1-10-2005

The behavior of MANET routing protocols in realistic environments

K. Chin
University of Wollongong, kwanwu@uow.edu.au

The behavior of MANET routing protocols in realistic environments

Abstract

This paper presents an analysis of MANET routing protocols' behavior in realistic channel fading scenarios. The motivation of this study was due to our previous testbed experimentations where we found that AODV and DSDV's performance did not match simulation results, primarily due to the use of a simple radio propagation model that did not take into account transient links caused by small-scale fading. Henceforth, we extended the ns-2 simulator with a realistic radio propagation model, that incorporated Rayleigh fading, to gain insights into the impact of transient links on AODV, DSR, and DSDV's behaviour. Our simulation studies explain each protocol's key behavior that leads to the following conclusions: (1) routing through stable routes is important, (2) hop count is the root cause of poor performance, (3) the 2-ray ground radio propagation model is inappropriate for simulating ad-hoc protocols in indoor environments, and (4) local recovery is important.

Disciplines

Physical Sciences and Mathematics

Publication Details

This article was originally published as: Chin, K, The Behavior of MANET routing protocols in realistic environments, Asia-Pacific Conference on Communications, 3-5 October 2005, 906-910. Copyright IEEE 2005.

2005 Asia-Pacific Conference on Communications, Perth, Western Australia, 3 - 5 October 2005.

The Behavior of MANET Routing Protocols in Realistic Environments

Kwan-Wu Chin
Telecommunications Information Technology Research Institute
University of Wollongong
Northfields Ave, NSW, Australia 2522
kwanwu@uow.edu.au

***Abstract*— This paper presents an analysis of MANET routing protocols' behavior in realistic channel fading scenarios. The motivation of this study was due to our previous testbed experimentations where we found that AODV and DSDV's performance did not match simulation results, primarily due to the use of a simple radio propagation model that did not take into account transient links caused by small-scale fading. Henceforth, we extended the *ns-2* simulator with a realistic radio propagation model, that incorporated Rayleigh fading, to gain insights into the impact of transient links on AODV, DSR, and DSDV's behaviour. Our simulation studies explain each protocol's key behavior that leads to the following conclusions: (1) routing through stable routes is important, (2) hop count is the root cause of poor performance, (3) the 2-ray ground radio propagation model is inappropriate for simulating ad-hoc protocols in indoor environments, and (4) local recovery is important.**

I. Introduction

Mobile **a**d-hoc **net**work (MANET) routing protocols play an important role in applications involving mobile wireless devices that are deployed in an ad-hoc manner. Examples of MANET applications include military applications and in emergency situations[1]. In all these applications, MANET routing protocols must provide a communication platform that is solid, fault tolerant and dynamic to wireless characteristics. To this end, it is crucial that we perform comprehensive studies on the suitability and feasibility of recently proposed MANET routing protocols in a realistic environment.

This paper addresses the behavior of Ad-Hoc On Demand Distance Vector (AODV) [2], Destination-Sequenced Distance-Vector (DSDV) [3] and Dynamic Source Routing (DSR) [4] ad-hoc routing protocols over networks with unreliable links. Unreliable links have not received much attention in the past due to the prevalent use of the 2-ray ground radio model in simulation studies of ad-hoc routing protocols. The 2-ray ground model [5] only describes large-scale fading of transmitted signals, where the receiving power is directly proportional to the distance between transmitter and receiver. The only time when a link breaks is when a node migrates out of range. Hence, the dynamics of an ad-hoc network are determined by the mobility model used to simulate link-breakage, i.e., nodes moving in and out of each other's communication range. In this paper we will show that in addition to mobility, channel fading plays an important role in determining protocol performance.

We augmented the popular *ns-2* simulator with the Rayleigh fading model that models small-scale fading accurately. Then we studied the performances of AODV, DSR and DSDV over the new radio propagation module. Our simulation results concurred with our practical experience in that we observed similar behaviors and performances in all tested routing protocols. Our simulation studies also identified several issues concerning the operation of ad-hoc routing protocols over unreliable links. We found that HELLO messages and route optimization also degraded performance, causing routing protocols to spend a significant number of their time performing route updates (or route requests) due to the frequent selection of transient links. In addition, we found that caching, as performed by DSR, helped increase throughput and reduced route request overheads.

