The Effects of MAC Protocols on Ad hoc Network Communication

Elizabeth M. Royer*, Sung-Ju Lee†, and Charles E. Perkins‡
* Department of Electrical and Computer Engineering, University of California, Santa Barbara
† Department of Computer Science, University of California, Los Angeles
‡ Communication System Laboratory, Nokia Research Center

Abstract ***– As mobile computing gains popularity, the need for ad hoc routing protocols will continue to grow. There have been numerous simulations comparing the performance of these protocols under varying conditions and constraints. One question that arises is whether the choice of MAC protocol affects the relative performance of the routing protocols being studied. This paper investigates the answer to that question by simulating the performance of three ad hoc routing protocols when run over different MAC protocols. It is determined that the choice of MAC layer protocol does, in fact, affect the relative performance of the routing protocols.***

I. INTRODUCTION AND MOTIVATION

The number and variety of wireless devices and applications has dramatically increased within the past few years. As these products begin to permeate the marketplace, the need to provide communication between them is becoming increasingly important. In an effort to establish and maintain routing paths in these ad hoc mobile networks, numerous unicast and multicast routing protocols have been designed. To determine the relative merits of the protocols, there have recently been investigations comparing the performance of these protocols under various conditions and constraints [2], [4], [7], [10].

There has been some discussion as to the correct Medium Access Control (MAC), or link layer (level-2 of the OSI reference model), protocol to use for channel access when performing these simulations. Many early protocol simulations utilized the Carrier Sense Multiple Access (CSMA) protocol [9]. Since the advent of the IEEE 802.11 protocol [5], however, most protocol evaluations have elected to run over this channel access protocol, since it provides both prevention and detection of the hidden terminal problem [16].

It is the intent of this paper to compare the performance of different ad hoc routing protocols to determine whether the selection of the MAC layer affects the relative performance of ad hoc routing protocols. It is likely that the performance of the protocols will be best when run over IEEE 802.11, due to its channel acquisition characteristics. However, the question is whether protocols degrade proportionately to each other when run over the other MAC layer protocols. To determine whether the selection of MAC protocol is a factor when comparing routing protocols, this paper explores the behavior of different unicast routing protocols when run over varying MAC protocols.

The remainder of this paper is organized as follows. Section II provides an overview of each of the routing protocols used in the study. Section III then in turn describes each of the MAC protocols to be utilized. The simulation environment is described in Section IV-A, and then the results are presented in Section IV-B. Finally, Section V concludes the paper.

II. ROUTING PROTOCOLS

To analyze the effects of MAC protocols, three ad hoc routing protocols are selected for study. The first is the Wireless Routing Protocol [11], which is a distance vector table-driven protocol. Table-driven protocols periodically exchange routing table information in an attempt to maintain an up-to-date route from each node to every other node in the network at all times.

The second protocol studied is the Fisheye State Routing protocol [12]. This protocol is a variation on the basic link state table-driven algorithm, whereby update message entries are exchanged between nodes at different frequencies, depending on their distance from each other. Routing information for a node's immediate neighborhood is kept the most up-to-date, while that for nodes further away is less accurate. This method helps reduce the table size in routing table exchanges while still maintaining routes to each network node.

Finally, the Ad hoc On-Demand Distance Vector Routing protocol [13], [14] is included as an example of an on-demand protocol. On-demand protocols only establish routes when they are needed by a source node, and only maintain these routes as long as the source node requires them.

The following sections provide overviews of the protocols.

A. Wireless Routing Protocol

The Wireless Routing Protocol (WRP) [11] maintains routing information through the exchange of triggered and periodic updates. When a node notices a link break with one of its neighbors, it broadcasts an update message containing the distance and second-to-last hop information for each destination for which the routing information has changed. The second-to-last hop information is used to reduce routing loops. A neighboring node receiving an update message modifies its distance table entries and checks for new paths through other nodes. Any new paths are relayed back to the original node so that routing consistency is maintained throughout the network. Furthermore, a node successfully receiving an update message transmits an acknowledgment back to the sender, indicating the link is still viable.

