Control co-design and resource allocation in edge computing and dynamic networks (Tutorial Session Proposal)

Nikolaos Athanasopoulos, Dimitris Dechouniotis, Raphael Jungers, Aris Leivadeas, Nathalie Mitton, Symeon Papavassiliou

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***Abstract*— The tutorial session brings together researchers in control, as well as networks and communications, with the aim of presenting recent advances, and leading open problems, in modeling and decision making for network optimisation, resource allocation and management in distributed computing, wireless sensor and actuator networks, and control co-design.**

I. TOPIC

The proposed tutorial presents the basic principles and approaches in resource allocation, in the context of edge computing, dynamic computer networks, communication networks and Internet of Things. Moreover, it exposes the main unwanted phenomena in analysis and design of control systems that appear due to limited availability of computing, communication, and storage resources in a feedback loop. Finally, co-design methods are explored, i.e., simultaneously designing resource allocation strategies for dynamic networks as well as decision mechanisms for controlling dynamical systems over these networks.

Resource allocation is one of the most important open research problems in the era of Internet of Things (IoT) and Edge Computing (EC). Resources are typically limited and of shared nature by end users and respective applications, thus, dynamic modelling and intelligent allocation algorithms are essential. In that respect, both centralized and distributed approaches have been proposed in the recent literature to jointly consider the computation and communication limitations in the EC environment within IoT [1]. In the Network Functions Virtualization (NFV)-enabled IoT, isolated service chains comprising of a series of Virtual Network Functions (VNFs) and implemented as Virtual Machines (VMs) or containers, are deployed in the available EC infrastructure. The objectives for this resource allocation mechanism in this case can be diverse, such as the overall deployment cost, the overall delay, energy consumption, scheduling of available resources, enabling multiple heterogeneous SCs/slices servicing heterogeneous IoT applications in the MEC layer, minimization of resource idleness, bandwidth consumption, load balancing etc [2], [3], [4], [5], [6], [7], [8], [9], [10]. All of the above solutions target valid and open challenges in resource allocation in the IoT/EC and demonstrate promising performance advances, nevertheless they propose static approaches, leading often to under or over-provisioning.

Modelling and estimation of dynamic processes in IoT

applications is also a major topic, as it is crucial in order to formally analyse and design resource allocation mechanisms. A number of approaches have been explored, such as deep or machine learning [11], ARIMA [12], Thompson sampling [13] or Bayesian approaches have mainly been investigated for navigation and position prediction, medium occupation and data prediction respectively. System-theoretic approaches have also emerged that allow the control of QoS metrics in Cloud and Edge computing, such as response time and request admission rate, using, e.g., linear parameter varying switching and bilinear dynamical model [14], [15], [16].

In *control over networks*, shared and imperfect communication networks between the controller and the sensor/actuator have been studied for almost three decades, generating the separate branch of Networked Control Systems (NCS) [17]. Several methods address time delays and packet dropouts of NCS, utilizing perturbation theory, Lyapunov stability theory and hybrid systems analysis, including probabilistic methods involving Markov chains and stochastic automata [18] [19], [15] [20] [21]. Moreover, researchers in

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real-time computing have dealt with the schedulability problem of distributed control settings, leading to the design of several protocols for a stable closed-loop behaviour [21]. Rather than designing the control and communication protocol in two steps, the existing co-design methods aim to synthesize simultaneously controllers and the communication patterns (sampling, delays, scheduling protocols) [22]. A breakthrough is the emergence of event triggered and self-triggered control mechanisms that allow asynchronous sampling, thus reducing the network traffic, while at the same time they provide guaranteed trade-offs of the degradation of the closed-loop system performance [23]. Furthermore, recent works have shown that under a hybrid systems framework the control performance can be associated explicitly with the network quality [24].

II. Relevance to the scope of the conference

Given the practical and theoretical relevance of the topic as well as the high degree of current interest in this challenging research domain, our anticipation is that the session will attract great interest within the participants of the European Control Conference. Summarizing the state-of-the-art techniques for resource allocation in dynamic networks and edge computing, analysis and control co-design of systems over dynamic networks, and addressing the main future challenges, inevitably intersects with the content of a number of advertised topics of the European Control Conference, such as Complex Systems, Control Applications, Internet of Things, Decentralized Control, Hybrid Systems, Network Control Systems, Nonlinear Systems, Optimization, System Identification, Cyber-Physical Systems and many more. Additionally, exposition of the advances in resource allocation and control co-design methods from different perspectives will allow the unification of the challenges faced in a number of practical settings. Given the expertise of the confirmed contributors to the tutorial session, we believe that the quality and importance of the topics suits the conference scope and objectives. Overall, the main goal of the tutorial session is to attract and inspire young researchers and foster collaborations for future research projects.

