Teaching Wireless Networking in the Age of Softwarization and AI

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ABSTRACT

In this short paper, we describe the learning goals, course topics, and teaching experiences associated with a course on the principles and practice of modern wireless networks at the advanced undergraduate or master's level, including the open educational resources we have developed for such a course. We emphasize 5G and Wi-Fi networks, but also include Bluetooth, IoT, and LEO satellite networking technologies. Unlike a wireless networking course that focuses on radio communication at the edge, our courses and materials focus on a softwareized (and programmable), full-stack mobile system that includes wireless access networks, as well as core networks, network control, management, and orchestration. While the radio access network (including the physical radio layer) is a critical part of any wireless network course, we also emphasize the levels of abstraction at which students can understand the radio channel and learn how it is programmed and managed, notably through concepts such as Radio Resource Blocks. We also address teaching challenges and opportunities in the age of AI that extend beyond wireless networking.

KEYWORDS

Networking Education, Wireless Networks

1 INTRODUCTION

Wireless networks are becoming increasingly ubiquitous. In 2023, there were nearly five times as many mobile cellular broadband Internet subscribers [1, 2] as fixed broadband Internet subscribers [3]. With nearly 90% of US fixed (wired) broadband subscribers using Wi-Fi in the home [4], the ratio of wired-to-wireless device connectivity is even higher. Given this ubiquity, a course at the advanced undergraduate or master's level on the principles and practice of modern wireless networks (which are typically only a small part of an introductory networking course) would seem natural and compelling for students.

But what are the principles, practices, and perspectives that might infuse such a course today? What types of hands-on experiences (labs, assignments involving "real" wireless networks) might be part of such a course? And how might the advent of LLMs influence how such a course is taught? In this paper, we describe various course learning goals, topics, and perspectives, as well as our experiences teaching and developing materials for such a course. We emphasize 5G and Wi-Fi networks, but also include Bluetooth, IoT, and LEO satellite networking technologies.

Many wireless courses and textbooks focus on radio communication (modulation, coding, transmission, propagation, reception, antennas) at the edge [5–7]. Certainly, the radio access network is a critical part of any modern wireless network. But the radio access network is only one part of a course on softwarized, full-stack mobile systems that includes core networks; network control, management, and orchestration; and topics such as mobility, security, QoS, and application-layer edge services (including AI-driven computing at the edge). In keeping with such a more computer science-y (rather than EE) approach to wireless networks, issues of abstraction, programmability, and a cross-layer and end-to-end systems perspective are important. Students should understand how wireless channel dynamics and link-layer decisions affect transport protocols, mobility, application performance, core-network functions, edge/cloud placement, and orchestration. This perspective will become increasingly important as wireless networks evolve towards O-RAN/RIC, AI-RAN, and AI-native architectures, where communication, computation, data, and control are jointly designed across the RAN, edge, core, and cloud.

The following section discusses the course's high-level learning goals, and the principles, practices, and perspectives that we hope a student would take away from such a wireless course. Section 3 then discusses possible course topics. Section 4 presents open teaching and learning materials that we have developed for the type of wireless course, and provide pointers to these materials. Finally, Section 5 reflects on our experiences as teachers and writers in the age of LLMs.

2 LEARNING GOALS

When we teach or develop materials for a wireless networking course, what is it that we want students to learn?

Perspective. For decades, anyone who has taught a networking course has grappled with the question of what topics to teach and how to teach them, given the complexity of today's networks. For an introductory class (including a first course in wireless networks), one answer to this question is to teach the course so that the network can "fit in a person's head" [8]. In [8], one of us recently wrote, "This 'mental model' is what students take away, and it needs to include only the essentials, with everything else abstracted away. Carefully choosing examples to cover in detail is an important part of that, but ... [t]he details are a means to an end, not the end itself."

Part of this "mental model" is developing a sense of wireless network architecture, as well as an understanding of the fundamental challenges that must be addressed in almost any type of wireless network. The answers to these foundational questions are the principles (see below) that we hope students will take away from the course. These principles will stand the test of time (or at least have a long shelf life) and provide a framework for understanding the many new technologies and practices that will inevitably emerge over time. The abstractions used in a wireless network are also a key part of this mental model. Abstractions teach students about the structure of complex wireless systems without becoming overwhelmed by implementation details. Examples include the resource block as an abstraction of a minimal unit of transmission scheduling, tunneling as a virtual link between two possibly mobile endpoints, circuit-like QoS-related performance abstractions such as guaranteed bit-rate service, the abstraction of network services as network functions (NFs) in the 5G core, "slices" of a 5G RAN and Core network, and more.

