CS244 Final Project Report

Reproducing "Capacity of Ad Hoc Wireless Networks" (2001)

Thea Rossman
Daniel Classon

1 ABSTRACT

We describe our reproduction of two simulations from the 2001 paper “Capacity of Ad-Hoc Wireless Networks”.[18] As in the original paper, our simulations isolate the efficacy of 802.11 MAC in making effective use of the medium in multi-hop wireless topologies. We focus our work on chain-like traffic patterns with asymmetrical origination, scenarios common in rural networks.[21]

We are able to reproduce the pattern observed in the original paper: that 802.11 MAC schedules traffic origination sub-optimally in these topologies. In other words, **the limitations on multi-hop throughput in a wireless ad-hoc network are imposed not only by interference at the physical layer, but also by how medium access itself is scheduled.**

2 INTRODUCTION

In the early 2000s, ad-hoc wireless networks were of significant interest to the networking community as a method for bootstrapping low-cost communications infrastructure. Though the technology originated in a military context, projects such as Roofnet (2002)[4] began to adapt it to provide neighborhood-level Internet access with low infrastructure, a practice which community groups and organizers continued as part of digital self-determination[6] projects.[5][17][1]

Despite early interest, vision, and some successes, **wireless ad-hoc networks do not perform well compared to wired infrastructure**. Indeed, when researchers began to explore broader deployment, a primary concern was the total capacity and throughput that an ad-hoc wireless network could actually provide. A key feature of the network is that nodes forward each others’ traffic – meaning that the throughput available for a user is limited not only by raw channel capacity and competition with independent traffic, but also by the forwarding load imposed by other nodes along the path. That is, unlike in a wired network, a single flow interferes with itself. (Ultimately, low performance became a primary reason that wireless ad-hoc networks failed in a commercial context.[i]

Li et. al.’s paper, “Capacity of Ad Hoc Wireless Networks” (2001), offered two key contributions in the early analysis of the capacity and throughput possible in a mesh. First, they show through simulation that 802.11 medium access control under-utilizes network capacity for multi-hop traffic. In other words, limitation on throughput, in these cases, is due not just to a physical-layer ceiling, but also sub-optimal medium access coordination. Second, they demonstrate, largely through formal analysis, mathematical properties for the kinds of traffic patterns that “work” in large ad-hoc networks. At a high level, they conclude that performance remains usable as network size scales if traffic patterns remain local.

In this reproduction, we focus on the first result regarding medium access. We reproduce the paper’s figure 3, which showed the relationship between throughput and path length within a chain topology, and figure 8, which does the same in a lattice network with horizontal flows. Our key finding matches that of the original paper, wherein the 802.11 MAC protocol is unable to provide optimal scheduling for multi-hop paths in these networks. We assume familiarity with the 802.11/802.11b CSMA/CA-based MAC protocol.[20][10][7]

3 THROUGHPUT ACHIEVED ALONG A CHAIN OF NODES

The paper presents an analysis of the throughput achieved within a chain topology, with the first node sending packets to the last node as fast as its 802.11 MAC permits. They first present the theoretical maximum imposed by the physical layer, then demonstrate through simulation that 802.11 does not achieve it.[ii] We recreate this analysis here.

3.1 Theoretical Maximum

Figure 1 depicts a wireless ad-hoc network with a chain topology and omni-directional links. Neighboring nodes are just within effective transmission range. If we consider an

[i] This conclusion comes from Sachin Katti, during his lecture on ad-hoc wireless networks in CS244.

[ii] The authors validate this claim in hardware, finding that the data from their simulations closely, but not exactly, match the real-world experiment.

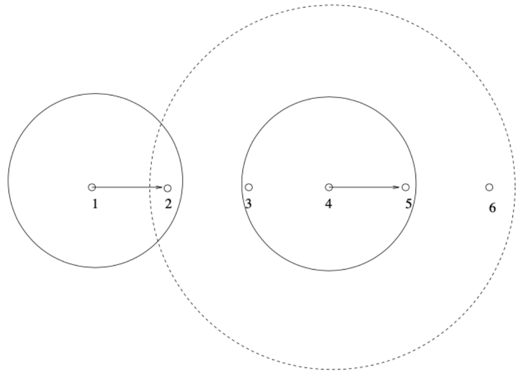

Figure 1: Figure 2 from the original paper. This shows the effective transmission range (solid lines) and interference range (dotted lines) along a chain of nodes. Ranges are only pictured for some nodes for clarity.

additional interference range – which the authors do and we do not – nodes up to two hops away may interfere with each other.

