# IEEE 802.11 over Multi-hop Wireless Networks: Problems and New Perspectives

Hung-Yun Hsieh and Raghupathy Sivakumar
GNAN Research Group
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA
{hyhsieh, siva}@ece.gatech.edu

*Abstract*—**The IEEE 802.11 standard for medium access control in wireless local area networks has been adopted as the de-facto medium access control standard in multi-hop wireless networks. In this paper we contend that the unique characteristics that differentiate multi-hop wireless networks from local area wireless networks render the IEEE 802.11 MAC protocol inefficient in the former class of networks. Through simulations we substantiate our arguments, and consider the key changes required to adapt the IEEE 802.11 MAC protocol for multi-hop wireless networks.**

***Keywords—ad-hoc networks; multi-hop wireless networks; band of contention; fairness model; protocol dependence***

## I. INTRODUCTION

The IEEE 802.11 standard [1] defines a medium access control protocol for wireless local area networks that solves the unique problems of such environments like the *hidden terminal* problem. While the IEEE 802.11 standard was primarily designed for the distributed operation of a local area wireless network, it has also been assumed as the de-facto standard in a different class of wireless networks called *ad-hoc networks*. Ad-hoc networks are stand-alone wireless networks that lack the services of a backbone infrastructure. They consist only of a collection of mobile stations, where the mobile stations double up as forwarders or routers for other mobile stations in the network. Such networks were initially designed for use in military and emergency-relief applications. Lately, the ad-hoc network model has also been proposed and used in other applications such as sensor networks, personal area networks, and regular wireless network applications by virtue of their better spatial reuse characteristics in comparison to the conventional cellular wireless network model [2]. Future wireless network standards including the fourth generation wireless systems are expected to incorporate the ad-hoc model in some form [3]. Given the de-facto acceptance of IEEE 802.11 as the MAC protocol in multi-hop wireless environments, understanding its performance in such environments has gained significance. In this paper, we investigate the performance of the IEEE 802.11 medium access protocol in an ad-hoc multi-hop wireless network, compare its behavior against that of ideal MAC protocols, profile its interaction with higher layer protocols and suggest approaches to improve its performance over a multi-hop network environment.

Although wireless LANs and ad-hoc networks share a few similar characteristics, they differ in the following respects: (i) Unlike in wireless LANs where the diameter of the network is typically small, ad-hoc networks can have a large diameter (e.g. a 1500m by 1500m grid with 100 nodes and a transmission range of 250m exhibits a diameter of approximately 10). (ii) Paths in ad-hoc networks typically consist of multiple hops. Hence, routing is an important factor that affects network performance, and the efficiency of the routing protocol used can indirectly depend on the underlying MAC protocol. (iii) In a wireless LAN, since the traffic generated by each node is typically its own, providing per-node fairness is tantamount to providing per-flow fairness, especially if nodes perform intelligent scheduling. However, in an ad-hoc network where nodes cooperatively act as relays for other flows, per-node fairness is potentially unfair to heavily loaded nodes. We contend that the above differences necessitate changes in the IEEE 802.11 protocol that are specific to the ad-hoc network environment. Through simulation results we substantiate our argument that the IEEE 802.11 medium access protocol does not perform well in multi-hop wireless environments. We identify the critical issues with the protocol and therein provide guidelines for a medium access control protocol that does not suffer from such issues.

Specifically, we study two properties of the IEEE 802.11 medium access control protocol:

- *Band of Contention:* The area of the network inhibited by each per-hop transmission such that no other transmissions or receptions can occur within that area. While this property will have a direct impact on the throughput utilization in the network, we demonstrate that its impact has a wider scope including network fairness, and amount of performance gains achieved through better routing protocols.
- *Fairness Model:* The IEEE 802.11 MAC protocol supports a per-node fairness model. We show that such a model significantly lowers both the network throughput and fairness performance. We consider an alternative fairness model and study the performance improvements gained through the new model.

The rest of the paper is organized as follows: In Section II, we present the different algorithms that we use in this paper for both the evaluation of the IEEE 802.11 MAC protocol and studying alternative approaches to improve network performance. In Section III we study and compare the performance of the IEEE 802.11 MAC protocol with other alternative approaches. Finally, in Section IV we discuss some related work and conclude the paper.