A network class will also typically study the "pieces," or building blocks, that make up a network. A structured approach (e.g., edge/core, layering) provides the larger system-wide perspective and context into which individual building blocks fit. A systems perspective emphasizes how the pieces fit together to build a network. Case studies illustrate their use in practice and make the pieces concrete. We've found that all students appreciate a balance of principles and practice, although the precise balance varies among students.

Principles. Introductory networking courses have converged on a fairly common set of principles to be taught, including reliable data transfer, connection management, congestion and flow control, multiplexing and resource scheduling, determining "good" paths through a network, packet forwarding through a switching device, the importance of scalability, and sharing a multiple-access channel. If network security is included, techniques for providing confidentiality, authentication, and message integrity are all based on cryptographic fundamentals. Indeed, one networking textbook [9] that we've appreciated is structured around principles rather than following a more traditional layered approach. A wireless networking course of the type we are considering here and that might follow such an introductory general networking course, is too new and has too few data points to identify any consensus principles. However, we can present a set of principles that we have attempted to teach in our courses.

The characteristics, properties, and theoretical foundations of the underlying radio communication channel are clearly first-class principles in a wireless networking course. Resource allocation, whether the "resource" is a wireless channel resource (e.g., an OFDMA resource block) or computation, storage, or wired-network resources (in the case of function placement), is also important, as are performance considerations (latency, throughput, and energy use) and the provision of quality-of-service guarantees. The principles behind providing support for mobile users and network access and security are similarly important. As discussed above (Perspectives) an understanding of wireless network architecture and an appreciation for the building blocks that make up a wireless network and how they fit together to build a network are also foundational elements of a wireless network course. Students should also develop cross-layer and end-to-end reasoning to understand how physical- and link-layer behavior affects other parts of a network (e.g., transport performance, application quality, mobility, QoS, edge/cloud placement, and orchestration) in full-stack wireless systems.

Practice. As teachers, we've noticed that students are increasingly interested in how networks "really" work and how the network principles we teach are used in practice in deployed systems. Studying real systems grounds principles in practice but, as noted above, is a means to an end (that end being a deep understanding of wireless networking that can "fit" in one's head) , not the end itself. This is a reason that, in our opinion, good teaching materials lead with principles first and then follow with practice, rather than simply describing current practice.

Seeing principles concretized in practice allows students to develop cross-layer and end-to-end reasoning to understand how physical- and link-layer behavior affects transport performance, application quality, mobility, QoS, edge/cloud placement, and orchestration in full-stack wireless systems. An appreciation of practice can also include the business aspects of wireless networks. This includes the ecosystem of 5G carriers, MVNOs, and private 5G; application use cases (enhanced mobile broadband, real-time communications, and

IoT), and policy issues, such as spectrum allocation and privacy.

And, of course, the study of practice allows students to "learn by doing," which our experience as teachers tells us is important for learning. This aligns with the old proverb, "Tell me and I forget. Show me and I remember. Involve me and I understand." As discussed in Section 4 below, we've developed teaching materials in support of such "hands-on" experience, including Wireshark labs, programming assignments, and labs based on bringing up a live cloud-based open-source 5G network and performing experiments and measurements in that network. We consider these experiences an essential part of the wireless networking courses that we teach.

3 TOPICS IN A WIRELESS COURSE

In this section, we outline topics that we teach in our wireless networks courses and that we've included in our teaching materials. Our aim here is not to be prescriptive. Indeed, there are more topics than we think can be covered in a one-semester course, and none of us teaches all of the topics below. Instead, we offer this list simply as a starting point. We expect that any teacher will choose various topics for a course, treating them in more or less detail, and adding additional topics and perspectives as well.

Characteristics of the wireless channel. Radio waves: amplitude, frequency, and phase; radio transmission: power, bandwidth; radio channel: noise, Signal-to-Noise (SNR) ratio, capacity, path loss, multipath, hidden terminals; antenna; radio spectrum.

Coding and Modulation. From bits to symbols to waveforms. Physical-layer coding; modulation: amplitude, frequency, phase; QPSK, QAM; abstractions: symbols, resource elements, and resource blocks.

