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A Journey from End Systems to Backbone Routers: A Virtual Lab Environment for Online Computer Networking Courses

Dr. Zhaohong Wang, California State University, Chico

Dr. Zhaohong Wang received his Ph.D. in Electrical Engineering from University of Kentucky in 2016. Prior to joining the faculty of EECE at CSU, Chico, he had worked as an embedded system engineer and software engineer throughout his graduate study. His teaching interests include embedded systems, computer networks, and digital signal processing. His current research is about algorithm design for digital signal processing in the encrypted domain and Internet of Things. He has been an active member of IEEE with the Signal Processing Society and Computational Intelligence Society since 2012 and 2016 respectively.

Dr. Jing Guo, California State University, Chico

Dr. Jing Guo got her Ph.D. in Epidemiology and Biostatistics from the University of Kentucky in May 2015. She had worked as a statistician at the Center of Healthcare Services Research at the University of Kentucky before she joined California State University, Chico, as an Assistant Professor in Statistics. Her research interests include nonparametric regression, ensemble machine learning, and relative survival analysis. She is also interested in statistics in information security. She has taught statistics, research methodology in nutritional science, and research methods for healthcare education.

A Journey from End Systems to Backbone Routers - A Virtual Lab Environment for Online Computer Networking Courses

Zhaohong Wang* Jing Guo†

Abstract

Carrying out purely online laboratory for the computer networking course is challenging in a few aspects. Students lack tangible interaction with the physical user interface of physical networking equipment, and for the instructor, setting up a virtual environment precisely matching the real physical lab is unrealistic. To address the problem, we developed a novel virtual lab environment that sheds light on computer networking by showing students components of typical computer networks with both hosts and backbone infrastructure using Wireshark and Mininet. The tools we utilized are a packet sniffer and emulated networking testbed. Even though students do not physically build a computer network as was done in the real lab, they still got insights into a packet's journey from a source host through routers before getting to the destination host. Our data analyses provided the information about the perceptions of these tools for online computer network laboratory from students' perspectives and its associated factors.

1 Introduction

The computer networking course is a critical component in the undergraduate computer science and engineering curriculum. In an era of mobile and ubiquitous computing, almost every embedded device can connect online to make full use of its potentials and accommodate task needs. Hence, a good understanding of computer networking opens doors for many high-tech jobs for computer science and engineering majors. Traditionally, computer networking courses utilize switches and routers in the laboratory environment to give students hands-on projects to enhance their learning experience. However, due to the pandemic situation, many institutions have switched to online learning. The computer networking class is not allowed to access the physical networking equipment in the laboratories. Consequently, computer networking learning loses the critical element of the learning experience, on top of the challenges brought about by online learning.

While instructors could utilize packet capture tools such as Wireshark to teach popular networking protocols, the experience is still not matching the laboratory's real experience with networking equipment. The reason is that it lacks the design and implementation element with

*Dr. Zhaohong Wang is affiliated with the Department of Electrical and Computer Engineering at California State University, Chico. Correspondence concerning this article should be addressed to Zhaohong Wang. E-mail: zwang25@csuchico.edu

†Dr. Jing Guo is affiliated with the Department of Mathematics and Statistics at California State University, Chico.

real equipment. An alternative is to have students run network simulations and emulations to explore various computer networking scenarios by commercial and open-source tools. One of the tools is Mininet, typically used in software-defined networking (SDN) research [1–3]. Without configuring the SDN features, Mininet can still emulate many networking scenarios constructed in the networking laboratory and is more real than simulations.

However, no prior studies were found on students' perception on the usage of both Wireshark and Mininet and the associated factors with students' perceptions on the usage of these tools. The major contribution of this paper is as follows. To our knowledge, this work is the first one to explore the combination of Wireshark and Mininet in the online teaching mode for an introductory computer network course. Moreover, we studied the effect of students' prior perception of the online learning model on students' perception of whether the combination of the two helped students overcome the online learning challenges.