The remainder of this paper is organized as follows. In Section II we provide the motivation of this paper, and show how we extended the *ns-2* simulator to incorporate a realistic channel fading model that matches that of our test-bed. Then in Section III we present the performance of AODV, DSDV and DSR in various network topologies. We then present works related to ours in Section IV before presenting our conclusions in Section V.

II. Motivation

The motivation for this paper stems from our practical experience with the AODV and DSDV routing protocols on a real testbed. From our practical experience with two MANET routing protocols [6] we found that the key factor that determined ad-hoc routing protocol performance was link reliability. Especially so when transient links occured due to small scale fading effects. The occurrence of transient links caused nodes to conclude that shorter routes to given node existed, which given the short lifetimes of transient links caused any route established to fail almost immediately after it was established. Throughout our experiments we found that AODV and DSDV frequently chose links that turned out to be transient links due to these links offering shorter hop count, resulting in high route maintenance, and thus poor performance. Even if a route was established, the amount of data carried was small since the established route was likely to fail.

Follow on from our test-bed experience we decided to further our understanding of MANET routing protocols via simulations. We augmented the *ns-2* simulator with the Rayleigh channel fading model [5]. The Rayleigh model is used widely and has been widely validated through empirical studies [7]. The Rayleigh model describes the reception of N multipath waves at the receiver having equal power. Given large N, it can be shown that through the central limit theorem that the in-phase and quadrature components of the signal tend to be Gaussian of zero-mean. Thus, the received signal, $r(t)$ can be modeled using the following equation:

$$r(t) = \sqrt{x(t)^2 + y(t)^2} \qquad (1)$$

where x(t) and y(t) are Gaussian random variables. The distribution of received signal can be shown to have a Rayleigh distribution [5]. Figures 1 and 2 compare the different between the signal strength generated using our Rayleigh model and data collected from our testbed. In our implementation of the Rayleigh model in-phase and quadrature components were generated using the Gaussian distribution with zero mean and unity variance.

The log-normal link-budget model [5], was used to calculate the mean signal strength at a given transmitter and receiver separation,

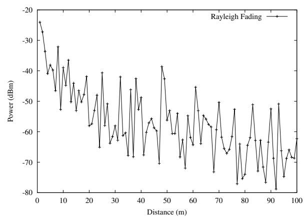

Fig. 1: Rayleigh Model

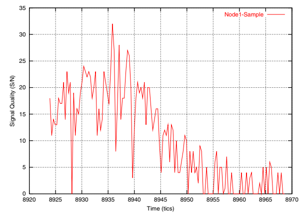

Fig. 2: Signal Strength Measured from Testbed

i.e., the large scale fading component. Then, the Rayleigh model was used to attenuate the signal strength. This attenuated signal was then passed back to *ns-2*'s physical layer which then determined whether a packet can be received. Throughout our simulation, we use $n = 2.4$ $X_\sigma = 9.6$ corresponding to an office with soft partitions [5].

III. Performance of Ad-Hoc Routing Protocols

Once the Rayleigh model is implemented we proceeded with experiments that mirrored those on our test-bed. In all our simulations we experimented with the DSR, AODV, and DSDV routing protocols. To illustrate the effects of a realistic radio channel, we used three different network topologies. The first experiment investigated the effect of varying the distance between nodes on packet loss. For the second experiment we ran each routing protocol over a static five node topology which investigated the behaviors of ad-hoc protocols in the presence of transient links.

A. Effects of T-R Separation

In this experiment we had two nodes being separated increasing further apart. One node was designated as the source and the other as the receiver. For each simulation runs, we increased the distance by five meters and we recorded the packet loss ratio. The routing protocol used was AODV[1].

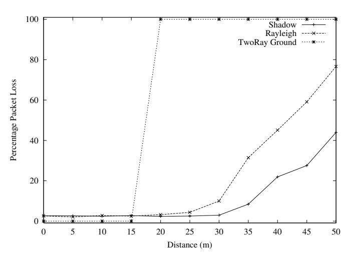

Fig. 3: Percentage packet loss with increasing distance between two nodes.