## II. ALGORITHMS AND PROTOCOLS

### A. *The IEEE 802.11 Medium Access Control Protocol*

The IEEE 802.11 MAC protocol is based on the carrier sense multiple access with collision avoidance (CSMA/CA) approach [1]. When a source *S* wants to transmit to a destination *D*, it senses its local channel. If the channel is idle, it transmits a *request-to-send* (RTS) control frame to the destination and inhibits its neighboring nodes from accessing (and thus interfering on) the channel. If the local channel around *D* is also free, *D* replies with a *clear-to-send* (CTS) control frame, thus inhibiting its neighboring nodes from using the channel. Upon receiving the CTS, *S* proceeds by sending the data frame (DATA) to *D*. The transmission completes when *S* receives the acknowledgment (ACK) control frame from *D*. After a successful transmission, *S* releases the channel by backing-off with a randomly chosen timer before contending for the channel again. Since a data transmission inhibits neighbors of both the source (through the RTS) and the destination (through the CTS), we refer to the band of contention in the IEEE 802.11 MAC protocol as being *two*. Moreover, since the MAC protocol aims to provide every node equal opportunity for channel access, we refer to the fairness model it supports as a *per-node* fairness model.

### B. *Ideal Node Scheduling - Band 2 (INS-2)*

In order to focus on the impact of the band of contention and the fairness model supported by IEEE 802.11, and mask the overheads and inefficiencies of its implementation and distributed operation, we use a *transmission scheduler* that is a centralized version of the IEEE 802.11 MAC protocol during its evaluation and comparison with other approaches [4]. When the simulation begins, the MAC protocol at every node registers with the centralized scheduler if it has a packet to transmit. The scheduler, for every transmission slot, chooses the node that has received the minimum service thus far. When more than one node with the minimum service counter exists, the node with the minimum 2-hop degree is chosen. Based on the first choice, it finds the second node that has received the minimum service among the other nodes and can transmit without interfering with the first transmission. The process continues until no more node transmissions can be accommodated for that transmission slot. The scheduler thus supports a per-node fairness model. Meanwhile, it has a band of contention of *two*, since like IEEE 802.11 the centralized scheduler does not allow any transmissions or receptions to occur in the vicinity of any transmitter or receiver. The protocol is referred to as the INS-2 protocol in the rest of the paper.

### C. *Ideal Node Scheduling - Band 1 (INS-1)*

The INS-1 protocol is similar to the INS-2 protocol in that a centralized scheduler is used to achieve the transmission scheduling. However, unlike the INS-2 where the band of contention is two and hence no transmitters or receivers are allowed in the vicinity of both the transmitter and receiver, INS-1 has a band of inhibition of only *one*: transmissions are allowed subject to the condition that there can be no other transmissions in the vicinity of a receiver, or no other receptions in the vicinity of a transmitter. The choice of the nodes for transmission is based on the service enjoyed by the nodes until that point. Ties are broken based on the 2-hop node degree as in INS-2.

### D. *Ideal Flow Scheduling (IFS)*

The INS-1 and INS-2 protocols are scheduling protocols where the fairness model is node-based. In other words, service counters are maintained purely on a per-node basis, and nodes are chosen for transmissions. In ideal flow scheduling (IFS), the centralized scheduler is responsible for scheduling flows instead of nodes. Service counters are maintained per flow and not per node. When a flow is scheduled for transmission, all hop-by-hop transmissions for that flow are scheduled sequentially. If after a flow is scheduled but before its first hop transmission commences, another flow with a lower service counter arrives, the former flow may be re-scheduled to accommodate the latter flow to ensure short-term fairness. However, flows that have completed their first hop transmission are not preempted. The band of contention is equal to *one* (as in INS-1) in the IFS implementation.

### E. *Shortest Path Routing (SPR)*

Similar to our centralized implementation of the IEEE 802.11 MAC protocol, we also implement a centralized and ideal version of a shortest path routing protocol (SPR). Once the network is initialized, the centralized routing protocol computes the shortest paths between every source-destination pair in the network and updates the routing tables in the network accordingly. We still use the Dynamic Source Routing (DSR) [5] as the routing layer. However, the routes for DSR are furnished through the centralized routing module.