Physical interference imposes the following restrictions on throughput:

- Adjacent nodes cannot successfully transmit simultaneously, because a node cannot receive and transmit at the same time.
- Nodes up to two hops away cannot send at the same time, due to competing transmissions perceived at the intermediate node.
- Finally, if we consider interference, nodes up to 3 hops away cannot transmit at the same time, due to interference in the medium for an intermediate receiving node.

As the authors note, the limitations above offer a **theoretical throughput of $\frac{1}{4}$ of the one-hop bitrate** for this topology. If we ignore the additional interference range, this fraction is $\frac{1}{3}$.

3.2 Simulation

Our goal was to recreate the authors' conclusion that 5h3 throughput for traffic along multiple hops in a chain is lower than the ceiling imposed by the physical medium; and we wished to do so in a way that isolates the impacts of 802.11 MAC.

We simulate radio nodes with an effective transmission range of 250 meters, positioned 200 meters apart, and with a 2Mbps data rate.[iii] We calculate throughput for multiple chain lengths and multiple packet sizes. Note that, in a chain topology, routing is irrelevant; and we further isolate the impacts of 802.11 MAC by disabling adaptive bitrate.[iv]

[iii]A full documentation of our parameters can be found on our GitHub repository, linked at the end of this paper.

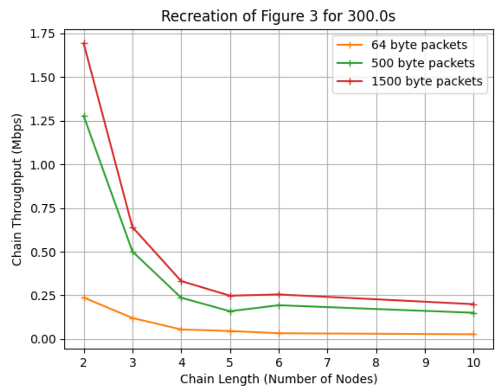

Figure 2: Our reproduction of figure 3, which modeled the throughput of a chain of nodes as a function of chain length. The nodes are 200m apart and the link rate is 2Mbps. The first node forwards packets to the last node as fast as 802.11 allows.

Like the authors seem to, we use a range-based propagation loss model. However, while the default in *ns* at the time created two-hop interference depicted by the dotted line in figure 1, we use a model that sets the effective transmission and interference ranges to be the same.[v]. Our contention is that the additional interference is unnecessary. First, it is not clear that the hardware used in the paper achieves two-hop interference, or if there is any reason for using these parameters other than that they are the default in *ns*. Second, we can perform the same analysis (above), observe the fundamental pattern, and achieve similar values just as effectively with a simpler propagation model – the only difference is the degree to which 802.11 under-performs.

3.3 Results

Our results are depicted in figure 2, alongside the original in figure 3. As the chain gets longer, our throughput – like the authors' – levels out at around 1/7 of the one-hop throughput, or 0.25 Mbps. This is far lower than the physical-layer maxima of 1/3 and 1/4.

[iv]NS-3 documentation of the Constant Rate WiFi Manager, which we set to send packets at a constant 2Mbps rate, is here: https://www.nsnam.org/doxygen/classns3$_{11c}onstant_rate_wifi_manager.html$

[v]We experimented with ns-3's log- and three-log distance propagation models, with various parameters, but struggled to remain confident that we were setting the ranges correctly. See documentation of these models here: https://www.nsnam.org/docs/models/html/propagation.html

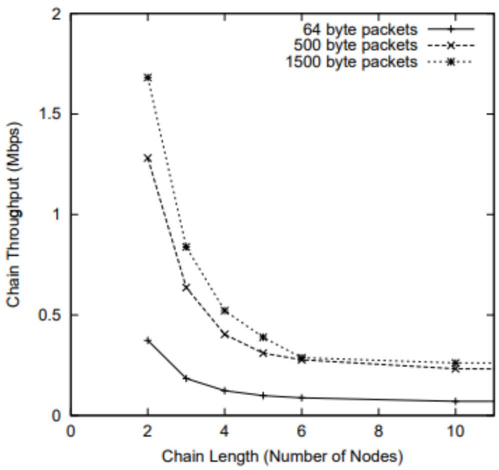

Figure 3: The original figure 3 from the paper. The authors additionally modeled chains of length 20 and 50, which they note had identical throughputs to chains of length 10. We did not replicate these due to computing resource constraints.