Figure 3 shows the results from the three simulations using the three models. The 2-ray ground model has a *cut-off* point in packet reception which was around 15m. In the other models, we see that packet reception was still possible however with higher packet loss. This agreed with our observations from running AODV and DSDV on our testbed where reception of packets were possible outside the transmission range but with varying probability of reception. Maltz et al. [8] also reported similar behaviors during their experimentation with DSR. They found that there were able to receive packets outside the specified range of their Wavelan cards. As we will show in the next section, the assumption of a *cut-off* point in packet reception had adverse consequences on performance.

[1]Other protocols exhibited similar results

B. 5 Nodes Static Topology

Figure 4 shows the linear topology used to investigate the effects of small-scale fading model and its impact on existing ad-hoc routing protocols. This topology was chosen to coincide with our testbed topology, thus served as a point of reference in our simulation studies. More importantly, a simple topology enabled us to gain a better understanding of the complex interactions between routing protocols and transient links.

Initially we used the 2-ray ground model to gauge the minimum distance between nodes such that each node was only within range of its immediate neighbors. This had the effect of reliably routing packets successfully through all nodes since each node was able to hear its neighbors reliably. Figure 4 shows the "stable route" used. In our simulation runs of the 2-ray ground model, no packets were lost and all packets were routed hop-by-hop through $Node_0$ to $Node_4$, in other words using the "stable route" shown in Figure 4. However, this behavior did not match practical experiences.

To show the effect of Rayleigh fading, we setup the following experiments. $Node_0$ set to transmit 1000 packets from a CBR source to $Node_4$ at a rate of 20KB/s. Each simulation ran for 1000 seconds and was performed 10 times with the Rayleigh model. Note that the nodes in this experiment were not mobile. This topology may not conform to other topologies widely used in MANET literature, however in our case this topology simplified the analysis of routing protocol behavior in the presence of frequent transient links. Similar behavior could be obtained where mobile nodes moved in and out of each other's transmission range with a given probability. However, this would have made the analysis difficult since we would have had to ensure that the effects were not caused by mobility itself.

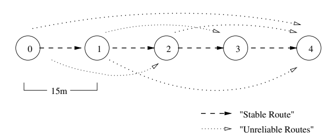

Fig. 4: Five nodes topology separated 15m apart.

In each simulation run we collected the following information on a per-route [2] basis: (1) route lifetime (network and receiver's perspective), (2) number of successful and failed packet transmissions, and (3) number of times a route was used. In simulations involving AODV and DSDV, the route metric (i.e., hop count to the destination) was also logged. To record the path taken by a packet we augmented the packet structure in the simulator to include an array containing nodes that the packet had traversed. The array was then printed before the packet was dropped by the MAC layer of an intermediate node or at the destination upon arrival.

The following sections explain further how each statistic were collected and calculated.

- Number of successful or failed packet transmission over routes of a given length. For example, assume routes {0 1 4} and {0 2 4} have 10 packets transmitted successfully and 10 failed transmission. Therefore, for routes of hop count two, we have 10 successful and 10 failed transmissions.
- The lifetime (or uptimes) of routes from the network and receiver's point of view. The rationale behind having two views was as follows. Take for example a router node-1 that tries to forward on the route {0 1 2}. It discovers that link between node-1 and node-2 is down, therefore a route error is sent back to

[2]E.g., {0 1 4}, {0 1 2 3 4}

the source by which time the link has reestablished. The source then reconstructs a new route which happens to be {0 1 2}. If the receiver has been receiving through route {0 1 2} previously, it may not know that route {0 1 2} has gone down. Hence, from the receiver's perspective the route {0 1 2} has not gone down, but from the router's view route {0 1 2} may have gone down a number of times.

In our simulation, the route lifetime from the receiver's point of view was computed as follows. When packets arrived at the receiver, we recorded the time and the corresponding route. For example, {route, simulation-time}. If the next packet arrived on a different route, the uptime of the previous route was calculated as the difference between current time and time the last route was instantiated. After that, a new entry containing the new route and the current time was created.