### F. *Widest Shortest Path Routing (WSR)*

In order to demonstrate the effect of the MAC protocol on the performance gains achieved by a better routing layer, we use a load-balanced routing algorithm called widest shortest path routing (WSR). Unlike SPR which is based on a single metric – the hop count – for route selection, WSR uses a 3-tuple – (interference along a path, interference caused by the flow, hop count) – to choose from the available set of paths. Each link is associated with a single weight. When a flow is assigned a particular path, the weights of all links that will contend with the flow are incremented. The first parameter of the 3-tuple is the maximum of the link-weights of the path being considered. The second parameter is the aggregate increase in weights of the links that lie within a one-hop distance from the considered path if the flow were to be assigned to it. The third parameter is a simple hop count. The

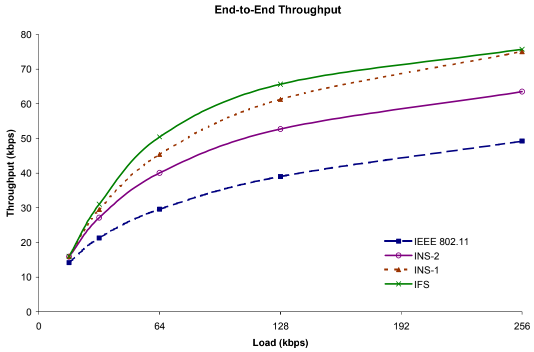

Figure 1. End-to-End Throughput (Random Traffic)

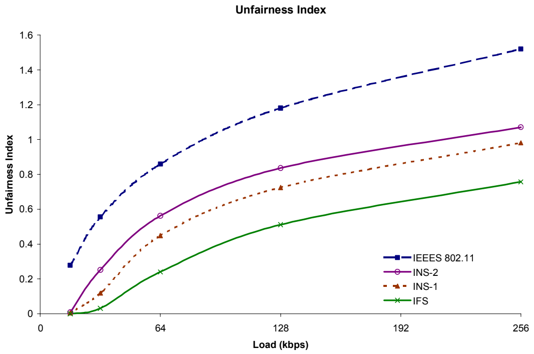

Figure 2. Unfairness Index (Random Traffic)

path that has the minimum lexicographic value for the 3-tuple is chosen by WSR. WSR is also implemented as a centralized routing module that furnishes routes to DSR.

## III. PERFORMANCE STUDY OF IEEE 802.11

### A. *Simulation Model*

We use the *ns-2* [6] network simulator for all the simulations presented in the paper. We present details of the simulation environment as follows.

- *Physical Layer*: A combination of the free space propagation and two-ray ground reflection model is used to model the signal propagation in the simulations. The signal strength falls as $1/r^2$ ($r$ is the distance) within a constant *crossover distance*. Above the crossover distance, the signal strength falls as $1/r^4$. The crossover distance used for all our simulations is around 90m.
- *Topology*: We use a 1500m by 1500m network grid with 100 nodes randomly distributed within the grid. The random seed for the topology creation is varied for the different scenarios used. A constant node transmission range of 250m is used. We do not consider mobile scenarios in this paper.
- *Traffic Model*: We primarily use 100 TCP flows as the traffic content in the network where the source and destination pairs for each TCP flow are randomly chosen from the set of 100 nodes. *Constant Bit Rate* (CBR) sources are used to control the load of TCP flows. Different loads from 16Kbps to 256Kbps are used in the simulations. In order to depict the validity of our results for other traffic scenarios, we also use UDP flows with a different traffic model wherein sources are clustered instead of being randomly distributed. The source cluster size from which source nodes are chosen is varied from 1 to 100.
- *Metrics*: The average throughput and normalized throughput deviation are used as measures of the throughput and fairness performance. Throughput is measured at the TCP sink. The throughput deviation is normalized to the average throughput and used as the *unfairness index*. Each simulation is run for 60 seconds, and results of 20 different scenarios are averaged for every data point shown in the results.

We present simulation results that demonstrate the performance of the IEEE 802.11 MAC protocol and those of the alternative MAC approaches described in Section II, in a multi-hop wireless network. We organize the rest of the section into three parts: (i) First we study the performance of MAC protocols in a random traffic distribution environment with TCP traffic and show that the performance of IEEE 802.11 can be greatly improved by reducing the band of contention and using a per-flow fairness model. (ii) We then evaluate the MAC protocols using a clustered traffic distribution environment with UDP traffic and substantiate that our arguments remain valid even when operating over different traffic models. (iii) Finally, we study the interaction between the MAC protocols and higher layer protocols by using different routing and transport protocols.