Channel access techniques. The multiple access problem, TDMA, FDMA, CDMA, random access, polling, OFDMA, dynamic spectrum sharing, CBRS.

Wi-Fi (802.11). Architectural elements, channels, standards, AP association, CSMA/CA, OFDMA in WiFi 6/7; the 802.11 wireless link layer, protocols, MAC scheduling, energy management, joining a WiFI network.

5G Radio Access Network. Architectural components of 5G networks; 5G RAN: the physical radio channel; physical and logical control and data channels; the 5G link layer; local breakout; resource black scheduling; energy management, channel measurement, joining a 5G RAN.

Softwarization. Using open-source software platforms and tools for hands-on experience. Includes Software-defined radios (SDR), Software-defined networks (SDN), and Software-defined RAN (SD-RAN).

5G Core Network. Evolution: from 2G to 3G to 4G to 5G; 5G Core Network Functions; user-plane function and tunneling; user identity, registration, session establishment.

Mobility. Principles and approaches; mobility in a WiFi network; mobility in 5G: home and visited networks, handover (within home network; among networks), paging, tracking; mobile IP.

Wireless network security. Primer: cryptography, digests, digital signatures, authentication; 802-1x; WPA3; identity, authentication, key derivation in 5G.

QoS. RAN Slicing. End-to-end slicing. Signaling and control mechanisms.

Managed Cloud Service. Building blocks for a modern cloud service for 5G control, management, orchestration: Docker, Kubernetes, Helm, Fleet, Terraform; example deployment; cloud management platforms.

Cross-layer and AI-native wireless systems. Explore how wireless dynamics and RAN decisions affect transport protocols, applications, latency, reliability, and QoS; interactions among the RAN, core, edge/cloud, and applications; and emerging O-RAN, AI-RAN, and AI-native architectures for joint communication, computation, data, control, and orchestration. Examples of AI/ML-driven control and management.

Bluetooth, satellite, IoT networks. These are important types of networks beyond cellular and WiFi networks, each with a unique architecture that reflects its purpose and each of which teaches new principles. Many teachers may want to dive deeply into one or more of these networks. In addition to teaching their overall architectures, an instructor might want to consider their unique "specializations," which include the radio channel, non-IP stack, and BLE energy management (for Bluetooth); infrastructure mobility, satellite constellations, and localization (for satellite networks) and energy management and application case studies (for IoT).

4 OPEN EDUCATIONAL RESOURCES

In the lists below, we provide pointers to open materials that we have developed and/or use for wireless networking courses that embody the ideas from Sections 1 - 3 above. We provide these in the hope that many will find them useful, adopt and adapt them for their own use, and provide us feedback about how to further improve and extend these resources.

- https://5g.systemsapproach.org/index.html. An in-depth look at a cloud-native implementation of 5G based on the Aether open-source project. It includes both a systems-focused decomposition of the design and tutorial to help readers install, study, and experiment on a 3GPP-compliant platform (including commercial 5G small cells).

- https://gaia.cs.umass.edu/wireless_and_mobile_networks/. This page contains open teaching/learning materials for a full-semester course (at the advanced undergraduate or master's level) on the principles and the practice of wireless and mobile networks, with an emphasis on 5G cellular and Wi-Fi networks. The material includes a draft textbook, more than 700 Powerpoint slides (many animated), Wireshark Labs, and programming assignments (including MAC scheduling and programming a live SD-RAN xApp).
- https://gitlab.noc.onelab.eu/2026-cell-projects/5G-Cell-Class.git. This course contains open teaching/learning materials for a full-semester course on 5G cellular networks taught at the second year of the Master's program. It is composed of 13 classes of 2 hours , including projects, labs, and Powerpoint slides (many of these slides are borrowed from the reference above). Lab activities are integrated with the development of the 5G concepts so that students can deploy their own "5G-in-a-box" system at the end of the class. It uses the SLICES-RI 5G blueprint.
- The following open-source platforms support a teaching flow that begins by illustrating the 5G Core (using free5GC), then moves to observing UE registration and session setup (using UERANSIM), and finally introduces OAI for more realistic RAN/SDR-based experiments.
  - https://github.com/free5gc/free5gc. An open-source 5G Core implementation suitable for teaching the service-based architecture of 5G. Students can study major network functions such as AMF, SMF, UPF, NRF, AUSF, and UDM, and how control-plane and user-plane functions interact.
  - https://github.com/aligungr/UERANSIM. A 5G UE and gNB simulator. It is especially useful in classes because students can understand 5G registration, PDU session establishment, NAS/RRC behavior, and core-network interaction without SDR hardware.
  - https://github.com/OPENAIRINTERFACE. A practical open-source platform for learning how real 4G/5G systems are implemented. It is useful for teaching RAN, UE, 5G Core, SDR-based experiments, protocol stacks, and O-RAN concepts.