The lifetime from the network's view was calculated from when the route was established to when a node's MAC layer in the network drops a packet traversing a given route. The calculation of network route lifetime was similar to what was described for the case of receiver's view, but instead the calculation was performed by forwarding nodes (or routers) as opposed to the receiver.

From these metrics (lifetimes from two views) we quantified how many times a given route was tried and failed. In DSR, a route tended to remain up but was not used when shorter routes were present. For example, the "stable route" shown in Figure 4 would have been used initially. If $Node_1$ detected that it had a direct route to $Node_4$ (i.e., $Node_1$ can hear $Node_4$'s HELLO messages), it would send a RREP containing the shorter route {0,1 4} to $Node_0$. In this case, since no MAC error was generated, the "stable route" remained up albeit not in active use.

The above scenario was only true for DSR. In AODV only one route was used, therefore if a route failed, no other routes were present, thus new RREQ messages were broadcast each time a link on a route failed. For the same scenario, DSDV's route lifetime from the network's view indicated that the route was down. Despite this packets were still forwarded using the failed route given that routing tables were only updated periodically.

- The downtime has the converse meaning to a route's up time as described previously. This metric was calculated by taking the difference between the recorded time when the route went down to the time when it came up again.

  The downtime could also be estimated from the Rayleigh model using the average fading duration and level crossing rates of a given channel [5]. However, since we were interested in the downtime of an entire route instead of on a per-link basis, we did not derive downtime analytically.
- Per-route throughput (network and receiver's perspective). When a route was first established, we recorded the number of packets that arrived on the given route. This data was then averaged over 10 simulation runs for each route.

  The difference between the results obtained from the network and receiver's point of view was as follows. From the receiver's view, the packet counter for a route stopped when a packet arrived on a different route. From the network view, the packet counter stopped when any node along the path detected an error, in other words the MAC layer of a node was unable to transmit to the next hop.

1) Route Lifetime: The route lifetime measured how long a given route was up. As mentioned, there were two views to this metric: receiver and network perspectives. This metric was important since the routing protocol could end up choosing the same route after a route failure. From the receiver's point of view, packets may be arriving on the same route, thus the route would be deemed up. However, from the network's view, the route and have failed numerous times.

Tables I and II shows the route lifetime from the network and receiver's level respectively. In Tables I and II, we see that for DSDV and DSR the longer the route, the more reliable it was. Although the route lifetime increased with hop count, we show in the next section that routing was mainly performed on the shorter hop count, i.e., short-lived routes. Note that route lifetime does not reflect the number of packets delivered, it only indicates the average lifetime of a route. For example, a rarely used stable route could remain up for some time thereby resulting in high number of packets being delivered, while at other times the rarely used route would die as soon as it was formed.

Hop Count	1	2	3	4
AODV	None	0.12	0.58	0.14
DSDV	0.08	0.13	0.16	0.31
DSR	0.29	0.33	14.15	19.48

TABLE I: Network's perspective of route lifetime (in seconds) vs. Hop count

Hop Count	1	2	3	4
AODV	None	189.67	412.99	267.89
DSDV	263.26	242.47	234.45	163.90
DSR	0.28	0.31	0.22	0.48

TABLE II: Node 4's perspective of route lifetime (in seconds) vs. Hop count

Intuitively the route lifetime should be less affected by fading with increased route length, however this was not the case with the routing protocols investigated. This was mostly due to the preference of shorter hop count routes. Thus, from both Table I and II, one sees that the lifetime of higher hopcount routes was not the highest with the exception of DSR. In DSR the longest route was often available in the cache and rarely used. When choosing a route, DSR tried the shortest route first, and when a route failed, the next shortest route was chosen. On occasion when the stable route was used, only a few packets were transmitted through it before a node downstream informed the sending node of a shorter route to the destination. From a destination's perspectives (Table II) the routes remained short-lived regardless of route length.

In DSR, when a packet transmission failed, a node's cache was consulted and an alternative was chosen. The source route in the packet was then changed to reflect the new route. This resulted in a shorter route length from the receiver's perspective. Referring to Figure 4, assume $Node_0$ has a source route of {0 1 3 4} to $Node_4$. If a packet transmission error occurs at $Node_1$ (link from $Node_1$ and $Node_3$ dies), assuming the route {1 4} is available in $Node_1$'s cache, the source route header of the packet is updated with the route {1 4}. From the receiver's perspective, the packet arrived on a one hop route, i.e., route {1 4}.