This paper describes our practical way of teaching the computer networking course using hands-on activities with Wireshark and Mininet. Inspired by existing work in Wireshark and Mininet in their use, we designed our novel combination of the two in 12 laboratories. Students would first observe specific protocols by packet capture in Wireshark and then emulate networking scenarios in Mininet for the same protocols. As such, students would be able to investigate end systems and backbone routers in many networking scenarios. Given that students already felt challenged by online learning, our research question is whether our approach to designing the online laboratory through the hybrid-tool helped students remove online learning obstacles on computer networking.

The remaining of the paper is structured as follows. We formulate our research question and briefly survey related work in Section 2. Our proposed virtual lab methods are explained with examples in Section 3. The analysis of results is described in Section 4 and the paper is concluded in Section 5.

2 Related work and problem statement

In this section, we briefly review the existing literature about teaching computer networking course, especially the ones that utilize software tools. Then we describe the specific problem of developing a purely online laboratory for our computer networking course.

Deploying packet sniffers and network emulation tools is always an interest in the teaching community. The authors in [4] provided some hands on practice on networking protocols using Wireshark. Recently, Wireshark played a key role in upgrading data communication and computer network courses [5–8]. Wireshark has been utilized in teaching forensics of SCADA systems [9]. On the other hand, previous research suggested that Mininet is a cost effective approach to introduce physical networks as in the physical laboratory using emulation [10]. In [11], the authors proposed an open online course in computer networks and used Mininet as an emulation tool for prototyping and evaluating SDN implementations. Similarly, Mininet provides opportunites to create hands-on experience in configuring software-defined network [12]. Mininet has also been proposed to train and teach students cybrsecurity in high-throughput networking, emulating private clouds [13]. An alternative to using packet sniffers and network emulation is simulation, a typical open-source one is ns-3 among others [14–17].

As for conducting purely online laboratory for computer networking classes, there is little existing published work as of the writing of this paper. Some related discussion on delivering computer networking lectures online focuses on explaining the theory part with pedagogy methods such as flipped-classroom, but not the online laboratory [18–22].

Given that the computer networking lab instructions were only carried out online, we wanted to design a series of networking laboratories that show students both the end users' perspective and the traversal of packets from end hosts through backbone routers. Therefore, we have chosen to use open-source tools that lowered the cost on the students' side. Section 3 overviews our sample laboratory exercise.

3 Methods of the proposed virtual labs

In this section, we overview some online laboratory exercises built on Wireshark and Mininet, two open-source tools, that aims at providing students a complete perspective on how end hosts as well as backbone routers work for certain communication protocols. The Wireshark portion was adapted from materials generously provided by the authors of the textbook "Computer Networking, a Top-Down Approach" [23] and the Mininet portion was designed by the instructor with documentation available on the Mininet and Mininet-WiFi websites [24, 25].

3.1 Hosts at the edge - Wireshark examining packets

Wireshark, as a packet sniffer, works on many popular end hosts. Therefore, students' laptops or PCs are already platforms to deploy real-life network traffic capture using Wireshark. The setup of Wireshark is straightforward. A user needs to bring up Wireshark first, selecting the user's computer's correct active network interface. Then usually, the user starts a web browser and carries out specified network activities. After some time, the user stops the packet capture in Wireshark. We have utilized Wireshark in almost all laboratories associated with protocols covered in our computer networking course.

In the remaining of this subsection, we describe an example laboratory on TCP using Wireshark. In the next subsection, we describe how we utilized Mininet to build a lab for TCP, showing an analysis of the protocol's internal characteristics.

We deployed the fact that the application layer messages are encapsulated in the transport layer segments. Therefore, we used the HTTP as the application, and all packets leaving and coming in the network interface would have their transport layer information captured by Wireshark. Students then analyzed the TCP header information to interpret the TCP SYN segment that was used to initiate the TCP connection between the client and the remote server, the sequence number of the SYNACK segment, the minimum amount of available buffer space (scaled value) advertised at the receiver client as flow control information, among others. In summary, studying the client end-host reveals some aspects of the protocol design and performance. What is missing is the remote server-side. We deployed Mininet to make up the gap.

