

Tutorial Proposal

Distributed Resource Orchestration in Realistic 6G Wireless Systems: From Practice, to Theory, to Practice

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Abstract

Conventional distributed resource management approaches in realistic 6G wireless systems with shared resources, fail to capture the deep inter-dependencies among the user behaviors, interactions, and decisions, under partial system information availability, uncertainty of system available resources, and hence, potential user/system risks and gains. In this tutorial, we first identify the practical challenges of realistic 6G wireless systems, and subsequently, introduce a series of mathematical tools and mechanisms to deal with the issues of: (i) resource sharing under incomplete/partial information (via Contract Theory), (ii) distributed resource allocation based on Quality of Service (QoS) satisfaction (via Game Theory and Satisfaction Games), (iii) risk-aware resource sharing (via Prospect Theory). The application of the aforementioned theories and models in real-life problems in the field of bandwidth sharing in wireless networks and computing resource sharing in Multi-access Edge Computing (MEC) systems, complements the overall tutorial's scope.

Keywords

Contract Theory, Satisfaction Games, Prospect Theory, Resource Allocation, Spectrum Sharing, Edge Computing Resource Sharing, 6G Systems

Duration

Half-day (3 hours of instruction)

Tutorial Proposal Description

1 Scope & Objectives

The focus of this tutorial is placed on the distributed resource orchestration in realistic 6G wireless communications and computing systems. We adopt a scientific and technical path, that is enabled by and enables, the following vision: from practice, to theory, to practice. In that respect, we initially highlight the specific and inherent characteristics and features that are present in realistic NextG wireless communication systems and challenge the application of traditional resource allocation approaches. Such characteristics range from resource uncertainties, partial information availability for decision making, involved stochasticity in particular due to the nature of the shared

resources, and the involved risks in the corresponding decision making both from user and system perspective. Then, we present the foundations, theoretical tools and mechanisms to deal with those issues in the resource allocation process. Furthermore, respecting the need for distributed and scalable solutions and algorithms, the focus is placed on the study of user-driven and non-cooperative game theory paradigms, where decisions are taken autonomously by devices interacting with each other. Finally, we demonstrate the application of those solutions to some indicative realistic scenarios, involving both communications and computing resources and different networking paradigms.

The specific topics that are covered in this tutorial are the following:

- Resource sharing under incomplete/partial information via Contract Theory: Contract Theory provides the mathematical foundations to create mutually agreeable contracts or arrangements between economic players, i.e., principal/employer(s) and agents/employees, in presence of complete or incomplete information (often referred to as partial or asymmetric information). The incompleteness of information regards the unknown distinguishing characteristics of the agents from the principal's behalf, which may be conflicting to the latter's objective and requirements. The purpose of the contract is to motivate the agents smartly leverage on their private information and perform actions that are mutually beneficial for both contracting parties.
- Distributed resource orchestration relying on QoS satisfaction via Satisfaction Games: A Satisfaction Game (or equivalently a Game in Satisfaction Form) denotes a specific representation form of a game in game theory, different from the typical normal or strategic form game, the purpose of which is to capture the idea of "satisfy instead of maximize". In this tutorial, the basic formulation of a non-cooperative game in satisfaction form is pursued, according to which each user aims at investing sufficient resources towards satisfying its QoS prerequisites, rather than purely maximizing its utility, mitigating the unjustified resource drainage and the unfair resource allocation among the users.
- Risk-aware resource sharing based on Prospect Theory and the Tragedy of the Commons: Prospect Theory and the Tragedy of Commons are theoretical tools used to appropriately formulate utility functions of the users, towards examining resource allocation cases where the users can discriminate between a safe resource and a resource prone to failure (Common Pool of Resources, CPR), when over-exploitation takes place under specific probabilistic assumptions. The designed utility functions of the users may, then, be utilized along with game theory-based methodologies to treat common resource sharing problems, while at the same time taking into account the users' relative sensitivity to gains and losses, or satisfaction and risk.
- Application of the aforementioned models and methodologies in the field of communications and computing systems: In particular the resource orchestration process and decision-making will be demonstrated in the realistic scenarios of bandwidth sharing in wireless networks and computing resource sharing in Multi-access Edge Computing (MEC) systems.