In Table II we see that the single hop route lifetime for DSDV was the highest. This was because the route {0 4} was repeatedly used for packet transmission. However, this route had the lowest lifetime from the network's perspective (Table I), lasting on average 0.08 seconds. This low value was due to MAC layer feedback when a link died. In the case of route {0 4}, transient link occurrence was the highest, thus link breakage was very likely. As the routes became longer, we see that route breakage was less likely. However, due to the use of hop count as a route metric, there were less packets traveling on longer routes. Note that, the lifetime shown in Table I does not reflect DSDV's routing table. Therefore, the one hop route existed in the routing table until the next update. The upside to this is that the node continued to route packets over the broken link albeit with a high probability of error. Another observation with DSDV was that the variety of routes to the destination was small compared to AODV and DSR. This was attributed to the use of periodic updates where new routes were only generated on a periodic basis [3] compared to on-demand protocols where each new route could be generated with every new RREQs.

With AODV, the lifetime was at its maximum when the route length was three hops. These results were obtained with HELLO messages turned on. This meant link breakages were only detected by the loss of three succesive HELLO messages. In addition to detecting link breakage, the HELLO messages also provided reachability information thereby enabling routes to be shortened. For example, assume that the route $\{0\ 1\ 3\ 4\}$ has been established. If $Node_0$ hears HELLO message from $Node_4$, $Node_0$ concludes that it had a one hop link to $Node_4$. Thus, the next packet will be transmitted over route $\{0\ 4\}$.

We mentioned that the stable route (for topology shown in Figure 4) existed within node's cache in DSR. We observed that once all other routes in the cache had failed, the stable route was used. However, its use was short lived due to the intermittent reception of RREPs from downstream nodes. Given that the topology was static, we conjecture that an improvement could be made if tapping or eavesdropping was disabled. This would prevent downstream nodes from supplying the source with a shorter route. The use of HELLO messages in AODV has the same effect since they acted as a feedback mechanism to any node in the network to shorten its route.

An examination of the trace data generated from our simulations, DSR had the highest number of unique routes to the destination, followed by AODV and DSDV. DSR used the next shortest route from its cache whenever a route failed. Since nodes along the path to the receiver cached different permutations of routes to the destination, a variety of routes could be seen. Since AODV and DSDV do not maintain multiple routes to a given destination, the number of unique routes was less.

2) Packet Transmissions vs. Hop Count: Table III shows the number of packets transmitted over a given route length between Nodes 0 and 4. The main trend from Table III was that as the route became longer, fewer packets were dropped. This was not suprising since routes with higher hop counts used hops of shorter length that were more reliable. Unfortunately, the routing protocols attempts to minimize hop count resulted in the majority of the packets being routed over shorter routes, with a route length of one or two hops.

Hop Count	1	2	3	4
DSDV	387 (4774)	1230 (4304)	429 (352)	39 (4)
AODV	0 (1061)	386 (3004)	1408 (621)	1132 (109)
DSR	1396 (1459)	6608 (1507)	2138 (667)	291 (42)

TABLE III: Number of packet Success (Failed) Transmission vs. Hop count.

Due to duplicates the number of packets actually received was actually higher than those sent. The likely cause of this was the loss of MAC acknowledgment packets. Further duplication was also caused by the buffering of packets by routing protocols when a link-layer break was detected.

3) Throughput: This section examine how many packets were transmitted on average over a given route once when it had been established. As before we present the results from the receiver and network's perspectives. Table IV and V shows the results computed for each routing protocol.