3.2 Backbone infrastructure - Mininet emulating computer networks

Continued with the TCP end host experience, we introduced students to internal mechanism of TCP, such as congestion control on the sender's side. We would study the dynamics of TCP in a home network, involving a home host and a remote server. Figure 1 below shows a "typical" home network with a Home Router connected to an end host [26]. The Home Router is connected via Cable or DSL to a remote Server through the Internet service provider's infrastructure. We then guide students on what happens when the end host download data from a remote server to the end host in this home network.

One factor influencing TCP performance is queueing delay, which includes the time packets spend in various buffers or queues. In a real network, it is hard to measure the congestion window (cwnd) because it is private to the Server. The measurement of the router's buffer occupancy is challenging too because it is private to the router itself. However, emulating the network in Mininet makes our measurement job more manageable, and the emulated network allows students to repeat the experiment easily.

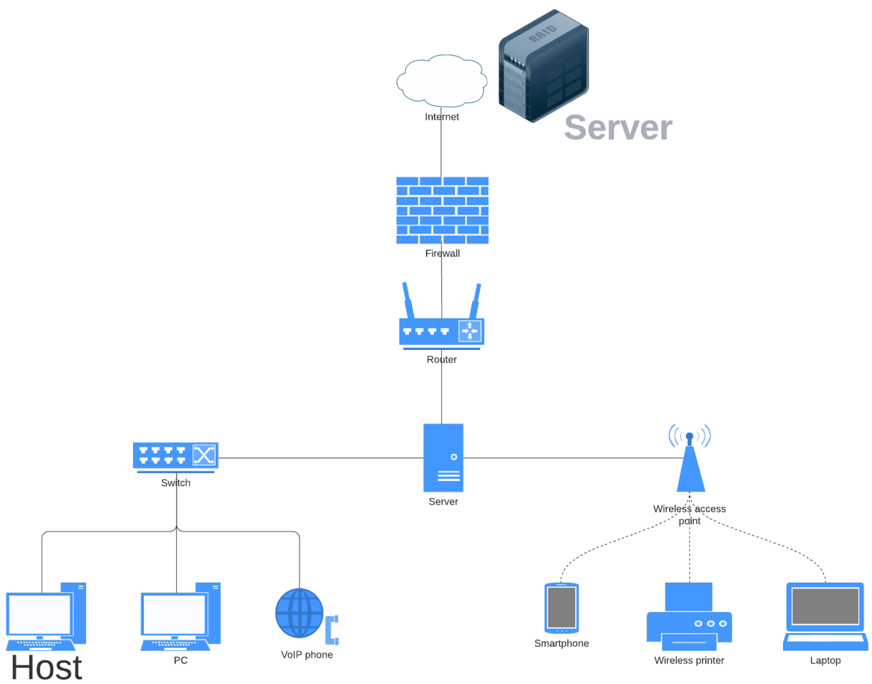

Figure 1: The emulated network for hosts with backbone routers

The script in the lab will setup the Mininet topology as shown in Figure 2. The network in Figure 2 will emulate a scenario shown in Figure 1. The host h2 is the end host and h1 is the Server. The IP address of h1 is 10.0.0.1.

Upon successful setup of the emulated network, students can study what has been missing in the Wireshark portion. Specifically, as the client, the end host can test the congestion control by issuing a series of ping operations toward the emulated Server. More importantly, the Server is also adjusting its cwnd, as the mechanism of congestion control requires. Students will learn TCP Reno in the emulated scenario, giving them hands-on knowledge not learned from the Wireshark part.

The Mininet also provides flexible configuration on the emulated hardware in the experiment.