In the event that a node has not transmitted anything within a specified period of time, it must transmit a *Hello* message (instead of exchanging the entire route table) to ensure connectivity. Otherwise, the lack of messages from a node indicates the failure of that link. When a node receives a Hello message from a new node, it sends that neighbor a copy of its routing table information.

B. Fisheye State Routing

Fisheye State Routing (FSR) [12] is a variation of link state table-driven routing which maintains a topology map at each node. To reduce the overhead incurred by control packets, FSR modifies the link state algorithm in three ways. First, link state packets are not flooded; only neighboring nodes exchange link state information. Second, the link state exchange is time-triggered, not event-triggered. Finally, instead of transmitting all routing table information at each iteration, FSR uses different exchange intervals for different entries in the table. More precisely, entries corresponding to nodes that are nearby (within a predefined *scope*) are propagated to 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 networks since link state exchange overhead is kept low. As mobility increases, routing information for remote destinations may become less accurate; however, as a packet travels nearer to its destination, it is forwarded by nodes with increasingly more accurate routing information.

C. Ad hoc On-Demand Distance Vector Routing

The Ad hoc On-Demand Distance Vector (AODV) Routing protocol [13], [14] is an on-demand routing protocol which utilizes a route discovery cycle for the establishment of routes. A node desiring a route to some destination broadcasts a *Route Request* (RREQ) packet across the network. When either the destination or an intermediate node with a current route to the destination receives the RREQ, it responds by unicasting to the source node a *Route Reply* (RREP). Once the source node receives the RREP, it can begin using the route for data packet transmissions.

Route maintenance in AODV takes the form of *Route Error* (RERR) messages. When a link break in an *active* route occurs, the node upstream of the break sends a RERR to any upstream neighbors which were using that link to reach the destination. The RERR message lists each destination which is now unreachable due to the loss of the link. When a source node receives a RERR message, it may re-initiate route discovery if it still requires the route.

III. MAC PROTOCOLS

The MAC protocols selected for this study represent a progression in protocol development. Each one builds upon the previous one through the addition of either control overhead or carrier sensing in order to mitigate the effects of the hidden terminal problem and achieve better network throughput. Table I summarizes the mechanism of each MAC protocol included in the study. Packet sensing (PSMA) implies that carrier sensing is not performed before packet transmissions. The following sections describe each of the MAC protocols utilized in this evaluation.

TABLE I
SUMMARY OF MAC PROTOCOLS

Protocol	Mechanism
CSMA	CSMA
MACA	PSMA/RTS/CTS
FAMA	CSMA/RTS/CTS
IEEE 802.11 DCF	CSMA/CA/RTS/CTS/ACK

A. Carrier Sense Multiple Access

The Carrier Sense Multiple Access (CSMA) [9] protocol is the most primitive of the MAC protocols utilized in this study. The CSMA version used is non-persistent CSMA. In this protocol, a node senses the channel for ongoing transmissions before sending a packet. If the channel is already in use, the node sets a random timer and then waits this period of time before re-attempting the transmission. On the other hand, if the channel is not currently in use, the node begins transmission.

B. Multiple Access with Collision Avoidance

The Multiple Access with Collision Avoidance (MACA) [8] protocol improves upon CSMA by taking steps towards the avoidance of the hidden terminal problem. The protocol defines Request-To-Send (RTS) and Clear-To-Send (CTS) control packets to announce an upcoming transmission. A node wishing to send a data packet broadcasts a RTS message containing the length of the data frame that will follow. Upon receiving the RTS, the receiver responds by broadcasting a CTS packet which also contains the length of the upcoming data frame. Any node hearing either of these two control packets must be silent long enough for the data packet to be transmitted. In this way, neighboring nodes will not transmit during the data transmission, and the number of collisions is reduced. Fig. 1 illustrates the basic idea behind the RTS/CTS control messages. When S broadcasts the RTS message, both nodes A and B receive it and delay their transmission attempts. Similarly, when node D responds with a CTS, nodes B and C also receive the CTS and are silent during the data transmission.

