

AODV routing protocol is also based upon distance vector, and uses destination sequence numbers to determine the freshness of routes. It operates in the on-demand fashion, as opposed to the proactive way of the DSDV protocol. AODV requires hosts to maintain only active routes. An *active route* is a route used to forward at least one packet within the past *active timeout* period. When a host needs to reach a destination and does not have an active route, it broadcasts a route request (RREQ), which is flooded in the network. A route can be determined when RREQ is received either by the destination itself or by an intermediate host with an active route to that destination. A route reply (RREP) is unicast back to the originator of RREQ to establish the route. Each host that receives RREQ caches a route back to the originator of the request, so that RREP can be sent back. Every route expires after a predetermined period of time. Sending a packet via a route will reset the associated expiry time.

3. Experiments

The most recent version (2.1b9a) of the network simulator ns2 is used for the simulation study. Each mobile host uses an omni-directional antenna having unity gain. The wireless interface works like the 914 MHz Lucent WaveLAN direct-sequence spread-spectrum (DSSS) radio interface [15]. WaveLAN is modelled as a shared-media radio with a nominal bit rate of 2 Mb/s, and a nominal radio range of 250m. The IEEE 802.11 distributed coordination function (DCF) is used as the MAC layer protocol. The implementation uses carrier sense multiple access with collision avoidance (CSMA/CA).

We use our own implementation of DSDV instead of the one provided by ns2, which has bugs that may lead to infinite loops. The implementation closely matches the specifications [17]. The AODV implementation is provided by ns2, which is according to the specifications [16]. This implementation enables expanding ring search and local repair.

3.1. Simulation settings

The *random waypoint* model [3] is used to generate movements for mobile hosts. At the beginning of a simulation, mobile hosts are randomly placed on a square field of 1000m x 1000m. Each host randomly chooses its destination and a moving speed ranging from 0 to the given maximum speed. All destinations and speeds are independent and identically distributed. After a host reaches the destination, it waits for a specified time (i.e., pause time), and then repeats the above steps. In this model, the mobility is represented by the maximum speed and the pause time.

The constant bit rate (CBR) traffic is used in the simulation. Each connection is specified as a randomly chosen source-destination (S-D) pair. The packet sizes are fixed as 512 bytes. The packet sending rate is 4 packets per second. Each connection starts at a time randomly chosen from 0 to 100 seconds.

Every host has an initial energy level at the beginning of a simulation. For every transmission and reception of packets, the energy level is decremented by a specified value, which represents the energy usage for transmitting and receiving. When the energy level goes down to zero, no more packets can be received or transmitted by the host. According to the manufacturer specifications [15], the power requirements of the WaveLAN card are shown in table 1, column 2. Column 3 shows the actual power requirements measured in [13], without any power management mechanism. In the simulations, we use the values in column 3. We let the initial energy of each host to be 4000 joules so that the energy level does not reach zero in the simulation period.

Table 1. Power requirements

State	Documented Requirements	Measured
suspended	0.00 W	0.00 W
receiving	1.48 W	1.52 W
transmitting	3.00 W	3.10 W

3.2. Performance metrics

The following four quantitative metrics are used to assess the performance:

- *Packet Delivery Ratio*: The ratio of the data delivered to the destinations (i.e., throughput) to the data sent out by the sources.
- *Average End-to-end Delay*: The average time it takes for a packet to reach the destination. It includes all possible delays in the source and each intermediate host, caused by routing discovery, queueing at the interface queue, transmission at the MAC layer, etc. Only successfully delivered packets are counted.
- *Normalized Protocol Load*: The routing load per unit data successfully delivered to the destination. The routing load is measured as the number of protocol messages transmitted hop-wise (i.e., the transmission on each hop is counted once). A unit data can be a byte or a packet.
- *Normalized Power Consumption*: The total consumed energy divided by the number of delivered packets. We measure the power consumption because it is one of the precious commodities in mobile communications. Wireless devices may consume over 50% of total system power for current handhold computers, and up to 10% for high-end laptops [13]. This poses challenging demands on the design of power-efficient routing protocols.

In the simulation, five scenarios are generated using the random waypoint model for each experiment, and the average values are used for analysis.