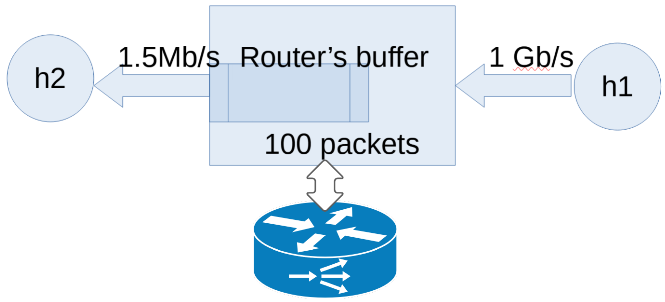

Figure 2: The internal buffer of the router serving the host in the home network

The emulated scenario in Figure 2 allows the student to change the buffer size and the number of independent buffers to separate different traffic types, giving students the experience of performance tuning not feasible with Wireshark alone. The configuration of buffers allows the instructor to explain some scheduling algorithms to students.

As a final example showing Mininet in Wireshark's place, we use Mininet-WiFi to emulate some wireless networks to explain the physical layer. Figure 3 shows a scenario where two mobile hosts are trying to access one access point, where the computer and access point icons were added. Mininet-WiFi can emulate the scenario. While using Wireshark, students can examine packets on their laptops, but with Mininet-WiFi emulated scenario, they learn the mobile hosts and the access point that is difficult to run Wireshark packet capture. Overall, students experiment with the wireless scenario with knowledge of all devices involved in the scenario. It is a strength of Mininet and Mininet-WiFi.

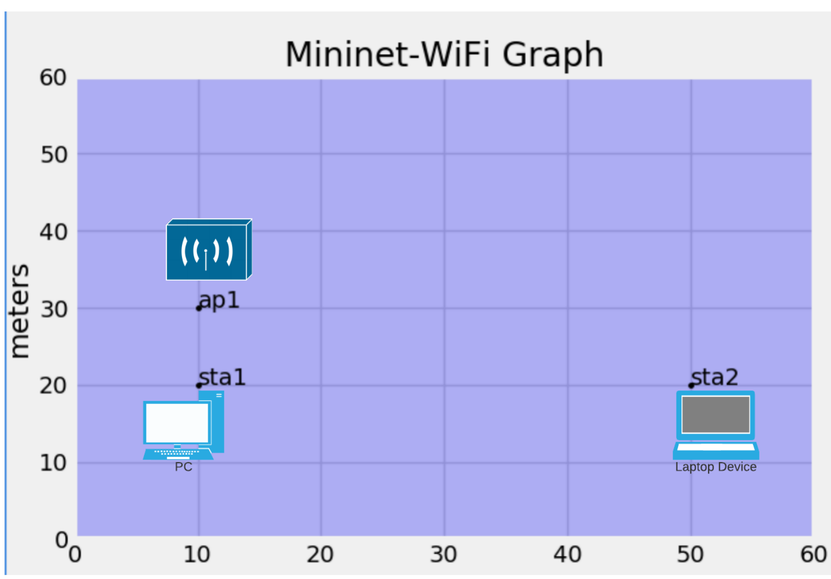

Figure 3: The emulated network for mobile hosts with an access point emulated in Mininet-WiFi

4 Analysis of results

In this section, we present our data collection process and its analyzed results, trying to quantify whether our hybrid approach of developing online laboratories with both Wireshark and Mininet/Mininet-WiFi helped students remove online learning obstacles.

We have designed purely online computer networking labs, 12 in total, for students enrolled in our networking course. Student came from majors of Computer Science and Computer Engineering, with a total of 59 students. All students participated in the 12 labs.

The data we collected is a set of anonymous responses from students to our survey questions. A total of 65 students received the online survey, among which 47 (72.30%) participated the online survey.

4.1 Student survey

We tried to understand students' online laboratory experience by comparing their perspectives before and after completing the computer networking class. We carried out a post-survey of their hybrid-tool laboratory experience by administering an online anonymous survey. Our survey questions are related to the following specific research questions.

- Research question 1: How many students have prior feeling that online learning is challenging before taking the online computer network course and its laboratories?
- Research question 2: How many students have felt the online lab remove the obstacles of online learning? We also wanted to study whether students' prior perception about online learning is associated with students' perception about the online lab tools.
- Research question 3: Compare the students' perception on the use of Mininet and Wireshark: how well did the use of Mininet and Wireshark fulfill their purposes in the instruction?