In the event that two nodes send simultaneous RTS frames to the same node, the RTS transmissions collide and are lost. If this occurs, the nodes which sent the unsuccessful RTS packets set a random timer utilizing the binary exponential backoff algorithm for the next transmission attempt.

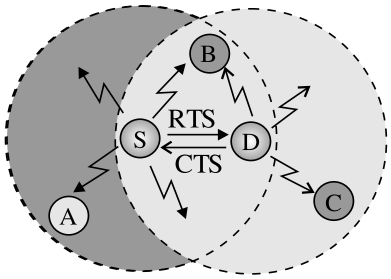


Fig. 1. Effect of RTS/CTS Control Messages.

C. Floor Acquisition Multiple Access

The Floor Acquisition Multiple Access (FAMA) variant utilized in this study is FAMA-NTR (Non-persistent Transmit Request) [6]. FAMA-NTR builds upon the MACA protocol by adding non-persistent carrier sensing to the RTS-CTS exchange. Before transmitting a RTS frame, a node first listens to the channel to determine if it is already in use. If the channel is busy, the node calculates a random backoff period to wait before sensing the channel again. The addition of this carrier sense to the control packet exchange aids in the prevention of control packet collisions.

D. IEEE 802.11 DCF

The IEEE 802.11 MAC protocol specifies a Distributed Coordination Function (DCF) [5] which is based on the same RTS/CTS message exchange for unicast data transmissions as the previous MAC protocols. Where 802.11 differs, however, is in its use of collision avoidance before RTS transmission, and its requirement of an acknowledgment (ACK) transmission by the receiver after the successful reception of the data packet. The inclusion of the ACK allows immediate retransmission if necessary by verifying that the data packet was successfully received. In the case of node mobility, the ACK may also aid in the detection of hidden-terminal interference that was not detectable when the CTS message was sent.

IV. SIMULATIONS

A. Simulation Environment

The simulations were performed using the GloMoSim Network Simulator developed at UCLA [1]. This simulator models the OSI seven layer network architecture and includes models of IP and UDP routing. The simulator also allows for network node mobility, thereby providing for simulation of mobile ad hoc networks.

Node movement is modeled by the random waypoint mobility model [2]. Nodes move at a speed between 0 and 10m/s. When the node arrives at its randomly chosen destination, it rests for some pause time. It then chooses a new destination and begins moving once again. The pause times are varied between 0 and 300 seconds. Each MAC protocol/routing protocol/pause time combination is run for five different initial network configurations.

TABLE II
PARAMETER VALUES

	Parameter	Value
WRP	HELLO Interval	1 sec
	Max Allowed Missed HELLOS	4
	Update ACK Timeout Interval	1 sec
	Retransmission Timer	1 sec
	Retransmission Counter	4
FSR	Scope	2 hops
	HELLO interval	5 sec
	Max Allowed Missed HELLOS	3
	INTRASCOPE UPDATE interval	5 sec
	INTERSCOPE UPDATE interval	15 sec
AODV	HELLO Interval	1 sec
	Max Allowed Missed HELLOS	3
	RETRANSMIT TIME	750 msec

Each run is executed for 300 seconds of simulation time and models a network of 100 nodes in a 1500m$\times$1500m area. Each node has a transmission radius of 250m. The propagation model is the free space model [15] with threshold cutoff. This model has a power signal attenuation of $1/d^2$, where d is the distance between nodes. The radio model also has capture capability, whereby a node may successfully receive a packet even in the presence of noise. There are 20 data sessions between randomly selected sources and destinations. The bandwidth is 2 Mb/s, the data packet size is 512 bytes, and packets are sent at a rate of four per second by each source.

Table II shows the parameter values used for the routing protocols in the experiments. The majority of the parameter values for WRP were taken from those suggested by the designers of the protocol and specified in [11]; however, a few of the values were modified to maximize WRP's performance in the simulation environment. The timer values were set so as to send more frequent connectivity updates but less frequent retransmissions than suggested. The former modification is needed because of the high mobility speed in the experiments, and the latter is due to the fact that with the MAC protocols selected, retransmitting at twice the round trip time would flood the MAC buffer, in addition to causing unnecessary collisions with cross traffic in the channel.