III. Layout of the sessions and contributors

The proposed tutorial session consists of a forty minute lead presentation followed by four contributed talks of duration of twenty minutes each, focusing on specific challenges and methods. A number of international experts has accepted to participate in the tutorial session. The presentations are organised as follows:

1. Symeon Papavassiliou (Professor) and Dimitris Dechouniotis (Postdoctoral Fellow), School of Electrical and Computer Engineering, National Technical University of Athens, Greece (lead presentation, 40 minutes).
2. Aris Leivadeas, Assistant Professor, Department of Software and Information Technology Engineering, Ecole de technologie Supe´rieure (ETS), Montreal, Canada, (20 minutes).
3. Nathalie Mitton, Full Researcher and Head of the FUN group, Institut national de recherche en informatique et en automatique (Inria) Lille, France, (20 minutes).
4. Raphaël M. Jungers, Professor, Institute of Information and Communication Technologies, Electronics and Applied Mathematics (ICTEAM), Universite catholique de Louvain (UClouvain), (20 minutes).
5. Nikolaos Athanasopoulos, Lecturer, School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Northern Ireland (20 minutes).

IV. Contributions overview and talk abstracts

The talk abstracts are presented below, in the same order they will appear in the tutorial session.

A. Modelling and Resource Scheduling approaches on Cloud Computing

This talk will be delivered by Professor Symeon Papavassiliou and Dr Dimitris Dechouniotis.

Abstract: Cloud computing is the dominant service delivery paradigm over the last decade. The rapid development of the Internet of Things (IoT)-based applications shifts the cloud model to more decentralized approaches, such as Edge Computing and Fog Computing. The resource allocation in such distributed environments must guarantee both the

Quality of Service (QoS) requirements of each application and the optimal utilization of the underlying computing resources. Thus, the static resource allocation policies are not adequate to fulfill these objectives and lead to over or under provisioning. On the other hand, control-theoretic approaches guarantee important system properties, such as stability. This

presentation will present already proposed modeling and resource scheduling methodologies on cloud computing and the future challenges of this interesting research area.

B. From IoT to Cloud: an end-to-end virtualization approach

This talk will be delivered by Dr Aris Leivadeas.

Abstract: During the last decades, the Internet has been a key factor in building the global information society and leading economy growth. The mix of technologies in the Internet, such as Cloud Computing, Edge Computing, Network Function Virtualization (NFV), Data Analytics, and Internet of Things (IoT), provide the necessary tools to build a service-centric Future Internet Architecture. Future Internet is expected to rely on virtualization technologies, moving away from dedicated and expensive hardware middleboxes, while IoT will be one of the main sources of data generation in this communication paradigm. These data have no actual meaning unless they are analyzed and processed to extract meaningful information and knowledge. Nonetheless, apart from pure contextual data analysis additional services and functions maybe offered to the IoT stream. For example, appropriate networking functions may be applied (e.g. firewall, intrusion detection, encryption, etc.) or additional levels of analysis can be provided (e.g. network analytics for predicting the network access conditions, data filtering and cleansing etc.). Obviously, all these functions can not be implemented locally in resource constrained IoT devices and thus, they have to be offloaded to more powerful infrastructures like the Edge and the Cloud. To this end, this talk explores various network slicing considerations when deploying a chain of virtualized generic functions (data analytics, network analytics, and networking functions) expanding from the IoT devices till the Cloud, with the goal to provide a solution with high Quality of Service (QoS) and low communication cost.

C. Optimal dynamic edge device deployment: the challenges

This talk will be delivered by Dr Nathalie Mitton.

Abstract: With the increase of IoT, one can witness the deployment of more and more IoT devices. These devices are mostly characterized by heterogeneous mobility and connection patterns and limited resources such as memory, computing resources and energy. To overcome this, some of their computing tasks should be offloaded to a cloud or edge devices. In order to serve them as much as possible, there is a need to predict the kind and amount of resources these devices will request and the location of these resources. Some edge resources may need to be deployed sporadically and temporarily at different locations based on IoT devices needs and mobility.

D. Control in the IoT: How to deal with various heterogeneous non-idealities?

This talk will be delivered by Professor Raphaël Jungers.

Abstract: In the last decades, in the broad field of Systems and Control several different paradigms have emerged to deal with the control of IoT-enabled cyber-physical systems. Indicative examples include: hybrid behaviour, quantized control, varying delays, safety-criticality, nonlinear control, etc. Although these are typically met together in IoT environments, the research activities have led to disconnected communities, and likewise very specific control techniques, that limit their implementability in a holistic framework. In a real-life IoT control application, these non-idealities take place all together. We will survey the main classes of nonidealities and recent results that link them separately to the quality of performance guarantees for control systems. We will raise the question of how these results can be merged in a holistic IOT-control paradigm.

E. Reachability and set-based methods in resource allocation and co-design

This talk will be delivered by Dr Nikolaos Athanasopoulos.

Abstract: Set-based methods and in specific reachability analysis offer the appropriate theoretical tools to analyse and control dynamical systems, that may be subject to unwanted phenomena in dynamic networks, such as uncertainties, noise, packet dropouts etc. After briefly introducing the main concepts in reachability analysis of dynamical systems, we will highlight two instances where set-based methods can be successfully applied in edge computing and control over networks respectively, namely (i) in computation offloading in EC and (ii) analysing the reachability properties of linear systems over

faulty networks. Finally, we will attempt to pose several research challenges in these fields under the reachability framework.

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