4. Correlation between topology change and mobility

The performance of a routing protocol is effected by the rate of topology change (i.e., the speed at which a network's topology is changing). The topology change can be represented as link change or route change. It is difficult to control the either of them directly in simulations. Our study demonstrates that:

- The link change and route change can be perfectly fitted into linear functions of the maximum speed when the pause time is 10 seconds.
- The link change and route change can be perfectly fitted into linear functions of the pause time when the maximum speed is 4 m/s.

Thus, the topology change can be indirectly controlled by varying mobility.

As shown in figure 1a and 1b, the maximum speed is treated as the predictor variable, and link change and route change as the response variables (with the pause time to be 10 seconds). The fitting curve $b_0 = \overline{Y} - b_1\overline{X}$ is obtained by using linear regression with least squares [7]. If we assume that the variations of the sample points about the line are normal, we can test the null hypothesis $H_0 : b_1 = 0$ using the *t-test* [7].

For the link change versus the maximum speed, $|t|$ = 24.1445. For the route change versus the maximum speed, $|t|$ = 21.1927. Both of them exceed the appropriate critical value of $t_{0.995}(10)$ = 3.169 (because 12 sample points are used for the linear regression, the degree of freedom is 10 = 12 - 2). Thus the hypothesis H_0 that linear relationships between the link change and the maximum speed, the route change and the maximum speed does not exist is rejected with 99% confidence. The dotted lines in figure 1a and 1b indicate the confidence interval of 95%. In plain words, the values of the link change and the route change lie within the specified intervals, respectively, and the statement is made with 95% confidence.

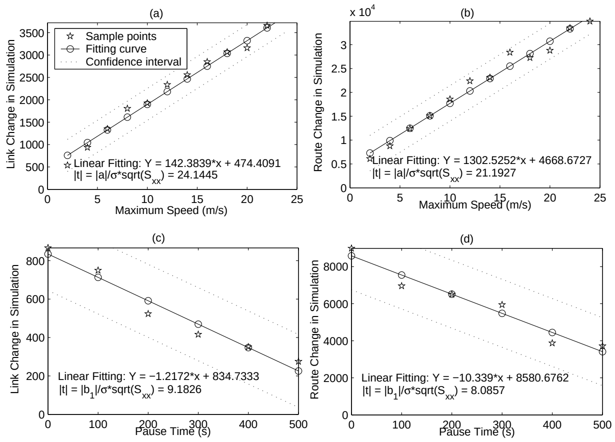

Figure 1. Topology change vs. mobility

Figure 1c and 1d show the linear regressions of the link change versus the pause time and the route change versus the pause time. H_0 hypothesis is also verified with t-test. Because only 6 sample points are used, the degree of freedom is 4. $t_{0.995}(4)$ = 4.604, while the observed $|t|$ is 9.1826 and 8.0857 respectively. Thus H_0 is rejected with 99% confidence as well. The dotted lines in figure 1c and 1d show the confidence intervals of 95%.

5. Results and analysis

To comprehensively measure the performance of a protocol, various network contexts are considered. The following parameters are varied in the simulation.

- *Host Mobility* is determined by the maximum speed (with 10 seconds pause time).
- *Traffic Load* is the number of the CBR connections.
- *Network Size* is measured as the number of mobile hosts. Since the simulation field is fixed, the network size also measures the density of mobile hosts.

5.1. Varying maximum speed

This set of experiments studies the impact of mobility on the performance metrics. The number of mobile hosts and the number of connections are both 30. The maximum speed ranges over $\{4, 8, 12, 16, 20, 24\}$ m/s.