### B. *Performance under Random Traffic Distribution*

Fig. 1 and Fig. 2 show the performance of IEEE 802.11, INS-2, INS-1, and IFS in terms of throughput and fairness. In the rest of the section we compare (i) *IEEE 802.11 vs. INS-2* to show the difference between the distributed and centralized versions of the IEEE 802.11 MAC protocol, (ii) *INS-2 vs. INS-1* to show the performance enhancement achieved by reducing the band of contention from *two* to *one*, and (iii) *INS-1 vs. IFS* to show the performance gains attained when the fairness model is changed from a *per-node* model to a *per-flow* model.

*1) IEEE 802.11 vs. INS-2:* As shown in Fig. 1 and Fig. 2, INS-2 shows a better performance than IEEE 802.11 both in terms of throughput and fairness. The throughput difference between IEEE 802.11 and INS-2 indicates the performance loss of IEEE 802.11 due to the inefficiencies of its distributed operations, such as packet collisions and unnecessary contention-based back-offs. Similarly, the fairness performance improvement is a measure of the unfair behavior of IEEE 802.11 due to its distributed nature. Although the IEEE 802.11 fairness model is based on node fairness, the unfair nature of IEEE 802.11 even with respect to such a model has been profiled in related works [7], [8], [9]. We acknowledge that the IEEE 802.11 MAC protocol can be significantly improved in terms of its distributed implementation. However, the focus of this paper is not to study the performance degradation in IEEE 802.11 due to the distributed operations. Rather, we profile the performance loss due to the distributed implementation in this section, so as to appropriately present only the performance gains achieved

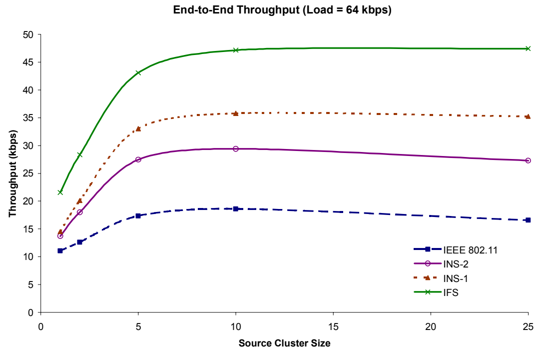

Figure 3. End-to-End Throughput (Clustered Traffic)

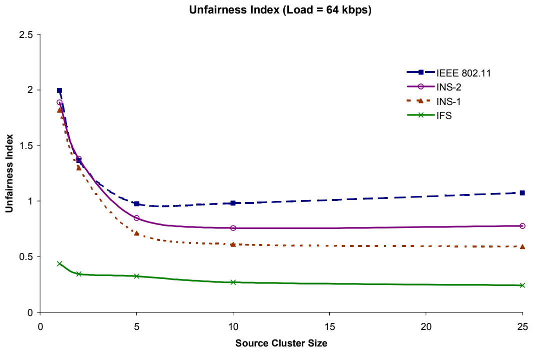

Figure 4. Unfairness Index (Clustered Traffic)

through improvements in the band of contention and the fairness model in subsequent comparisons.

*2) INS-2 vs. INS-1:* By comparing the performance of INS-2 and INS-1 in Fig. 1 and Fig. 2, we observe the throughput and fairness performance improvement achieved when the band of contention is reduced from two to one. The throughput enhancement is obvious since reducing the band of contention results in an increase in the amount of spatial reuse in the network (the per-hop inhibition area is reduced). However, it is interesting to note that the fairness also improves when the band of contention is reduced. This is a result of the reduced band of contention allowing less privileged flows to catch up to the more privileged flows in terms of throughput.

*3) INS-1 vs. IFS:* The performance difference between INS-1 and IFS in Fig. 1 and Fig. 2 presents the performance difference in throughput and fairness between per-node fairness model and per-flow fairness model. As expected, Fig. 2 demonstrates a significant improvement (close to 40% for a load of 128Kbps) in terms of fairness when IFS is used. However, it is interesting to note an improvement, albeit a small one, in terms of throughput also. The reason for the throughput improvement can be explained by the absence of losses in the IFS model (since one-hop transmission of a packet means that the other hops have also been scheduled) resulting in a better utilization of network resources. However, the fact that the improvement in performance looks marginal can be explained by the nature of the transport protocol used. TCP is an adaptive transport protocol that reacts to losses. Hence, the use of TCP ensures that not many such losses in the network occur. We substantiate our observation in Section III-D where we compare the performance of per-node and per-flow fairness models using UDP as the transport protocol.