4.2 Data interpretation

Research question 1: How many students have prior feeling that online learning is challenging before taking computer network course?

Nearly three quarters (74.47%) of the students had agreed or strongly agreed with the statement "I already feel that online learning is overall challenging before taking this computer network course" (95% confidence interval 59.36% - 85.58%).

Research question 2. How many students felt that the combination of Wireshark packet capture and Mininet emulations help them remove online learning obstacles on computer networking?

Nearly half (46.81%) of the students participating the survey had agreed or strongly agreed with the statement "the combination of Wireshark and Mininet emulations helps me remove online learning obstacles on computer networking" (95% confidence interval 32.37% - 61.77%).

Interestingly, as shown in Figure 4, when asked if online learning was challenging before taking this computer network course, 35 students agreed or strongly agreed with the statement. Among these 35 students, 13 students (37%) agreed or strongly agreed with the statement that "the combination of Wireshark and Mininet emulations helps me remove online learning obstacles on computer networking" (95% confidence interval 32.37% - 61.77%), while among the 12 students who had not agreed or strongly agreed with that online learning is challenging before taking computer network course, three quarters (75%) of the students agreed or strongly agreed with the statement that "the combination of Wireshark and Mininet emulations helps me remove online learning obstacles on computer networking" (95% confidence interval 46.8% - 91.1%).

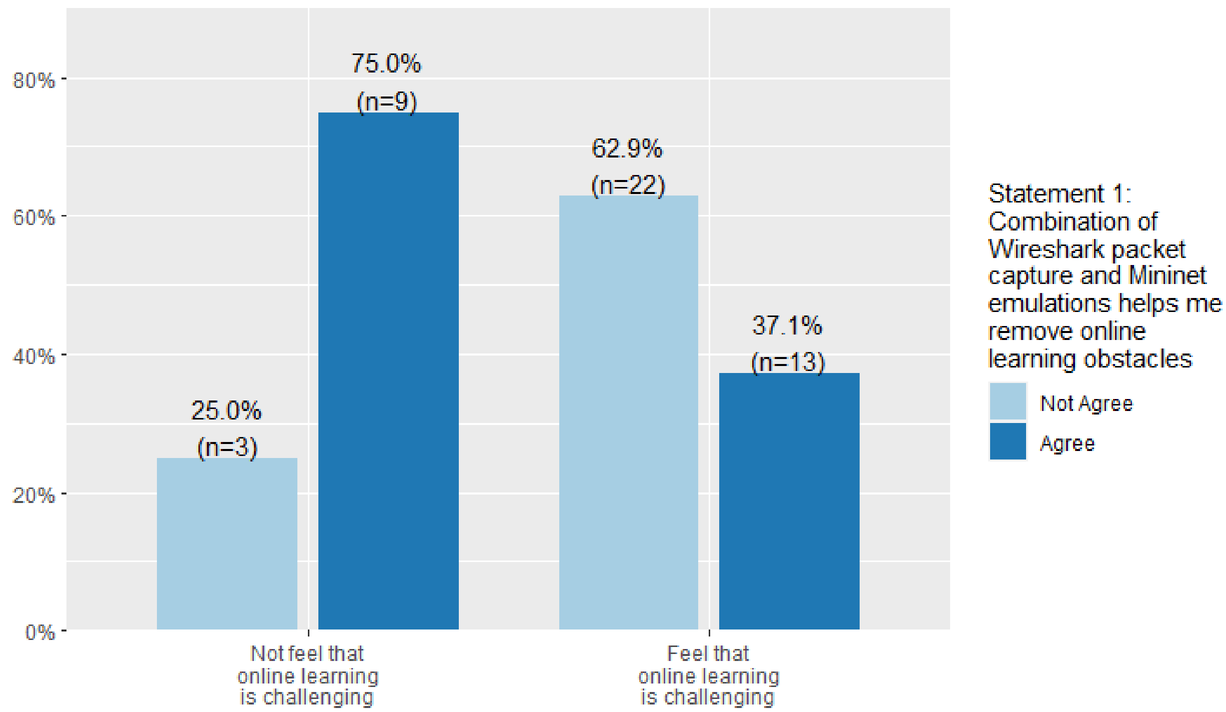

Figure 4: Students' perceptions on the computer network lab instruction modes by prior perception of online learning