Our results show a faster degradation in throughput than those of the original paper. This, along with the same leveling-off value, is particularly interesting due to the fact that we model less interference. We present hypotheses here, but we would be interested in future work that tests any of these theories.

A likely explanation for this discrepancy is that we are missing parameters, either because they were not clearly communicated in the paper, because we could not find documentation that would have been readily available at the time (e.g., default settings in *ns* or network card specifications), or because of our different propagation loss model. There could also be differences between *ns-3* and *ns*, e.g., in simulating randomness in the network.[vi] It is also possible that there is a bug in the *ns* model, original code, the *ns-3* models we use now, or our code.

A final, counter-intuitive hypothesis is that the additional interference could control the transmission rate of the first node without significantly limiting subsequent nodes. (Based on our explanation of 802.11 MAC below, this would improve throughput.) The discrepancy between our results and the paper's is largest for 4-node chains, which is where node 1 would perceive network busyness differently depending on the interference model.

[vi]We found some documentation that throughput values generated by *ns-3* models for ad-hoc networks exhibit more fluctuations over time than those simulated in *ns-2*; see the figure on page 45 of [16]. If the pattern for fluctuations extends beyond just time, then this could offer an explanation: our node-by-node bitrate does fluctuate, as depicted in figure 6, more so than the send rates reported by the original paper.

4 THROUGHPUT ACHIEVED IN A LATTICE TOPOLOGY

Our second reproduction calculated throughput along a square lattice topology with horizontal, parallel traffic flows and neighboring nodes within transmission range. Nodes are positioned 200 meters apart and tuned with the same parameters as in section 3. Again, our model, unlike the paper's, does not consider two-hop interference.

4.1 Theoretical Maximum

The theoretical, physical-layer argument described in section 3 applies to each row of the network – that is, operating independently, each chain could expect to deliver $\frac{1}{3}$ of the maximum bitrate (or $\frac{1}{4}$ with the two-hop interference range). In the lattice setup, each flow additionally experiences interference from its neighboring chains. If we do not consider the two-hop interference range, then every other row may be active concurrently without interfering.

Thus, if they were scheduled equally and perfectly, flows could on expectation deliver $\frac{1}{3} \cdot \frac{1}{2} = \frac{1}{6}$ of the maximum bitrate, or approximately 0.28Mbps for 1500-byte packets. If we consider two-hop interference, this is $\frac{1}{12}$, as argued in the paper.

4.2 Simulation and Results

In Figure 4, we show the average throughput of several horizontal data flows in a square lattice network for packet sizes of 64, 500, and 1500 bytes. Similar to the chain network, larger packet sizes had larger throughput since they incurred less of the per-packet congestion cost. Our square lattice networks had widths/lengths of 3, 4, 5, 6, and 7. The maximum average throughput is achieved with 1500 byte packets at 0.40 Mbps while larger lattices converge around 0.11 Mbps.

We note, as the paper does, that edge flows receive higher throughput than middle ones, due to experiencing interference from only one, rather than two, competing flows. As we would expect, this is most drastic in our 3 by 3 lattice simulation with 1500 byte packets: edge flows received 0.59 Mbps and 0.61 Mbps, nearly full capacity, while the innermost flow received just 0.01 Mbps. All other sizes of lattice, while less extreme, show this difference in measured throughput between the inner and outer flows.[vii]

[vii]Reference figure 8 raw data in our *outputs* directory.