### C. *Performance under Clustered Traffic Distribution*

For all simulation results presented thus far, a randomly distributed traffic model is used where sources and destinations are randomly selected from the 100 nodes. In this section we present representative results showing that the observations made in Section III-B on the performance of the IEEE 802.11 protocol and the other MAC schemes still hold good when other traffic models are considered. We consider a clustered traffic distribution scheme wherein the 100 flows in the network originate from $k$ sources, and $k$ is varied from 1 to 100. When $k$ is 100, the scenario is the same as the ones presented in Section III-B. Such a traffic distribution is representative of the typical Internet client-server realm where multiple clients can access the same server, or of wireless sensor networks where traffic in the network might be targeted toward few sinks. Fig. 3 and Fig. 4 show the throughput and fairness performance of all flavors of the MAC protocol considered thus far when the source cluster size is varied (results for $k > 25$ are not shown in the figures as the trend remains the same beyond $k = 25$). While it is evident that throughput performance remains consistent with our earlier discussions, fairness can become a serious issue when the sources are clustered and IFS remains the only protocol that can effectively address the issue of fairness even in such a heavily shared environment.

### D. *Impact on the Higher Layers*

To study the impact of MAC protocols on routing protocols, we first use SPR as the routing protocol over IEEE 802.11 and IFS respectively, and then use WSR in place of SPR. We show the performance enhancement achieved in IEEE 802.11 and IFS respectively in Fig. 5. It is clear that using WSR improves the performance over SPR. However, the performance gain due to WSR when using IFS is higher than when using IEEE 802.11. This can be explained as follows: WSR attempts to distribute flows in the network such that they do not contend with each other. However, such a distribution will be beneficial to overall network utilization only until there are unused resources in the network. When IFS is used, because of the smaller band of contention (which is *one*), such a saturation point (in terms of resource usage) is reached much later than in the case of IEEE 802.11 (whose band of contention is *two*) resulting in better network utilization.

To study the impact of MAC protocols on transport protocols, we again use IEEE 802.11 and IFS as MAC protocols and use TCP and UDP as transport protocols. Fig. 6 shows the performance difference of IFS and IEEE 802.11 when different transport protocols are used. IEEE 802.11 exhibits a lower throughput than IFS for both TCP and UDP. However, when UDP is used in place of TCP, the performance degrades more significantly in IEEE 802.11 than in IFS. Because a UDP source does not adapt to congestion in the network, the source will potentially waste network resources sending packets that will not reach the destination (hence the throughput degradation). A per-flow fairness model like IFS

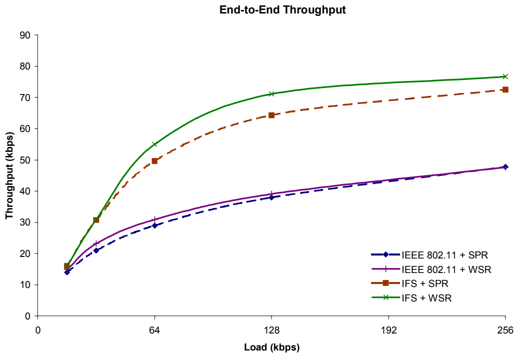

Figure 5. Impact on the Routing Layer

ensures that the network resources are allocated to end-to-end flows, instead of to individual nodes as in a per-node fairness model, thus reducing the wastage of resources even when using a non-adaptive protocol such as UDP.

### E. Summary

We have demonstrated in this section that the IEEE 802.11 MAC protocol can be significantly improved both in terms of its band of contention and in terms of its fairness model for multi-hop wireless networks. We have also shown that our observations remain valid under different conditions of transport protocols, and traffic distribution scenarios. Finally, we have shown that the performance of the MAC protocol not only has a direct impact on the performance of the network, but also indirectly impacts the performance gains achieved through using smarter higher layer protocols.