Using the FSR protocol, a node includes in its route update message entries for nodes outside its scope every Interscope update interval. Entries for nodes inside the scope are included in every update message transmission. Note that the Interscope update interval is much larger than that of Intrascope update.

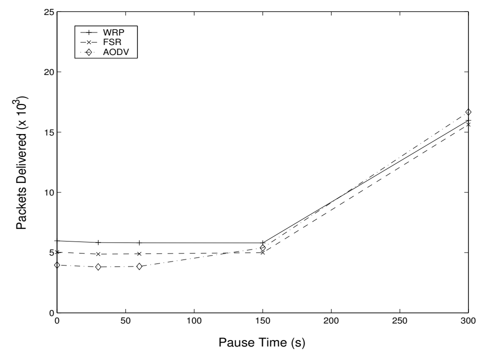
When AODV is run over IEEE 802.11, Hello messages do not need to be used due to the MAC layer feedback of unreachable next hops. When combined with the other MAC protocols, however, Hello messages are needed since such feedback is not available. When Hello messages are used, a node transmits a Hello once each second as long as the node has not broadcast any other control messages during the previous second. Additionally, promiscuous listening mode is enabled for AODV whenever Hello messages are utilized. This allows AODV to determine more quickly when link breaks have occurred. The RETRANSMIT TIME value in Table II is the maximum allowable time between promiscuous receptions of data packets from neighbors on active paths.

B. Results

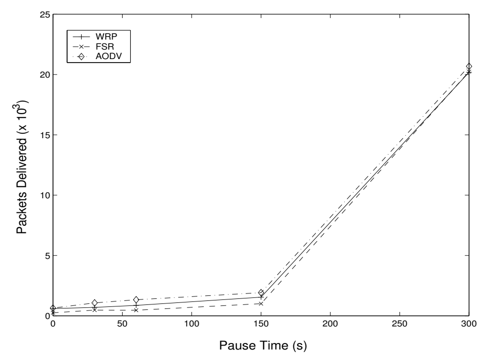
To determine whether the selection of MAC protocols affects the relative performance of the protocols, three results are examined: the number of data packets received by their destinations, the control packet overhead, and the normalized routing load. The control packet overhead is computed by counting the number of hop-wise control packet transmissions. The normalized routing load is calculated by taking the total number of per-hop control packet transmissions, and dividing this by the number of data packets successfully delivered to their destinations.

Fig. 2 illustrates the number of data packets delivered to destinations in each of the networks. The relative performances of WRP and FSR remains fairly constant while that of AODV tends to vary by the MAC protocol used. When run over CSMA, WRP performs best for the higher mobility scenarios; however, while using IEEE 802.11, AODV outperforms the other protocols. The protocols achieve nearly the same number of delivered data packets when combined with the MACA and FAMA protocols, with AODV performing slightly better using the FAMA MAC protocol. The protocols have better overall performance using CSMA than using MACA or FAMA because of the RTS/CTS messages. MACA sources transmit RTS packets whenever they have a data packet to send without first sensing the channel. This results in an increase in packet collisions and hence decreased throughput. The collision avoidance mechanism incorporated into IEEE 802.11 for the transmission of RTS packets aids in the reduction of the number of collisions. Consequently, more data packets reach their destinations. Further analysis of the MAC protocols under UDP can be found in [3].