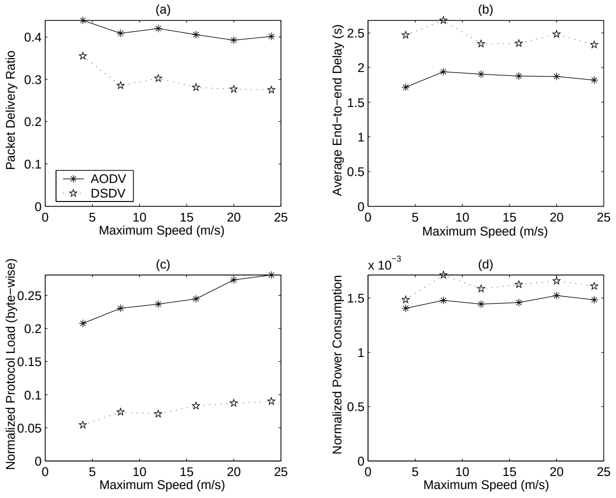

Figure 2. Varying maximum speed

As figure 2a shows, the packet delivery ratios for both protocols are less than 50% [1]. When mobility is low (i.e., the maximum speed is 4 m/s), AODV delivers about 43% of total packets, while DSDV delivers about 34%. As the mobility increases, the delivery ratios of both protocols drop gradually, but DSDV has a little bigger drop.

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[1] The implementation of IEEE 802.11 has been revised in ns2 since version 2.1b9. We have observed up to 100% more packet drop with the new implementation in two identical simulations. It, however, does not affect the performance comparison in this paper, because it has same impact on different routing protocols.

It is interesting that DSDV has a higher delay than AODV does in all cases, which seems to contradict to the advantage of the proactive approach. It results from the implementations of the protocols. Although both implementations apply the drop-tail approach for packet queues, AODV poses a limit on the time a packet can be queued, which currently is 30 seconds. Thus the delay of any received packet is bounded. DSDV keeps packets in queues no matter how long they have stayed. It delivers the older packets rather than the younger ones, and therefore increases the average delay.

Because a DSDV protocol packet contains many routes, while an AODV protocol packet contains at most one route (e.g., RREQ), we compare the byte-wise protocol load. DSDV introduces a significantly (3-4 times) lower protocol load than AODV does (figure 2c). The bad performance of AODV results from the following factors:

- Each host discovers routes individually.
- Unicasting RREP to the originator of the RREQ prevents valuable routing information from being propagated to other hosts.
- AODV treats network topology as a directed graph. It might need to discover two different directions for the same path twice due to a short reverse route lifetime.

As illustrated in figure 2d, the normalized power consumptions for both protocols are rather stable. Although DSDV introduces a much lower protocol overhead, it consumes more power. AODV "wins" in the way it handles link breaks. When a broken link of a route is detected, a route error (RERR) packet is sent to the source. Every host along the path notices the broken link immediately, and drops or queues packets locally. DSDV treats a broken link as a significant routing information and triggers a routing update, there is a minimum time interval between two triggered updates. The information about a broken link is delayed at each host. In the meantime, those hosts that have not received this information keep sending packets that will be dropped eventually to their next hops. A remarkable amount of power is consumed unnecessarily.

5.2. Varying number of connections

The next set of experiments demonstrates the effect of the traffic load. The number of mobile hosts is 30, the maximum speed is 4 m/s, and the pause time is 10 seconds. The number of connections varies from 10 to 80, increasing 10 each time.

The delivery ratio of AODV (figure 3a) drops dramatically from more than 90% to about 28% when the number of connections increases from 10 to 50, while that of DSDV drops from about 80% to about 20%. For more than 50 connections, the ratios of both DSDV and AODV drop more gradually because the network has already been fully loaded.

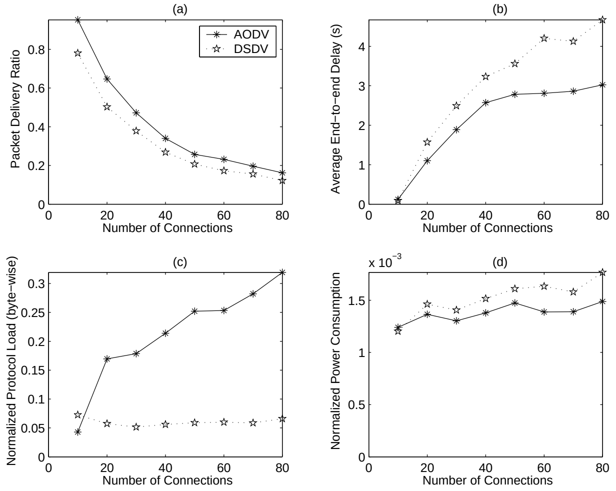

Figure 3. Varying number of connections

As figure 3b shows, for 10 connections, DSDV and AODV have similar delay. The delays for both protocols increase rapidly with the number of connections (from about 0.1 second to 3 and 2.5 seconds for 40 connections, respectively). After the number of connections reaches 40, the delay of AODV grows gradually, while that of DSDV increases almost as fast as before.

