Tutorial title – **A Systematic Framework for Cross-layer Optimization in Dynamic Communication Systems**

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Intended length of the tutorial: 1 day (or half a day, how the organizers prefer)

Motivations and objectives

In layered network architectures such as the Open Systems Interconnection (OSI) model, the functionality of each layer is specified in terms of the services that it receives from the layer(s) below and that it is required to provide to the layer(s) above. The advantage of layered architectures is that the designer or implementer of the protocol or algorithm at a particular layer can focus on the design of that layer, without being required to consider all the parameters and algorithms of the rest of the stack. However, in current layered network implementations, each layer often optimizes its strategies and parameters individually. This generally results in sub-optimal performance for the users/applications. Cross-layer optimization solutions have been proposed in recent years to improve the performance of network users operating in a time-varying, error-prone wireless environment. These solutions optimize the protocol parameters in an integrated fashion by jointly and simultaneously considering the dynamics at each layer and requiring layers to provide access to their internal protocol parameters to other layers. However, a majority of these integrated approaches violates the layered network architecture of the protocol stack, thereby requiring a complete redesign of current networks and protocols and leading to a high implementation cost. This motivates us to present a new, systematic cross-layer optimization framework, which adheres to the current layered network architecture, and allows layers to determine their own protocol parameters, and exchange only limited information with other layers.

Abstract:

Cross-layer optimization problems in wireless networks tend to be very complex, since they require the simultaneous optimization of a large number of algorithms and parameters within various layers of the protocol stack. Moreover, they need to explicitly consider the time-varying channels, networks and applications characteristics. Most existing solutions for cross-layer optimization rely on heuristic procedures to solve this problem. However, to obtain an optimal utility for the wireless user, the cross-layer optimization should be formulated rigorously as a sequential decision problem that takes into account the capability of the various layers to autonomously *forecast* their own locally experienced dynamics, and perform foresighted adaptation, without violating the current layered architecture of the protocol stack.

In this tutorial, we present a systematic framework for cross-layer optimization that allows each layer to make *autonomous* and *foresighted* decisions on the selected transmission strategies (e.g. protocol parameters and algorithms), while cooperatively maximizing the utility of the wireless user (e.g. multimedia quality) by determining the optimal information to be exchanged among layers. Specifically, this tutorial will focus on the following three areas:

- *Introduce a systematic cross-layer optimization framework* in which each layer optimizes its own protocol parameters and algorithms based on its own experienced dynamics and information exchanged with other layers, in order to cooperatively maximize the wireless user's utility in a foresighted manner. We will extend the proposed layered framework for dynamic cross-layer optimization to a networking scenario, where multiple users, with different cross-layer strategies, interact. We will also design a message exchange mechanism that can allow multiple users to make optimal cross-layer transmission strategies decisions and analyze how the interactions evolve over time, given different environment dynamics.
- *Introduce a formal message exchange mechanisms among layers* in which messages capture the experienced dynamics and the performed transmission strategies, but the format of the message is independent of the specific strategies/protocols deployed, and dynamics experienced at each layer. This message exchange framework enables wireless users to easily upgrade the protocols and algorithms implemented at the various layers, and it does not require any changes to the current layered network architecture.
- *Introduce on-line learning algorithms for the cross-layer optimization.* In practice, the environmental dynamics are often unknown. To overcome this obstacle, we show how layers can learn the impact of the environmental dynamics using reinforcement learning techniques. We show how a layered learning approach can be developed, which remains compliant with the layered network architecture. This layered learning solution allows each layer to interactively learn the experienced dynamics and other necessary information from other layers, such that the cross-layer strategies can be optimized cooperatively, in an on-line fashion.

This tutorial will draw from the fields of multi-user wireless networking, delay-sensitive communication, optimization and online learning. A unique and distinguishing feature of this course as compared to other cross-layer design courses is the rigorous approach and formalism used in defining, characterizing, solving and analyzing an entire range of wireless communications and networking problems. We will also pay specific attention to delay-sensitive applications, such as multimedia streaming and online gaming, because the impact of optimal cross-layer design is especially dramatic for such transmission scenarios.