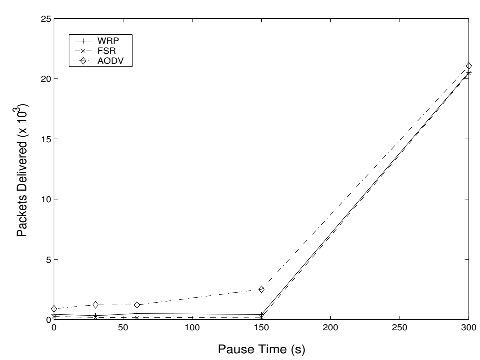
The number of hop-wise control packet transmissions during each simulation is shown in Fig. 3. Because FSR uses periodic messaging regardless of the underlying MAC protocol, the amount of control overhead generated by this protocol remains relatively constant over the different simulations. WRP has both triggered and periodic updates, and hence the amount of control overhead increases as mobility increases (i.e., as the



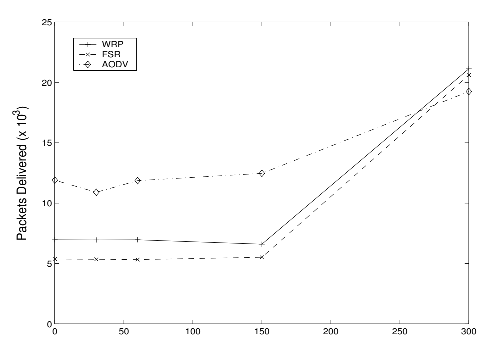
(a) CSMA



(b) MACA

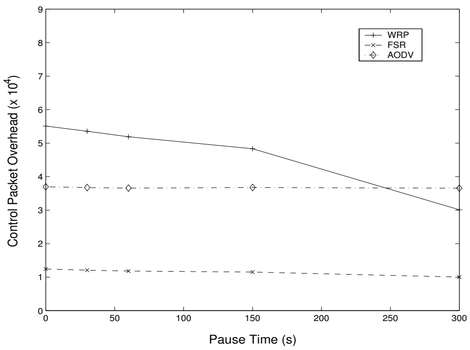


(c) FAMA

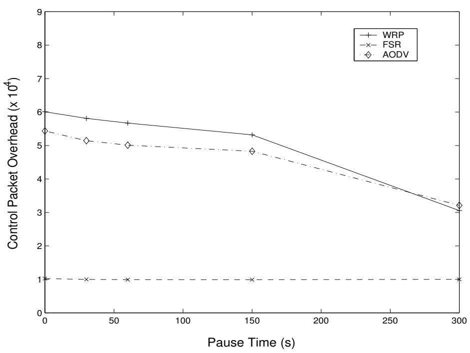


(d) IEEE 802.11 DCF

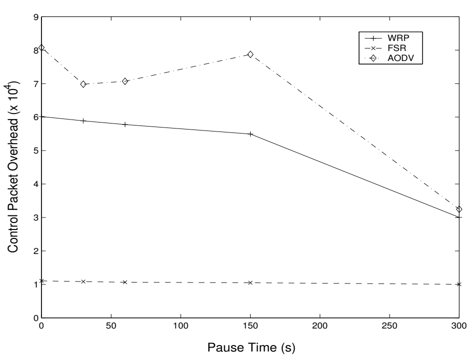
Fig. 2. Data Packets Delivered.