For DSDV, the number of protocol packets is determined mostly by the network size and mobility. The normalized protocol load stays fairly stable at 0.06 with an increasing number of connections (figure 3c). The protocol load of AODV increases sharply as the number of connections increases. AODV performs better than DSDV at 10 connections. At 80 connections, the protocol load for AODV is about 4 times higher than for DSDV.

As shown in figure 3d, DSDV consumes more power than AODV does except for 10 connections. The power consumptions for both protocols increases gradually from 10 connections to 80 connections (the increase is about 50% for DSDV, and about 25% for AODV).

5.3. Dropped packets

Since the delivery ratio drops dramatically with an increase in traffic load, we are interested in investigating the reasons for packet drop. We check this by studying the ns2 trace files.

Figure 4 shows the number of packets dropped for four reasons. A packet is dropped due to congestion if the packet buffer at MAC layer is full when it arrives. When a collision is detected, CSMA does a exponential backoff, which

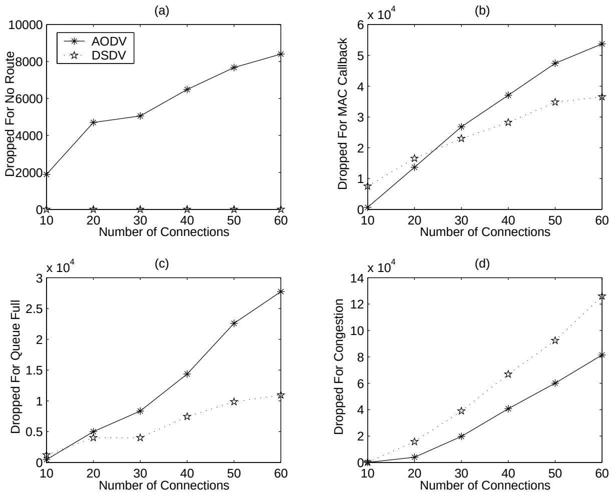

Figure 4. Dropped packets

increases the delay for sending the packet. It makes the packet buffer to be full quickly.

For DSDV, no packet is dropped due to “no route” to the destination. It is guaranteed by the design the protocol. For AODV, the number of packets dropped due to “no route” increases from 2000 to 10000, as shown in figure 4a.

As figure 4b and 4c show, for 10 connections, AODV almost does not drop packets due to a MAC callback (i.e., the next hop is not a neighbor now), or queue being full. However, the number of packets dropped for AODV increases with the number of connections at a rate higher than DSDV. DSDV drops fewer packets than AODV does for the above two reasons in most cases.

From figure 4, we can calculate that more than half of the dropped packets result from congestion. DSDV performs better for the first three reasons, but worse than AODV for avoiding congestion. Although both DSDV and AODV do not utilize any congestion control or avoidance mechanism to balance traffic load, AODV in fact distributes the data traffic more evenly in the network. AODV tries to build the shortest route when it originates a request, but it keeps the route as long as it does not break, even if a shorter route is available at a later time. In contrast, DSDV tends to always send packets via the shortest routes. Forwarding packets through the shortest routes will likely push traffic to several heavily burdened hosts and congest the network.

5.4. Varying number of mobile hosts

The last set of experiments investigates the effect of the network size. All hosts move randomly at the maximum speed of 4 m/s. The pause time between two movements is 10 seconds. The number of mobile hosts increases from 20 to 70 by 10s. The number of connections is equal to the number of hosts.