5 TEACHING IN THE AGE OF LLMS

In keeping with the theme of this workshop, in this section we offer concluding thoughts on teaching and learning. Our broader reflections here transcend the specific topic of wireless networks and consider our work as teachers and writers in the age of AI and LLMs.

AI provides an opportunity to rethink how students acquire skills, moving from conceptual understanding to deployment and experimentation. This approach is particularly well suited to hands-on and project-based learning environments, and naturally connects with emerging perspectives on personalized education. Perhaps courses could be organized around cycles of interactions between the AI/agent and the learner. LLMs are likely to profoundly transform the way students acquire knowledge and develop skills. Instead of spending most of their time searching for information or solutions, students will need to focus on framing relevant questions. In particular, critical thinking will become even more important, as they will be expected to assess the correctness, relevance, and limitations of AI-generated responses. In this transforming educational landscape, the role of teachers will increasingly evolve from providing information to guiding students in developing sound judgment, thought reasoning, and the ability to use AI tools responsibly and effectively.

As teachers, the advent of LLMs has naturally caused us to ponder the question of "Why should I teach in the age of LLMs?" For two of us, as textbook authors, we additionally think about "Why should I write a textbook given LLMs?" and "Why would a student want to learn from a textbook, rather than an LLM?" Perhaps one answer to such questions is that the questions themselves are wrong, that the "either/or" phrasing (either a teacher or an LLM, either a textbook or an LLM) is wrong. The right questions should really address the co-existence of class-based teaching/learning (whether in-class or online, whether synchronous or asynchronous), textbooks (and other teaching/learning materials) and LLMs.

LLMs are great (or are becoming great) as on-demand answer engines for specific questions. The universe of questions a student can ask is larger than any teacher can fit in their head, or any textbook writer could (or should) put in a book. As teachers, we've never hesitated to tell a student with a detailed question (e.g., about a bit in a protocol header that we didn't know off the top of our heads) that a teacher is not a walking compendium of RFCs; we'd then look up and discuss the RFC together. Now we'll ask an LLM (and then go to the corresponding source document to avoid any LLM-hallucinated answers). Humans already can't compete with LLMs when it comes to immediate, on-demand answers to specific questions.

What LLMs have not mastered is how to teach a body of knowledge and how to guide and inspire students toward learning and discovery. This relates to the notion of perspective discussed above and as nicely articulated in [10]. One might also call this a matter of "taste," particularly when it comes to which topics to leave in, and which to leave out. A particular networking course or textbook very much reflects such tastes. In addition to what is presented in a course or book, there is also an important question of "how" that material is presented. As teachers, this "how" a topic is taught is based on our past teaching of students (in many cases over decades), practicing it in industry, and/or discovering it in research. As teachers, we have learned what approaches work best, and where misconceptions and true "pearls of wisdom" and insight might lie.

When we teach and write, we do so with people (students, readers) in mind. As textbook authors, we often visualize students around the world whom we've never met in person. We hope that is reflected in our teaching and writing – that students and readers can feel that by-a-human-for-a-human creation and curation behind the work. Interacting with an LLM for too long a time leaves one a bit numb; being at a computer too long leads to "a dehydration of human interaction" [11]. Conversely, time spent in a lively class or with a good textbook (or novel) is enlivening and energizing; it encourages and enriches, rather than flattens, experience. The "people" connection matters.

Lastly, we'd note that teaching and writing bring each of us great joy. It's one of the main reasons that we do what we do! Putting aside the question of whether or not an LLM can teach a course or write a book about wireless networking (we've outlined above, though, why we think that's not the case), and even granting that an LLM might eventually produce a statistically-driven emulation of actually doing so, does that mean we should abandon these activities that bring us such great joy? A recent essay on writing in the age of LLMs [12]] argues that we should not give up these activities precisely because they do bring us such great joy. We believe that this enjoyment infuses our work and, indeed, during our best moments, our students and readers tell us so. They also tell us that that quintessentially human element provides them with motivation and engagement. That joy and that "people" connection do indeed matter.

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