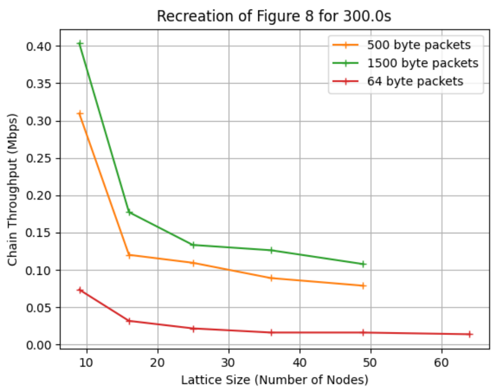

Figure 4: Reproduced figure 8. Note that we take measurements for smaller lattices due to computing resource constraints; thus, our axis values are different. Again, we observe the same overall patterns, but with slightly lower throughput for smaller lattices.

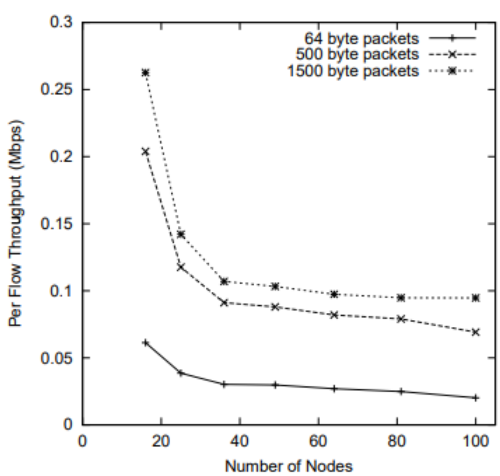

Figure 5: Original figure 8

Figure 5 has the paper's original results, which was figure 8 in the 2001 paper. Due to computational restrictions, we were unable to recreate the original paper's larger simulations– the singular 64-node simulation took overnight to complete.

Our results, again, show the same pattern, but with slightly lower throughput for smaller lattices and roughly equal throughput for larger lattices. We would expect a higher throughput in our simulation, as the theoretical maximum throughput for 1500 byte packets of our simulation is 0.19 Mbps versus 0.14 Mbps for the original. Our hypotheses for the discrepancy between our simulation and our expectation are the same as in the chain topology: that we are missing key information from the original paper to alter our *ns-3* simulation, differences between *ns* and *ns-3*, mistakes, or unexpected side effects of our propagation loss model.

5 DISCUSSION OF RESULTS: WHY 802.11 MAC UNDERPERFORMS

The authors provide a hypothesis, which later papers expanded upon (e.g., [25]) for why 802.11 MAC underperforms. We recreate and expand upon this analysis here.

The paper's first line of reasoning is that, if nodes originating traffic experience less interference and forwarding responsibility than subsequent hops, they are likely to overestimate network capacity. The subsequent packet loss and retransmission requirements degrade throughput.

To show one intuition for this, consider the chain topology with extended interference range (figure 1). Node 1 and node 3 have fundamentally different contention areas: node 1 is directly limited by 3 other nodes, while node 3 is directly limited by 4 other nodes (or, 5 in a 7-node topology). Node 1's MAC will "choose" not to transmit if it senses that the medium is busy (because node 2 or node 3 is transmitting) or if it does not receive a CTS from node 2 (because node 4 is transmitting). Node 3's MAC will back off if it senses that the medium is busy (because node 1, 2, 4, or 5 is transmitting), or if it does not receive a CTS from node 4 (in a longer chain, if node 6 is transmitting).

If node 1 injected packets into the network with a perfect "sliding window" pattern – with packet *n* injected exactly as node 4 finishes forwarding packet *n-1* – then we should observe maximum capacity utilization. However, due to randomness in backoff, packet loss, and so on, this will not necessarily be the case; for instance, node 1's MAC could reasonably believe it should schedule a transmission if node 4 is backed off, and node 4 may be more likely to back off than node 1 due to additional opportunities for interference.

Thus, in a chain-like traffic pattern, an originating node may send packets faster than later nodes can forward them. In these cases, packets will be dropped (likely, at nodes 2 and 3), and subsequent required retransmissions will degrade overall throughput. The average bitrates per node from our pcap files support this hypothesis (Figure 7).

The paper's second, and related, argument reasons that 802.11b's aggressive exponential backoff scheme leads to wasted backoff at the beginning of the chain. Wasted backoff has a cascading effect on throughput; in a chain, if node 1 is backed off when it should not be, then subsequent nodes cannot do

1	2	3	4	5	6
0.937	0.754	0.630	0.649	0.647	0.434

Figure 6: Bitrates (Mbps) for each sending node along a 7-node chain, extracted from pcap summaries for our reproduction of figure 3. We note fluctuations in the bitrate from node to node, as well as early nodes in the chain sending packets faster than later nodes are able to forward them. The full pcap summaries for this scenario are in the *outputs* directory on our GitHub.

useful work.