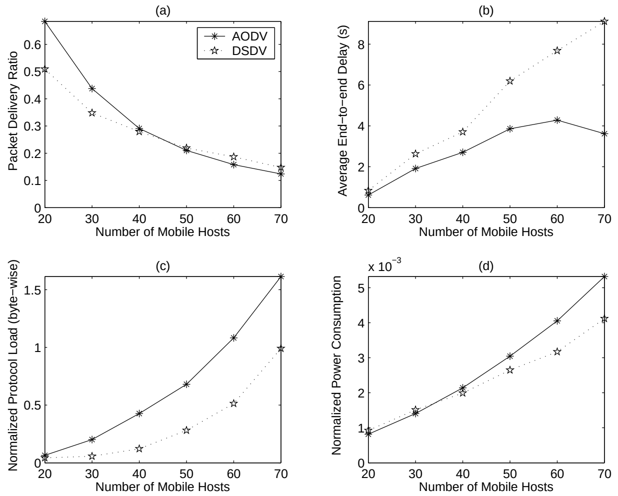

Figure 5. Varying number of mobile hosts

The delivery ratio of AODV decreases faster than that of DSDV does with the number of mobile hosts (figure 5a). AODV has a better performance in a sparser network (fewer than 40 hosts), and worse performance in a denser one. Figure 5b indicates that AODV outperforms DSDV in terms of end-to-end delay.

DSDV and AODV have similar protocol loads for 20 mobile hosts. Both of them introduce more overhead as the number of hosts increases, with the load for AODV growing faster than for DSDV (figure 5c).

Both DSDV and AODV have similar power consumption in a sparse network (figure 5d). For DSDV, the increase of power consumption is nearly linear with the host number. The power consumption for AODV increases faster than for DSDV. For 70 hosts, AODV consumes 33% more energy than DSDV does per 1k-byte delivered data.

From the results provided in figure 5, we can tell that DSDV is more scalable with respect to the number of hosts. It seems that 40 hosts per square kilometer is the turning point. For more than 40 hosts, DSDV equals or outperforms AODV for all metrics (the average delay is an exception that should not be considered).

6. Congestion-aware routing protocol - CADV

Although the published result [11] showed that on-demand protocols outperform proactive protocols and are better suited for mobile ad hoc networks, the proactive protocols have the following advantages.

- *Better support for Quality of Service (QoS):* Proactive protocols timely propagate network conditions (available bandwidth, delay, etc.) throughout the system, so that appropriate QoS decisions, including admission control, traffic shaping, and route choosing, can be made.

- *Better support for anomaly detection:* Proactive protocols constantly exchange the network topology information. It enables real-time detection and reaction to malicious behaviors and attacks such as false distance vector attack and false destination sequence attack [19].

As shown in section 5.4, DSDV performs better than AODV in denser networks, which demonstrates potential scalability of the proactive approach with respect to the number of mobile hosts. Figure 4 reveals that this approach is plagued by congestion, the dominant reason of performance decrease. To address the congestion issues, we propose a new proactive distance vector based ad hoc routing protocol called congestion-aware distance vector (CADV).

6.1. Overview

A mobile host in an ad hoc network can be viewed as a single server queueing system. The delay of sending a packet is positively correlated with congestion. In CADV, each routing entry is associated with an *expected delay*, which measures congestion at the next hop. Every host estimates the expected delay based on the mean of delay for all data packets sent in a past short period of time. Currently, the length of the period is equal to the interval between two periodical updates. The expected delay is computed as $E[D] = \frac{\sum D_i}{n} L$, where n is the number of sent packets and L is the length of MAC layer packet queue. $E[D]$ estimates the time a newly arrived packet has to wait before it is sent out. When a host broadcasts an update to neighbors, it specifies the delay it may introduce.

A routing decision is made based on the distance to the destination as well as the expected delay at the next hop. CADV tries to balance traffic and avoid congestion by giving priority to a route having low expected delay. For example, hosts A and B both advertise a route to the destination. If the expected delay at host A is significantly less than that at host B, A will be chosen as the next hop (given B is not A's next hop), even if the route via A is one hop longer than the one via B. When making routing decisions, a function $f(E[D], distance)$ is used to evaluate the value of a route. Various routing policies can be implemented by replacing this function.

A CADV routing module consists of three components.