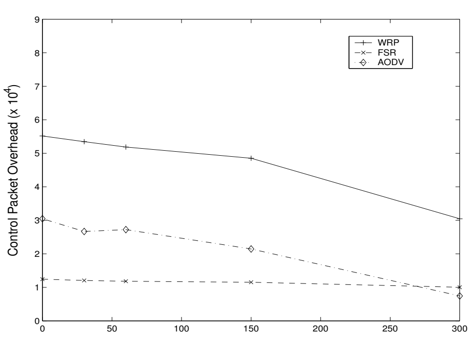
(a) CSMA



(b) MACA

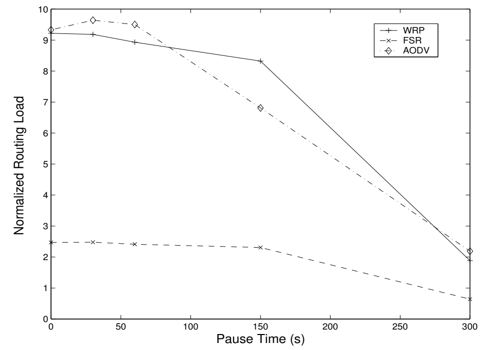


(c) FAMA

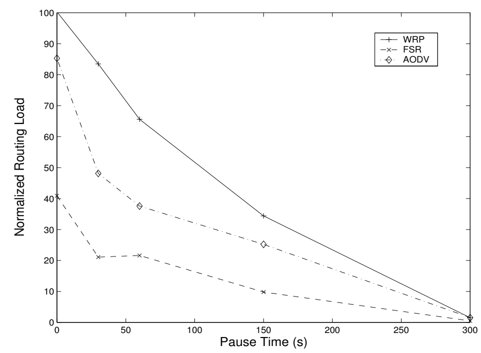


(d) IEEE 802.11 DCF

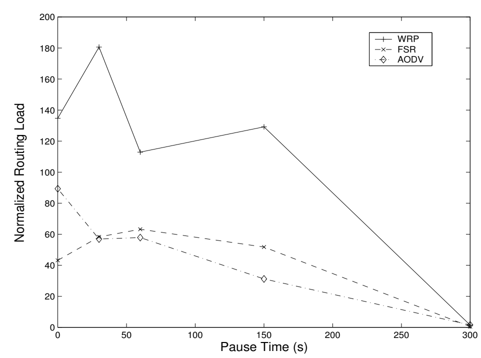
Fig. 3. Control Packet Overhead.



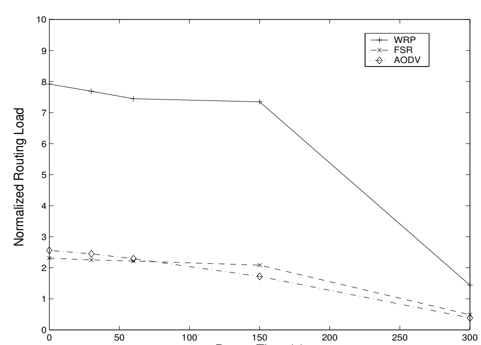
(a) CSMA



(b) MACA



(c) FAMA



(d) IEEE 802.11 DCF

Fig. 4. Normalized Routing Load.

pause time becomes shorter). AODV is the only protocol significantly affected by the MAC layer. When run over CSMA, MACA and FAMA, AODV must utilize Hello messages in order to maintain connectivity. Hence it is expected that the number of control messages in these simulations is greater than in the IEEE 802.11 simulation. Additionally, the amount of control overhead generated by AODV is directly related to the number of routes it is maintaining. Because there are so many packet collisions when utilizing the CSMA MAC layer protocol, AODV is not able to maintain as many routes. Hence the control overhead is lower for this simulation. As the number of routes AODV attempts to maintain increases, however, the amount of control traffic generated similarly increases.

The normalized routing load (NRL) is a measure of a protocol's efficiency. This measure is important because link layer protocols in ad hoc networks are contention-based. This result is shown in Fig. 4. WRP consistently has a greater NRL than FSR, and has greater NRL than AODV in all but a few cases of CSMA. The ratio of control messages generated by WRP and FSR remains approximately constant regardless of the underlying MAC protocol. Note the variation in y-axis scaling. The NRL quantitative measure varies because the throughput of WRP and FSR is dependent upon the MAC protocols used. Hence, this metric aids in the analysis of how efficiently the routing protocols utilize routing packets to deliver data packets. AODV is most efficient when used with IEEE 802.11. This result is expected since AODV does not need Hello packet transmissions when combined with IEEE 802.11.

V. CONCLUSIONS

This paper has presented a performance comparison of the WRP, FSR, and AODV routing protocols when combined with varying MAC protocols. The relative performance of the WRP and FSR protocols does not show notable variation when run over the different MAC protocols. Neither routing protocol requires operational changes dependent upon the underlying MAC protocol, and the results show that their relative performance remains approximately constant. This leads to the conclusion that table-driven protocols act similarly with different MAC protocols, although further study of additional table-driven protocols is needed to validate this conclusion.