Outline

1. Motivation
2. Cross-layer optimization problems in communication networks
3. Classes of cross-layer solutions
    a. Centralized vs. distributed
    b. Myopic versus foresighted solutions
    c. Packet-based versus flow-based solutions
4. Mathematical tools for cross-layer optimization
    a. Distributed optimization
    b. Markov decision processes
    c. Online learning
5. A systematic solution for cross-layer optimization of single-user wireless systems
    a. Heterogeneous traffic modeling
    b. Rigorously defining the QoS
    c. Properties of optimal cross-layer transmission policies
6. A systematic solution for cross-layer optimization of multi-user wireless systems

    a. Dynamic cross-layer optimization formulation
    b. Decomposition principles and corresponding multi-user solutions
    c. Message exchange mechanisms – inter-layer and inter-user
    d. Extensions to multiple-hop multi-user systems
7. Learning solutions for online cross-layer optimization
    a. Model-free learning solutions
    b. Model-based learning solutions
8. Applications to multimedia streaming, peer-to-peer networks, cognitive radios, and ad-hoc networks

Scope:
The tutorial will provide insights into

- Heterogeneous traffic modelling, including multimedia traffic modelling
- Different QoS provisioning in the various layers (Hard and Soft QoS)
- Solutions, comparisons and limitations of existing protection and adaptation mechanisms in the various network layers
- Pros and cons of the separation of layers and implications for cross-layer optimization for efficient wireless transmission
- Dynamic cross-layer design framework for multimedia transmission in time-varying wireless networks
- Decomposition principles across layers
- Designing optimal message exchange mechanisms across layers
- Multi-user cross-layer design
- Cross-layer design for ad-hoc wireless transmission
- Standards and industry forums
- Remaining technical challenges
- Examples and demonstrations

Intended audience:
The course is intended for professionals, researchers and students working in networking and communications industries, and interested in cross-layer design, wireless streaming solutions, delay-sensitive wireless communications etc.

Material used:
Very recent tutorial articles and journal papers from various magazines and journals

History of the tutorial:
Mihaela van der Schaar gave in the past 8 times a tutorial on Cross-layer design for wireless multimedia systems at various IEEE conferences. However, this new tutorial, while building on the past expertise, represents a significant departure from the past tutorials she presented. Different from our past work on cross-layer design, the emphasis is now on developing a systematic framework for cross-layer design aimed at maximizing the wireless users' utilities, while also obeying the current layered network architecture. The proposed systematic solution foresightedly optimizes the cross-layer transmission strategies by considering the dynamics experienced by various layers of the OSI stack. Also, as compared to the past, many more examples and a comprehensive review of the theory and practice of cross-layer design is given.

Biographical sketch of the presenters:

Mihaela van der Schaar is currently an Associate Professor in the Electrical Engineering Department at University of California, Los Angeles. She received in 2004 the NSF Career Award, in 2005 the Best Paper Award from IEEE Transactions on Circuits and Systems for Video Technology, in 2006 the Okawa Foundation Award, in 2005, 2007 and 2008 the IBM Faculty Award, and in 2006 the Most Cited Paper Award from EURASIP: Image Communications journal. She was an associate editor for IEEE Transactions on Multimedia, Signal Processing Letters, Circuits and Systems for Video Technology, Signal Processing Magazine etc. She also holds 32 granted US patents and three ISO awards for her contributions to the MPEG video compression and streaming international standardization activities. Her research interests are in multimedia communications, networking, processing and systems. She has extensive experience in giving short courses at IEEE conferences, companies and universities for both professionals and PhD students. She also gave 15+ tutorials at various IEEE conferences starting in 2001.

Fangwen Fu received the bachelor's and master's degrees from Tsinghua University, Beijing, China, in 2002 and 2005, respectively. He is currently finishing his Ph.D. degree in the Department of Electrical Engineering, University of California, Los Angeles. In 2008, he was selected by IBM Research as one of the 12 top Ph.D. students to participate in the 2008 Watson Emerging Leaders in Multimedia Workshop. His research interests include wireless multimedia streaming, resource management for networks and systems, applied game theory, video processing, and analysis.