- *Traffic Monitor* monitors traffic going out through the link layer. Currently, it keeps track of the average delay for sending one data packet in recent period of time. The time period is specified by the route maintenance component.
- *Traffic Control* determines which packet is the next to send or drop, and reschedules packets if needed. At present, it supports a drop tail FIFO queue and provides functionality to re-queue packets.
- *Route Maintenance* is the core component. Its functionalities include exchanging information with neighbors, evaluating and maintaining routes, managing the traffic monitor and traffic control components.

The detail of CADV routing protocol is omitted due to space constraints, please refer to [14].

6.2. Preliminary results

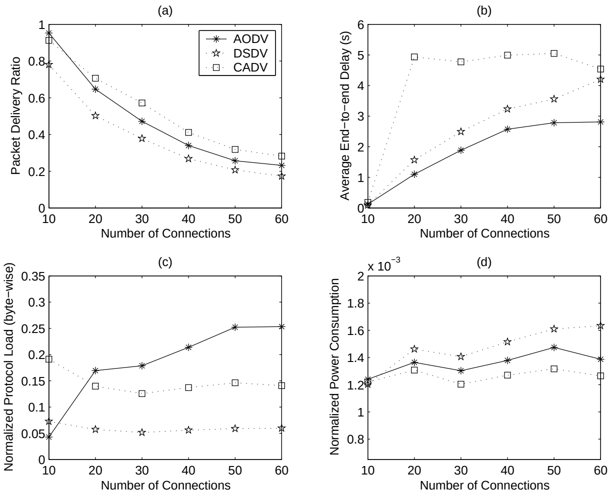

Figure 6. Comparison of three protocols

A preliminary study is conducted to investigate the performance of CADV with the number of connections. The maximum speed is 4 m/s, and the number of mobile hosts is 30. Figure 6 illustrates the performance comparison of CADV, DSDV, and AODV. AODV performs better than CADV only for 10 connections, where congestion is not likely to occur. For other cases, as shown in figure 6a, CADV outperforms AODV by about 5% in terms of packet delivery ratio. The tradeoff for the improvement is shown in figure 6c. CADV introduces about 2.5 times protocol load as DSDV does. However, the protocol load is still lower than that introduced by AODV when the number of connections is greater than 10. CADV introduces higher end-to-end delay than AODV and DSDV do when the number of connections is greater than 10 (figure 6b), because it may choose longer route to forward packets. The delay is rather stable with the increase of the number of connections. Figure 6d shows that CADV consumes less power. It results from packet rescheduling done by the traffic control component. When a neighbor becomes unreachable, all packets in the MAC layer packet buffer whose next hop is that neighbor will be rescheduled. This mechanism saves power by preventing a host from sending unnecessary Request-To-Send (RTS) messages.

7. Conclusions

Conclusion 1: For the movements of mobile hosts generated by the random waypoint model, the link change and route change are, with a very high probability, linear functions of the maximum speed, and linear functions of the pause time, respectively. The maximum speed does not affect much the performance of DSDV and AODV at the range from 4 m/s to 24 m/s.

Conclusion 2: In less stressful situations, AODV outperforms DSDV for all metrics except for normalized protocol load. DSDV performs better than AODV does in denser networks with a higher traffic load. In general, we can state: (1) The protocol load for the proactive routing protocols (such as DSDV) grows as the number of hosts increases, while that of the on-demand routing protocols (such as AODV) increases with the number of source-destination (S-D) pairs. The proactive approach performs better when the number of S-D pairs is close to the number of hosts. (2) The on-demand approach consumes less power, because it propagates the link break information faster, thus it avoids sending packets that are dropped eventually. (3) Network congestion is the dominant reason for packet drop for both proactive and on-demand approaches.

Conclusion 3: The preliminary study of CADV routing protocol demonstrates that the performance of proactive routing protocols can be improved by integrating with congestion avoidance mechanisms. Currently, only delay at the next hop and distance to the destination are considered when making routing decisions. We are working towards a complete version of CADV that takes advantage of other information such as available queue length, delay on a path, etc. A comprehensive study will be conducted to investigate how different congestion predication and load balancing mechanisms can cooperate with CADV to reduce congestion in ad hoc networks.

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