Because AODV requires periodic Hello messaging when run over link layer protocols that do not provide feedback when the next hop is unreachable, the amount of control traffic generated with these MAC protocols is considerably greater than when it is run over IEEE 802.11 DCF. AODV proves to be sensitive to the functionality of the MAC protocol, and hence its relative performance varies depending upon which MAC layer is used.

Table-driven and on-demand protocols may react differently depending upon the MAC protocol used; however, the question of whether two different on-demand ad hoc routing protocols would exhibit the same variation due to MAC layer effects remains open. The results show that the MAC protocol selected for simulation study is a key component of the performance of a routing protocol, and this aspect must be taken into consideration when doing comparative studies of the performances of routing protocols.

References

[1] L. Bajaj, M. Takai, R. Ahuja, K. Tang, R. Bagrodia, and M. Gerla. GlomoSim: A Scalable Network Simulation Environment. Technical Report CSD Technical Report, #990027, UCLA, 1997.

[2] J. Broch, D. A. Maltz, D. Johnson, Y.-C. Hu, and J. Jetcheva. A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols. *Proceedings of the* 4^{th} *Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom)*, pages 85–97, Dallas, Texas, October 1998.

[3] M. Correa, K. Tang, and M. Gerla. Isolation of Wireless Ad hoc Medium Access Mechanisms Under UDP. *Technical Report*, University of California, Los Angeles, Computer Science Department, 990035, June 1999.

[4] S. R. Das, C. E. Perkins, and E. M. Royer. Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks. *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, pages 3–12, Tel Aviv, Israel, March 2000.

[5] IEEE Standards Department. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Standard 802.11–1997*, 1994.

[6] C. L. Fullmer and J.J. Garcia-Luna-Aceves. Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks. *Proceedings of the Conference on Applications, Technologies, Architectures, and Protocols for Computer Communication (SIGCOMM)*, pages 262–273, 1995.

[7] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark. Scenario-based Performance Analysis of Routing Protocols for Mobile Ad-hoc Networks. *Proceedings of the* 5^{th} *ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom)*, pages 195–206, Seattle, WA, August 1999.

[8] P. Karn. MACA - A New Channel Access Protocol for Packet Radio. *Proceedings of the ARRL/CRRL Amateur Radio Ninth Computer Networking Conference*, pages 134–140, 1990.

[9] L. Kleinrock and F. A. Tobagi. Packet Switching in Radio Channels: Part I-Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics. *IEEE Transactions on Communications*, 23(12):1400–1416, December 1975.

[10] S.-J. Lee, W. Su, J. Hsu, M. Gerla, and R. Bagrodia. A Performance Comparison Study of Ad Hoc Wireless Multicast Protocols. *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, pages 565–574, Tel Aviv, Israel, March 2000.

[11] S. Murthy and J. J. Garcia-Luna-Aceves. An Efficient Routing Protocol for Wireless Networks. *Mobile Networks and Applications*, 1(2):183–197, October 1996.

[12] G. Pei, M. Gerla, and T.-W. Chen. Fisheye State Routing: A Routing Scheme for Ad Hoc Wireless Networks. *Proceedings of the IEEE International Conference on Communications*, pages 70–74, New Orleans, LA, June 2000.

[13] C. E. Perkins and E. M. Royer. Ad-hoc On-Demand Distance Vector Routing. *Proceedings of the* 2^{nd} *IEEE Workshop on Mobile Computing Systems and Applications*, pages 90–100, New Orleans, LA, February 1999.

[14] C. E. Perkins, E. M. Royer, and S. R. Das. Ad Hoc On Demand Distance Vector (AODV) Routing. *IETF Internet Draft, draft-ietf-manet-aodv-05.txt*, March 2000. (Work in Progress).

[15] T. S. Rappaport. *Wireless Communications, Principles & Practices*, chapter 3, pages 70–74. Prentice Hall, 1996.

[16] F. A. Tobagi and L. Kleinrock. Packet Switching in Radio Channels: Part-II - The Hidden Terminal Problem in Carrier Sense MultipleAccess Models and the BusyTone Solution. *IEEE Transactions on Communications*, 23(12):1417–1433–20, December 1975.