The main novelty of this tutorial is that it does not only lay the foundations of a solid theoretical network design framework based on the intersection of Game Theory, Prospect Theory, Tragedy of the Commons, and Contract Theory, but it can influence industrial thinking on technologies of next-generation networks. The tutorial gives a fresh and novel flavor to the real-life modeling for efficient resource management in heterogeneous multi-user and multi-tier systems, and the design of feasible energy-efficient protocols in interdependent resource-constrained 5G/6G systems.

2 Intended Audience

The tutorial is intended for a broad audience of both researchers and professionals, spanning the engineering, mathematical, operation research and finance communities. Owing to its modular content, the theoretical part of the tutorial that aims to provide the audience with the basic understanding of the different theoretical tools' principles and operation characteristics, is oriented towards the more interested researcher, graduate student or post-doctoral researcher. At the same time, networking and telecommunications engineers working in the industry, as well as professionals involved in the financial or social sciences, should be interested in the actual application of the considered theoretical tools to realistic resource sharing scenarios. It is remarkable that the timely problem of resource sharing is encountered in most disciplines in its generic form and hence, different concepts and ideas presented in the tutorial can be adopted by different disciplines and studies. Specific use cases and realistic scenarios will be used and selected for demonstration purposes stemming mainly from the emerging integrated wireless communication and computing networking environments, being of specific interest to the researchers and practitioners in the communication and computer engineering community.

3 Outline

The presentation of the tutorial is mainly steered by the adopted analytical methodology "from practice, to theory, to practice", and can be organized in a number of sections and subsections. The following list indicates the sequence of the topical areas to be included in the presentation:

1. Introduction to realistic 6G wireless systems (30 minutes)
 - 1.1. Existing challenges in traditional resource sharing in realistic systems
 - 1.2. Examples related to dynamic spectrum sharing and edge computing resource allocation
2. Contract Theory: Incentives in resource allocation under incomplete/partial information (60 minutes)
 - 2.1. Basic principles, classification and models
 - 2.2. Examples of contract-theoretic resource management in 6G wireless systems
3. Satisfaction Games: A game theory tool for QoS satisfaction in resource allocation (30 minutes)
 - 3.1. The concept of "satisfy" instead of "maximize" and basic principles
 - 3.2. Examples of satisfaction game-based resource management in 6G wireless systems
4. Prospect Theory and the Tragedy of the Commons: A risk-aware resource allocation approach (45 minutes)
 - 4.1. Introduction to Prospect Theory and differences from Expected Utility Maximization Theory
 - 4.2. Introduction to the Tragedy of the Commons and the common pool of resources
 - 4.3. Joint utilization of Prospect Theory and the Tragedy of the Commons in 6G network scenarios
5. Summary, future directions and vision (15 minutes)

The tutorial will, first, include an introduction to the major challenges of the realistic 6G wireless systems that limit the potential of conventional distributed resource management approaches. Specifically, examples from the fields of dynamic spectrum sharing in wireless networks and edge computing resource sharing in MEC systems will be used to provide a holistic picture of the emerging resource management problem. In the sequel, three distinct sections will be organized to independently treat the problems of resource sharing under incomplete/partial information (Section 2), distributed resource allocation based on QoS satisfaction (Section 3), and risk-aware resource sharing (Section 4). The scope of each of the aforementioned sections is to provide the basic notions, principles, and models of the corresponding mathematical tool under investigation, i.e., Contract Theory, Satisfaction Games, Prospect Theory and the Tragedy of the Commons, and then, present a set of broad application cases of these theories in the fields of communication and computing resource sharing in 6G wireless systems, as indicated earlier. Finally, an overview of the discussed topics in the tutorial will be provided, along with challenges and future directions.

