A high-level discussion of the UCLA Multimedia Communications and Systems Lab research focus

Motivation

In case you haven't noticed, multimedia communication over Internet and wireless networks is exploding: We talk to our friends using Skype; download movies from Netflix; stream news from websites such as CBSNews.com; stream TV shows and movies from websites such as hulu.com; view user-created content on YouTube; and watch peer-to-peer television using CoolStreaming, PPLive, and Joost. Multimedia communication also enables life-enhancing applications such as remote-teaching and telemedicine. However, to enable these various services to become truly ubiquitous and operate transparently, multiple networked devices and applications need to simultaneously compete for the scarce resources of, for instance, wireless networks.

We consider multimedia applications not only because of their practical importance, but also because they bring unprecedented theoretical challenges for next generation communication systems' designs due to their time-varying bandwidth requirements, stringent delay deadlines, and dynamic characteristics, and due to the informationally-decentralized environments in which they need to operate.

Why is a new theory needed?

The current communication boom was enabled by the pioneering work of Claude Shannon, who developed the mathematical basis of today's communication theory, now referred to as information theory. However, information theory does not provide a mathematical foundation to deal with applications having stringent delay constraints and time-varying characteristics over dynamic network infrastructures. Also, information theory does not provide separation principles, decomposition rules or rigorous methods for jointly optimizing the various layers of the protocols stack such that the performance of multimedia over IP and wireless networks is maximized. Moreover, it does not provide solutions for multi-user environments, where devices can strategically self-organize in order to share or compete for the resources based on limited information.

The analysis of multi-user interactions is considered in game-theory, to which another brilliant mind made key contributions: the mathematician and economist John Nash. However, microeconomics today mainly studies the design of game or system rules to achieve a specific outcome (e.g. mechanism design etc.), tries to explain the behavior of supply, demand and prices of existing markets (e.g. general equilibrium theory), or to characterize the equilibrium outcomes of given games (e.g. game theory). It most often neglects how users acquire information; how they interact and successfully compete with each other in repeated or stochastic games based on their local asymmetric information; how they learn over time based on this information; and how they cope with time-varying utilities and environments. Also, it rarely discusses how informationally-decentralized games can be constructed and equilibriums be selected such that the users can play a specific, hopefully efficient equilibrium, based solely on their local information. Finally, it does not discuss how multi-user interactions can be shaped by network policers making private observations about the users' interactions and deploying only minimal interventions to induce users to adopt desired behaviors.

Our goal

Hence, our focus in the past couple of years has been to develop a rigorous mathematical framework that enables us to analyze, design and optimize dynamic and heterogeneous multi-user environments and applications. We are working towards constructing a new theory for *architecting* next-generation wired and wireless networks and systems which are able to support media applications.

Our approach

We model the dynamic, repeated interactions among the heterogeneous devices as stochastic or repeated games played over time based on the dynamic changes in the network environment and the delay-critical characteristics of the applications. To enable the devices to successfully participate in the resource competition and maximize their performances as well as the overall network performance, we need to carefully “design” the devices’ utilities and allow them to strategically compete for resources. This is unlike current communication solutions, which requires them to follow prescribed and rigid interaction rules, thereby often result in inefficient resource allocations or the manipulation of rules.

In our proposed paradigm, the devices become *cognitive* entities, which can harvest knowledge about each other as well as the environment by proactively learning based on their locally available information, in order to strategically maximize their *designed* utilities. Note that the heterogeneous devices may have different utilities and cost-performance tradeoffs, and that the information acquired by different devices may be asymmetric and it may be inferred by the devices, based on their repeated interactions with environment or other devices, or directly exchanged as part of collaborative interactions. In the considered paradigm, the emerging collaborative interactions among devices are self-enforcing rather than being mandated by fixed, predetermined protocol rules, as in current network designs. Also, the cognitive devices will need to deploy online multi-agent learning solutions in order to be able to make accurate forecasts about the impact of their actions on the dynamic environment and other devices’ behaviors and, based on this knowledge, determine how to interact with the other users.

In the envisioned network architecture, the cross-layer transmission solutions deployed by the users become the strategies with which network users can interact, influence each other, compete and/or cooperate. However, in these dynamic, delay-sensitive and competitive environments, well known information theoretic concepts such as Shannon’s source and channel separation principles for communication systems designs no longer hold. Hence, in the past years, we tried to identify new decomposition principles and optimal multi-scale dynamic interactions across the various layers of the protocol stack, which can be used to architect and optimize next generation communication systems. We have shown that devices that are capable to adopt more efficient cross-layer transmission strategies can better compete or collaborate in the multi-user stochastic games.

Future vision

We hope that our new theoretical and practical framework for characterizing, designing and optimizing multi-user interactions will add a new dimension to well-established theories such as communication and networking theory, and even game theory. This will be done by enabling devices to proactively and strategically interact with each other in order to maximize their own performance based on their asymmetric information, and ability to form beliefs and heterogeneous knowledge, rather than obliging them to passively comply with *rigid*, *pre-determined*, *protocols* as in current networks and communication systems. Current protocols and system design today are not only easily manipulated by smart devices, thereby leading to a *tragedy of commons* and resource misuse, but also they inhibit the ability of devices to gather information and knowledge in order to improve their performance and, in many cases, the network performance.

In our proposed framework, rather than encourage rigid and passive interactions, our goal is to design individual users' goals such that higher efficiency outcomes from both a user’s perspective and a communication system’s perspective can occur when users are strategically maximizing their own goals. From a practical perspective, this can lead to a fundamentally new way for designing and optimizing next generation communication systems and applications, where devices evolve and become smarter, by learning from their interactions with other devices over time. It is our vision that designing communication systems as “markets”, where devices with different private knowledge can dynamically *compete* for resources based on their designed objective functions rather than passively obey the guidelines imposed by resource owners and protocol providers, will lead to unprecedented performance improvements for both individual users as well as the overall communication system and will catalyze the development of new algorithms, system designs and applications.

To test this framework in practice, we are currently considered wireless and wired communication systems and networks, as well as heterogeneous multimedia systems ranging from grid computers and multi-core systems to handheld and battery powered embedded systems.