## IV. RELATED WORK AND CONCLUSION

### A. Related Work

In [7], [8], the authors evaluate the performance of the IEEE 802.11 MAC protocol over wireless local area networks and identify its unfair performance characteristics. However, the scope of the evaluation is confined to last-hop wireless LAN environment, and does not include multi-hop wireless networks. In [9], the authors identify the unfair nature of the IEEE 802.11 MAC protocol over wireless ad-hoc networks. The authors propose a better scheme to provide fairness. However, the scheme proposed is targeted toward achieving better node fairness and does not support per-flow fairness addressed in this paper. Hence the performance inefficiency due to the per-node fairness model still exists. In [10], the authors investigate the performance of the IEEE 802.11 MAC protocol over multi-hop wireless networks. Although the key conclusion drawn in that work is the same as in this paper – that IEEE 802.11 is inappropriate for multi-hop wireless networks, the study is closely tied to using TCP as the transport protocol. Moreover, the work does not compare the performance of IEEE 802.11 in tandem with different routing and transport protocols, and does not provide insights into attainable performance improvement if such inefficiency is resolved, namely by reducing the band of contention and supporting a better fairness model.

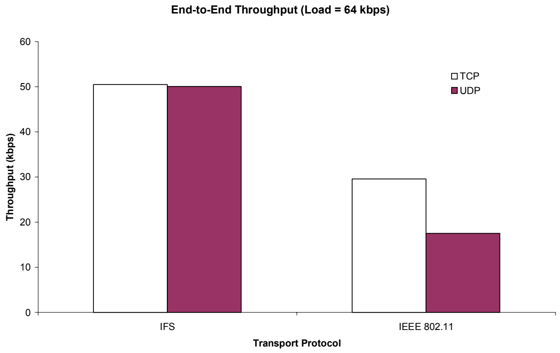

Figure 6. Impact on the Transport Layer

### B. Conclusion

The IEEE 802.11 MAC protocol was designed for wireless local area networks to provide fair and efficient medium access control to stations sharing a wireless channel. It has been adopted as the de-facto standard for medium access control in multi-hop wireless networks also. In this paper, we argue that certain improvements in terms of reducing its band of contention and fairness model are necessary in order to realize efficient and fair medium access. We demonstrate the performance gains that can be achieved both directly and indirectly by reducing the band of contention and by employing a per-flow fairness model. Two critical issues not considered in this paper are mobility and a distributed implementation of the new protocols. Ongoing work is investigating the impact of mobility, and studying possible distributed approaches to realize the ideal flow scheduling protocol.

## REFERENCES

[1] IEEE Standards Department, "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," *ANSI/IEEE Standard 802.11*, Aug. 1999.

[2] H.-Y. Hsieh and R. Sivakumar, "Performance comparison of cellular and multi-hop wireless networks: A quantitative study," in *Proceedings of ACM SIGMETRICS*, Boston, MA USA, June 2001.

[3] M. Frodigh, S. Parkvall, C. Roobol, P. Johansson, and P. Larsson, "Future-generation wireless networks," *IEEE Personal Communications Magazine*, Oct. 2001, pp. 10—17.

[4] H.-Y. Hsieh and R. Sivakumar, "Improving throughput and fairness in multi-hop wireless networks," in *Proceedings of ICN*, Colmar, France, July 2001.

[5] D. B. Johnson, D. A. Maltz, Y.-C. Hu, and J. G. Jetcheva, "The dynamic source routing protocol for mobile ad hoc networks," *Internet Draft draft-ietf-manet-dsr-07.txt*, Feb. 2002.

[6] The Network Simulator, "ns-2," http://www.isi.edu/nsnam/ns.

[7] E. Koksal, H. I. Kassab, and H. Balakrishnan, "An analysis of short-term fairness in wireless media access protocols," in *Proceedings of ACM SIGMETRICS*, Santa Clara, CA USA, May 2000.

[8] T. Ozugur, M. Naghshineh, P. Kermani, and J. Copeland, "Fair media access for wireless LANs," in *Proceedings of IEEE GLOBECOM*, Rio de Janeiro, Brazil, Dec. 1999.

[9] B. Bensaou, Y. Wang, and C. Ko, "Fair medium access in 802.11 based wireless ad-hoc networks," in *Proceedings of IEEE/ACM MobiHoc*, Boston, MA USA, Aug. 2000.

[10] S. Xu and T. Saadawi, "Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks," *IEEE Communications Magazine*, June 2001, pp. 130—137.