To describe one example of this, again consider the simple chain topology with extended interference (figure 1). Imagine that node 1 has just transmitted packet *n* and wishes to transmit packet *n*+1. While nodes 2, 3, and 4 are forwarding packet *n*, node 1 will initiate repeated exponentially-increasing backoffs: it will sense the medium and either conclude that it is busy, during node 2 and 3's transmissions, or send an RTS and fail to receive a CTS, during node 4's transmission. When node 4 is finished transmitting packet *n*, and the network is clear for node 1 to transmit packet n + 1, node 1 is likely to remain timed out due to the rapid increase in contention window.

The paper shows wasted backoff time in a 7-node chain topology.[viii] Unfortunately, we were unable to recreate this measurement in our simulations. As far as we could find, in *ns-3*, the trace sources for backoff are available only for EDCA-based WiFi MAC layers (e.g., 802.11e) and for wired CSMA MAC layers[ix], which we could not install on a WiFi net device running 802.11b.

The above analyses are analogous to a congestion control problem: packets are injected into the network either more rapidly than they can be handled, leading to packet loss and retransmission, or more slowly than they exit, leading to under-utilization of network capacity.

6 RELATED WORK

6.1 The current standard: 802.11s

802.11s, the standard for wireless mesh networks published in 2011, shifted the MAC protocol for ad-hoc wireless networks, but did not fundamentally address the congestion problem described in section 5.[14]

802.11s required the EDCA framework for medium access; unlike the original 802.11 DCF, this supports priority-based throughput differentiation. While QoS does not address node-to-node scheduling, it does have the potential to make, for example, real-time voice traffic possible over a multi-hop wireless mesh network. 802.11s also allows for multiple packet transmissions per contention, using the abstraction of "transmission opportunities" (TxOPs), rather than the frame-by-frame approach of the original 802.11.

An optional extension to medium access, that mesh network operators can choose to support, is the "mesh coordination channel access" function (MCCA), a distributed reservation protocol. A mesh station can negotiate an MCCA TxOP with its neighbors; if accepted, the reservation is (ideally) advertised to every node within interference range.[15][13]

Though MCCA, again, does not specifically address the MAC limitations described above, we could imagine an extension of this idea supporting topology-aware or multi-hop coordination – e.g., if subsequent nodes in a chain traffic pattern could "reserve" channel capacity in a way that temporarily blocks origination without triggering high backoff. The EDCA/MCCA combination on its own, though, exhibits the same throughput degradation present with 802.11's DCF (cited in [23]).

6.2 Getting around the problem: effective routing and better hardware

In the absence of solutions to MAC scheduling, researchers and engineers have moved to the other layers of the networking stack: designing custom routing protocols and reducing physical limitations.

As mentioned in our introduction, the paper we reproduce argues that if traffic patterns are local and average path length remains low, throughput will be usable, regardless of the overall size of the network. Concurrent and later work built on this idea (e.g., described in [19]). RoofNet designers, for example, design a custom routing protocol and justify feasibility of their network by noting that average packet hop count is low.[4] Routing can also regulate sending rate; Guaya-Delgado et. al. (2019) propose a routing protocol for mobile (non-static) wireless ad-hoc networks that aims to identify and deprioritize greedy senders.[11] 802.11s also came with significant changes to routing recommendations.[23]

It is important to note that, while routing-based solutions may be effective for some networks, chain topologies like

[viii]Page 4 of the original paper.