Hop Count	1	2	3	4
DSDV	17.82	24.85	24.56	40
AODV	None	32.78	152.21	227.4
DSR	2.32	2.31	2.33	2.35

TABLE IV: Average Throughput (in packets) Per-Route (End-User)

Hop Count	1	2	3	4
DSDV	1.10	1.31	1.74	2.2
AODV	None	1.54	2.21	5.65
DSR	1.41	1.46	1.32	1.48

TABLE V: Average Throughput (in packets) Per-Route (Network)

The DSR results above agreed with the route lifetime results shown in Tables I and II where different route lengths had almost equal lifetimes and also throughput. We see that routes of three and four hops resulted significantly in higher routes of one and two hops. From the network's view, the throughput was much lower. Most routes once established were only able to route one to two packets before they failed. The main conclusion from this obsevertion was that short routes were torn down due to Rayleigh fading whereas longer routes were shortened when the routing protocols detected route with a smaller hop count.

Protocol	Min	Route	Max	Route
DSDV	2	(0 3 4)	88	(0 2 3 4)
AODV	2	(0 2 3 4)	840	(0 2 3 4)
DSR	1	(0 1 4)	26	(0 1 3 4)

TABLE VI: Min and Max Value of packets routed over a given hop length route

Protocol	Min	Route	Max	Route
DSDV	1	(0 2 4)	10	(0 1 4)
AODV	1	(0 2 4)	39	(0 1 4)
DSR	1	(0 1 3 4)	19	(0 3 4)

TABLE VII: (Network) Min and Max Value of packets routed over a given hop length route

Tables VI and VII show the routes which carried the minimum and maximum number of packets. In general, the throughput on a per-route basis favoured longer routes over shorter ones. From the receiver's perspective, most of the packets arrived over routes of three hops. Conversely from the network's view there was no "reliable" route that exhibited high throughput.

The average number of RREQs generated for the simulations in this section (no mobility) for AODV, DSR and DSDV was 12.9, 640.1 and 213.1 respectively. Note that for DSDV we only recorded the number of updates received by the source. AODV had the lowest number of RREQs due to its use of HELLO messages to detect link breakage. However, when link-layer feedback was used the average number of RREQs generated by AODV was 708.8. This high number of RREQs was partly due to the frequent use of short-lived routes as shown in Table III. DSDV required the fewest updates due its use of periodic updates that were similar to AODV's HELLO messages.

[3]In ns-2, whenever the MAC layer reported a transmission error, the corresponding link was not removed from the routing table.

The use of these periodic mechanisms buffered the transient nature of the links going up and down. It should be noted that this would likely impair protocol performance once mobility is introduced. DSR suppressed RREQ transmissions by using its cached routes when available. Hence, delaying RREQ transmission until it was absolutely necessary to do so. However, the use of eavesdropping of packet transmission meant transient links were also recorded and sent to the source resulting in a cache consisting of stable and unstable routes.

In summary, the above results showed that the interaction of Rayleigh fading with each of the protocols resulted in transient links, poor performance, and increased routing overheads. In each case (with the exception of DSDV) routes involving multiple transient links were torn down almost immediately after they had been established.

C. Route Length on Performance

We concluded our experiments by investigating the effect of route length on throughput. The topology used was similar to that in Figure 4, with the exception that the number of nodes between the source and the receiver was increased by one after each set of simulation runs. Nodes were set 30m apart. The experiments stopped when there were 10 nodes in the topology. $Node_0$ was set to transmit 1000 packets to the furthest node from the source. For each run we measured the number of packets received successfully and the number of route requests (updates for DSDV).

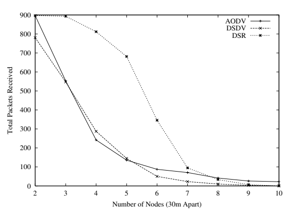

Fig. 5: Total Packets Received

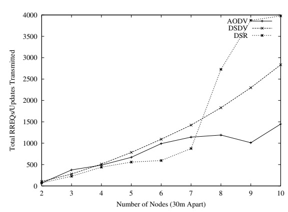

Fig. 6: Number of RREQs/Updates Transmitted

The results here showed that as the route length grew, the likelihood of establishing an end-to-end route became impossible when the Rayleigh model was used. This was because the routing protocols preference of shorter hop count made it became increasingly likely there were multiple unreliable links in each route. It would be beneficial to have a local retransmission scheme in such a scenario. The downside was, with local retransmission, packets may not traverse the optimal path from source to destination. For example, the packet may be forwarded upstream (toward the source) before taking another route to the destination. Hence, packets were likely to remain in the network for a long time. Nevertheless, we found that the existence of multiple paths as in DSR helped to reduce the need for RREQs.