4 Biographies of Presenters

Symeon Papavassiliou is currently a Professor in the School of ECE at National Technical University of Athens. From 1995 to 1999, he was a senior technical staff member at AT&T Laboratories, New Jersey. In August 1999 he joined the ECE Department at the New Jersey Institute of Technology, USA, where he was an Associate Professor until 2004. He has an established record of publications in his field of expertise, with more than 350 technical journal and conference published papers. His main research interests lie in the area of computer communication networks, with emphasis on the analysis, optimization, and performance evaluation of mobile and distributed systems, wireless networks, and complex systems. He received the Best Paper Award in IEEE INFOCOM 94, the AT&T Division Recognition and Achievement Award in 1997, the US National Science Foundation Career Award in 2003, the Best Paper Award in IEEE WCNC 2012, the Excellence in Research Grant in Greece in 2012, the Best Paper Awards in ADHOCNETS 2015, ICT 2016 and IEEE/IFIP WMNC 2019, as well as the 2019 IEEE ComSoc Technical Committee on Communications Systems Integration and Modeling best paper award (for his INFOCOM 2019 paper). He also served on the board of the Greek National Regulatory Authority on Telecommunications and Posts from 2006 to 2009.

Christos Pelekis received the B.Sc. degree in mathematics from the University of Crete (2005), the M.Sc. degree in applied mathematics from NTUA (2008), and the Ph.D. degree in mathematics from the Delft University of Technology (2014). He is currently a Post-Doctoral Fellow with the Network Management and Optimal Design Laboratory, School of Electrical and Computer Engineering, National Technical University of Athens (NTUA). Before joining NTUA he was a Postdoctoral fellow in the Computer Science Department at KU Leuven, Belgium (2014-2016), and a Postdoctoral Researcher at the Institutes of Computer Science and Mathematics, Czech Academy of Sciences (2017-2018). His research interests include game theory, combinatorics, resource sharing, discrete probability, and measure theory.

Maria Diamanti is a research associate in the Network Management and Optimal Design Laboratory, in the School of Electrical and Computer Engineering at the National Technical University of Athens. She received her Diploma in Electrical and Computer Engineering from the Aristotle University of Thessaloniki in 2018. She is currently involved as a researcher in several National and European R&D projects in the era of Future Internet. Her research interests lie in the areas of

5G/6G wireless networks, resource management and optimization, game theory, contract theory, and reinforcement learning.

5 Past Relevant Presenter Experience

The proposers of this tutorial have extensive experience in delivering several talks and presentations in various scientific forums, including conferences, workshops, graduate courses and other technological venues. Furthermore, they have been actively performing research in the topics covered by this tutorial, and have published several journal and conference papers relevant to the tutorial content (e.g., [1–7]). The development of this tutorial is supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “1st Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant” (Project Number: HFRI-FM17-2436). Preliminary and/or partial versions of the content of this tutorial have been presented by the proposers in the following indicative events:

- “Utility-based Resource Allocation in Wireless Networks via Game Theory: Evolution from 3G to 5G”, Eirini Eleni Tsiropoulou and Symeon Papavassiliou, AdHocNow Conference, 2015, Tutorial, attendees: 50.
- “Efficient and Pragmatic Resource Orchestration in 5G/B5G Networks”, Symeon Papavassiliou, IEEE Greece 5G Summit, 2018, Invited Overview Presentation, attendees: 50.
- “Smart Internet of Things: A Cyber Physical Social System Perspective”, Symeon Papavassiliou, International Conference on Sensor Networks SENSORNETS 2021, Keynote speech, On-line event, attendees: 50.
- “Mobile and Personal Communications – 6G Systems”, Symeon Papavassiliou and Maria Diamanti, Graduate course, School of Electrical and Computer Engineering, National Technical University of Athens, 2020 and 2021, attendees: 40.

6 Virtual Presentation Suitability

Yes. The tutorial is suitable for virtual presentation as well if needed, considering that it does not rely on hands-on experiments and demos.

References

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