[ix]See the list of all trace sources in *ns-3* here: https://www.nsnam.org/doxygen/_trace_source_list.html. We tried with the "ns3::Txop" "BackoffTrace" source and the "ns3::CsmaNetDevice" "MacTxBackoff".

those simulated in this paper remain necessary for backhauling connection (e.g., particularly for those operating networks in rural areas). In these cases, there is both no way to avoid multiple hops and little choice in how to route traffic.[20]

Of course, reducing physical layer limitations – making use of multiple channels, using finely-tuned directional antennas, and designing stations less susceptible to interference – also improves throughput. This opens possibilities for introducing more MAC control frames without overwhelming channels with overhead; assigning different frequencies to neighbors to reduce direct interference[9]; and, by increasing transmission opportunities overall, decreasing wasted backoff. There is also the promising, though politically challenging, project of implementing networks in the spirit of community mesh over cellular.[2]

6.3 Proposed Custom MAC protocols for ad-hoc forwarding

Finally, concurrent and subsequent works have attempted to improve MAC-level scheduling. Wang et. al. and He et. al. propose allowing receivers to initiate flows, rather than just senders, which could decrease wasted backoff.[24][12] Dhoutaut et. al propose increasing flow fairness – and avoid throttling nodes – by increasing the backoff window for stations that have recently sent more packets than their immediate neighbor.[8] Nandagopal et. al., similarly, take an approach that attempts to give each one-hop flow equal capacity allocation, potentially decreasing the problem of a sender transmitting more rapidly than the network can handle.[22].

As noted above, more fine-grained and flexible hardware, of course, opens additional possibilities. In one example specifically for long-haul networks, Raman et. al. (2005) proposed 2P, a MAC protocol that takes advantage of the fact that a directional node can concurrently receive on all of its links *or* transmit on all of its links. 2P takes advantage of this, scheduling medium access such that each node is in one of two modes at all times – able to receive on all links or able to transmit on all links – making much better use of network capacity than standard 802.11.[20][21]

7 CHALLENGES

Without a background in *ns-3* beyond this course, it was difficult to discern when divergent results were due to our error or to external factors. For instance, when we wanted to perform a simulation over 802.11s as a starting point, we realized that the module or example itself may have been broken.[x] On the other hand, after getting bizarre results using 802.11b and ad-hoc mode, we realized that we were simply not setting packet size correctly. Even in our final results, we cannot definitively explain discrepancies from the authors' – these could be due to a mistake that we made, a difference in experiment setup, or a genuine variation in results.

Of course, the nodes in our simulation do not account for two-hop interference, largely because we did not figure out how to correctly apply a different propagation loss model. We considered trying to increase the transmission range to two hops, hard-code one-hop routing tables, and compare to our original results, but we did not have time to implement this. Though we are reasonably happy with our reproductions, we would have loved to isolate the impacts of this clear, identifiable difference.

8 CONCLUSION

In this project, we were able to replicate two simulation that support a core result of Li et. al.'s paper: that scheduling decisions made by 802.11b can constrain throughput beyond the limitations imposed by the physical medium. We focus on multi-hop, chain-like traffic, in which an originating node experiences less contention and forwarding burden than subsequent, forwarding nodes. These topologies and traffic patterns exhibit notoriously low throughput, but they also resemble what is necessary for backhauling connectivity within a rural area.

Though the results of this paper are no longer new, and specific applications to ad-hoc wireless networks are fewer than they were in 2001, we believe there is value in returning to foundations. For us, reproducing this project involved thinking deeply about how 802.11b's distributed coordination function works, when it performs well and when it does not, and how it could be designed differently. Given the massive scale of wireless connectivity[3] – regardless of the present and future of wireless mesh – understanding the MAC protocols that support these networks remains a fundamental part of making sense of the Internet today.

9 GITHUB

Our scripts for reproducing figures 3 and 8 are in our GitHub repository, along with a more thorough justification of parameters:
https://github.com/thearossman/cs244-project-ns-3-dev-git/

[x]The *ns-3* "mesh.cc" example had 0Mbps throughput when we ran it out of the box, and we found discussion boards suggesting that others had encountered this issue as well.

REFERENCES

[1] 2015. Rural Wireless Mesh Network: A Design Methodology. *International Journal of Communications, Network and System Sciences*.

[2] 2018. dLTE: Building a more WiFi-like Cellular Network. *HotNets-XVII*.

[3] 2019. Wi-Fi 6, 5G play big in Cisco's mobile forecast. (2019). https://www.networkworld.com/article/3341099/wi-fi-6-5g-play-big-in-ciscos-mobile-forecast.html

[4] John Bicket, Daniel Aguayo, Sanjit Biswas, and Robert Morris. 2005. Architecture and Evaluation of an Unplanned 802.11b Mesh Network. *MobiCom*.