Figure 6 shows the aggressive nature of DSR when transmitting packets, as indicated by the number of RREQs transmitted with increasing nodes. On the other hand, AODV had fewer RREQs due to its damping mechanism that limited the number of RREQs sent at any given time interval. From our simulations we found damping of RREQ messages had a negative impact on throughput. As demonstrated by DSR, continuous RREQs helped keep the cache fresh with multiple routes to the destination. Thereby increasing the chances of successful packets delivery.

IV. Related Work

The authors of [9], [10] and [11] have similarly reached the conclusion that MANET routing protocols perform badly in realistic scenarios. Our findings complement these works in that we studied the behaviour of these routing protocols using different metrics such as route lifetime from both the network and receiver perspectives, and also identified the interactions of fading channels on DSR's caching mechanism. Therefore, our work provides new insights on the operation of each routing protocols studied, especially the effects of their respective features on the operation of MANETs.

V. Conclusion

We have presented simulation results complementing our test-bed observations that reinforce the importance of link reliability in MANET operations. Specifically, we have shown that hop based MANET routing protocols perform poorly over transient links, and link fades lead to frequent lost of connections that resemble node mobility. Amongst the protocols we experimented, DSR showed the best performance compared to AODV and DSDV at the expense of increased overheads due to its aggressive nature in acquiring routes and the retransmission of packets using cached routes when active routes failed. AODV, however, required the source to perform route establishment whenever link(s) on the established route failed. Our results showed that AODV required a significant amount of time to establish a reliable route. When more than a few hops were required AODV had difficulty establishing routes. On the other hand, DSDV was not as significantly affected by transient links when compared to DSR and AODV. This was mainly due to its use of periodic updates. Since the routing table did not reflect link failures until the next periodic update, numerous packets were forwarded on the route specified in the table. Thereby enabling some of the packets to get through provided the fade time of the link was short and the neighboring node was still within range.

VI. Acknowledgment

This work was done when the author was with the Motorola Australia Research Center. Thanks go to the ZHANET team for improving the quality of this paper.

References

[1] E. M. Royer and C.-K. Toh, "A review of current routing protocols for ad-hoc mobile wireless networks," *IEEE Personal Communications*, vol. 6, pp. 46–55, Apr. 1999.
[2] C. E. Perkins, E. M. Royer, and S. R. Das, "Ad hoc on-demand distance vector (AODV) routing." draft-ietf-manet-aodv-06.txt, July 2000.
[3] C. Perkins and P. Bhagvat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers," *ACM Computer Communications Review*, pp. 234–244, Oct. 1994.
[4] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad-hoc wireless networks," in *Mobile Computing*, 1996. Kluwer Academic Publishers, Chapter 5, pages 113-118.
[5] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Prentice-Hall, 1996.
[6] K.-W. Chin, J. Judge, A. Williams, and R. Kermode, "Implementation experiences with MANET routing protocols." ACM/SIGCOMM Computer Communications Review, Nov. 2002.
[7] H. Hashemi, "The indoor radio propagaton channel," *Procedings of IEEE*, vol. 81, July 1993.
[8] D. A. Maltz, J. Broch, and D. B. Johnson, "Experiences designing and building a multi-hop wireless ad-hoc network testbed." Techical Report, CMU-CS-99-11, Mar. 1999.
[9] M. Takai, J. Martin, and R. Bagrodia, "Effects of wireless physical layer modeling in mobile ad-hoc networks," in *Proceedings of the 2001 ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHOC'2001)*, Oct. 2001.
[10] R. J. Punnoose, P. V. Niktin, and D. D. Stancil, "Efficient simulation of ricean fading within a packet simulator," in *IEEE Vehicular Technology Conference*, (Boston, USA.), Sept. 2000.
[11] J. Zhao and R. Govindan, "Understanding packet delivery performance in dense wireless sensor networks," in *The First ACM Conference on Embedded Networked Sensor System (Sensys'03)*, (Los Angeles, USA), Nov. 2003.