The results from Chi square test show that the difference of proportions of students who agreed or strongly agreed with that "the combination of Wireshark and Mininet emulations helps me remove online learning obstacles on computer networking" among those who had prior feeling that online learning is challenging versus those who had not is statistically significant ($\chi^2 = 5.144, df = 1, p = 0.023$). This also indicates that whether students had prior perception that online learning is challenging is statistical significantly associated with their perceptions on whether the combination of Wireshark and Mininet emulations helped them remove online learning obstacles on computer networking ($p < 0.05$).

Research question 3: Compare the students' perception on the use of Mininet and Wireshark: how well did the use of Mininet and Wireshark fulfill their purposes in the instruction?

Each student was asked how they agreed with the two statements with a score ranged from 1 (strongly disagree) to 5 (strongly agree). The first statement was "the emulation in Mininet helped me understand functionalities of routers better", and the second statement was "the packet-capture in Wireshark helped me understand networking protocols better." The summary

Table 1: Descriptive statistics of students' perceptions on the use of Mininet and Wireshark

Summary Statistics	Students' Perceptions(N = 47)
Perception on Mininet	
minimum	1
median (IQR)	4 (3.00, 4.00)
mean (sd)	3.77 ± 1.03
maximum	5
Perception on Wireshark	
minimum	2
median (IQR)	4 (4.00, 5.00)
mean (sd)	4.11 ± 0.91
maximum	5

statistics for the students' responses on these two statements are described in Table 1.

Paired t test was used to compare the students' perception on the use of Mininet and Wireshark. The results from paired t test show that there is a marginally significant difference between students' perception on the use of Mininet and Wireshark ($t = -2.07, df = 46, p = 0.044$). The results from summary statistics show a mean difference of students' perception on the use of Mininet and Wireshark is -0.34, and the standard deviation is 1.12 (Interquartile range from -1 to 0), indicating that students' perception on the use of Wireshark is slightly more positive than the use of Mininet in general.

4.3 Objective Assessment of Student Outcomes

While we collected students' feedback on their learning experience through the online virtual labs, we also gave exams to students to have an objective assessment of their learning outcomes. The exams covered typical concepts found in undergraduate computer networking courses and previous in-person classes:

1. Network performance; the concept of data encapsulation;
2. Application layer: HTTP, DNS, socket programming
3. TCP flow and congestion control
4. IP forwarding
5. IP routing: link state and distance vector routing
6. Physical and Data Link layers; Automatic Repeat ReQuest (ARQ);
7. Introduction to Wireless Networks.

Students' overall performance was almost the same as the previous cohort in the in-person sections. Learning the same topics, the cohort that took the online version achieved a very similar average score, median score, and standard deviation as the previous cohort in the in-person classes.

5 Conclusion and future work

Our findings demonstrated that students' prior perception on online learning is significantly associated with students' perception on whether the combination of Wireshark and Mininet emulations helped them remove online learning obstacles on computer networking ($p = 0.023$). We also show that compared with the students' perception on the use of Mininet, students' perception on the usage of Wireshark is slightly more positive with a difference of 0.34 ($p = 0.04$).

The reason behind the difference in students' perception of the two tools may be the following. Wireshark has a shorter learning curve, but Mininet's emulated network needs to change the configuration from one lab to another. Therefore, when students get used to the GUI of Wireshark, all they need to do in the lab was to examine the header information with some numerical calculation. Mininet involves more scripting and configuration. For future work, we plan to give students more time practicing the operation of Mininet as a pre-lab exercise. We hope the exposure to the emulated environment will help students fully realize the virtual environment's flexibility and power.

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