[5] Detroit Digital Justice Coalition. [n. d.]. Wireless Mesh. ([n. d.]). http://detroitdjc.org/wireless-mesh/

[6] Detroit Digital Justice Coalition. 2016. Digital Justice Principles. (2016). http://detroitdjc.org/principles/

[7] IEEE Computer Society LAN MAN Standards Committee. 1997. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. *IEEE Std. 802.11–1997* (1997).

[8] D. Dhoutaut and I. Guerin-Lassous. 2002. Impact of heavy traffic beyond communication range in multi-hops ad hoc networks. *INC*.

[9] J.J. Garcia-Luna-Aceves and J. Raju. 1997. Distributed Assignment of Codes for Multihop Packet-Radio Networks. *IEEE MILCOM*.

[10] Matthew S. Gast. 2005. Chapter 4: 802.11 Framing in Detail. In *802.11 Wireless Networks: The Definitive Guide, 2nd Edition*. O'Reilly Media, Inc.

[11] Lenin Guaya-Delgado, Esteve Pallarès-Segarra, Ahmad Mohamad Mezher, and Jordi Forné. 2019. A novel dynamic reputation-based source routing protocol for mobile ad hoc networks. *EURASIP Journal on Wireless Communications and Networking*.

[12] J. He and H. Keng Pung. 2003. One/Zero Fairness Problem of MAC Protocols in Multi-hop Ad Hoc Networks and Its Solution. *ICWN*.

[13] Jerome Henry. 2011. 802.11s Mesh Networking (Whitepaper), Marcus Burton (Ed.). *Organization of Certified Wireless Network Professionals*.

[14] Guido Hiertz, Sebastian Max, Yunpeng Zang, Thomas Junge, and Dee Denteneer. 2007. IEEE 802.11s MAC Fundamentals. *IEEE*.

[15] Guido R. Hiertz, Dee Denteneer, Sebastian Max, Rakesh Taori, Javier Cardona, Lars Berlemann, and Bernhard Walke. 2010. IEEE 802.11s: The WLAN Mesh Standard. *IEEE Wireless Communications*.

[16] Makoto Ikeda, Elis Kulla, Leonard Barolli, and Makoto Takizawa. 2011. Wireless Ad-hoc Networks Performance Evaluation Using NS-2 and NS-3 Network Simulators. *IEEE*.

[17] Red Hook Initiative. [n. d.]. Red Hook WiFi. ([n. d.]). https://redhookwifi.org

[18] Jinyang Li, Charles Blake, Douglas S.J. De Couto, Hu Imm Lee, and Robert Morris. 2001. Capacity of Ad Hoc Wireless Networks. In *ACM Annual International Conference on Mobile Computing and Networking*. 61–69. https://doi.org/10.1145/381677.381684

[19] Alagan Ramasamy Rajeswari. 2020. Mobile Ad Hoc Network Routing Protocols: A Comparative Study. In *Recent Trends in Communication Networks*.

[20] Bhaskaran Raman and Kameswari Chebrolu. 2004. Revisiting MAC Design for an 802.11-based Mesh Network. *Third Workshop on Hot Topics in Networks (HotNets-III)*.

[21] Bhaskaran Raman and Kameswari Chebrolu. 2005. Design and evaluation of a new MAC protocol for long-distance 802.11 mesh networks. *MobiCom*.

[22] Xia Gao Thyagarajan Nandagopal, Tae-Eun Kim and Vaduvur Bharghavan. 2000. Achieving MAC Layer Fairness in Wireless Packet Networks. *ACM/IEEE MobiCom*.

[23] Carlos M D Viegas, Francisco Vasques, Paulo Portugal, and Ricardo Moraes. 2014. Real-time communication in IEEE 802.11s mesh networks: simulation assessment considering the interference of non-real-time traffic sources. *EURASIP Journal on Wireless Communications and Networking volume*.

[24] Y. Wang and J.J. Garcia-Luna-Aceves. 2002. A new hybrid channel access scheme for Ad Hoc networks. *Med-Hoc-Net*.

[25] Shugong Xua and Tarek Saadawib. 2002. Revealing the problems with 802.11 medium access control protocol in multi-hop wireless ad hoc networks. *Computer Networks*.