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Complex Structures and Collective Dynamics in Networked Systems: A Tutorial

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***Abstract*—The study of complex networks and collective dynamics occurring in biological, social and technical systems has experienced a massive surge of interest both from academia and industry. Many of the results on the mechanisms underlying the self-organized formation of complex dynamic networks in natural and man-made systems have been derived based on a statistical physics perspective. In this tutorial, we provide a basic introduction to this perspective which will help attendees to benefit from the vast literature on self-organization and self-adaptation phenomena available in the fields of network science and complex systems. We cover basic models and abstractions for the study of static complex networks as well as dynamical processes like, e.g., information diffusion, random walks, synchronization or the propagation of cascading failures. We further introduce recent advances in the study of dynamic (social) networks and demonstrate how the resulting methods can be practically applied in the engineering of self-organizing and self-adaptive distributed systems and protocols.**

***Keywords*-complex networks; network dynamics; collective dynamics, self-organization; self-adaptation; distributed systems;**

I. Introduction

The quantitative study of complex systems has significantly changed our understanding of the self-organization and self-adaptation characteristics of biological, social and physical systems. Many of the intriguing results on the mechanisms governing the structure and function of these natural systems have been obtained based on the agent-based modeling of complex networks and their influence on collective dynamics. Among those works, interdisciplinary approaches that integrate methods, models and abstractions from dynamical systems theory, graph theory, computer science, agent-based modeling and statistical physics have been particularly successful [1], [2], [3], [4]. The resulting interdisciplinary methods for the modeling and analysis of complex systems have not only been successful in the study of natural and social systems; they are also becoming increasingly important for the modeling and design of man-made systems: Models for the evolution of complex networks in natural systems can be adapted to technical infrastructures and facilitate statements about the robustness of computing systems that have become critical infrastructures for our society [5]. Furthermore, the use of simple distributed mechanisms which result in complex collective behavior can facilitate the engineering of massively distributed systems that inherit some of the "organic" properties of natural complex systems [6], [7], [8], [9], [10]. Finally, the increasing importance of social aspects in the online world necessitates interdisciplinary modeling approaches capable of capturing the complex feedback between the increasingly intertwined social and technical layers of today's socio-technical systems [11], [12], [13].

II. Tutorial Contents

Targeting an audience of computer scientists and engineers, this tutorial introduces the statistical physics perspective on self-organizing and self-adaptive network structures, a perspective that is becoming increasingly popular in the modeling and analysis of complex systems. A particular goal of this tutorial is to help attendees who are interested in self-organization and self-adaptation phenomena to make use of the vast literature on the structure and dynamics of complex networks.

A. Complex Networks and Distributed Systems

A particular focus of the tutorial will be the use of results on the properties of complex networks in the context of engineered distributed systems. We introduce a basic mathematical framework that facilitates analytical results on macroscopic network properties like robustness and resilience [14], [15]. We then discuss a practical example for a simple distributed network formation protocol for which the macroscopic properties of the emerging topology can be analytically related to a microscopic stochastic model of the network formation process. We further highlight parallels between threshold phenomena in complex networks and phase transitions in thermodynamic systems. We demonstrate the use of this phenomenon in the design of a stochastic protocol for the construction of overlay topologies that allows a fast switching between phases of high robustness and high efficiency [16], [17].

B. Dynamical Processes and Distributed Protocols

Apart from mechanisms for the self-organized evolution of topologies with adaptable structural qualities, the tutorial

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covers the modeling of dynamical processes like, e.g., information diffusion, synchronization or random walks [18], [19], [3] in networked systems. We introduce some basics of spectral graph theory and show how spectral properties of complex networks can be used to make analytical statements about the evolution of dynamical processes which are at the heart of distributed protocols for information dissemination and epidemic aggregation in distributed systems [20], [21], self-organized synchronization in ad hoc networks [22], [23], [24] or random walk protocols for P2P systems [25], [26].

C. The Influence of Network Dynamics

While the traditional perspective on complex systems has mainly been focused on the the modeling and analysis of (more or less) static network topologies, recent studies have shown that the topological dynamics in real-world complex systems critically influences the evolution of dynamical processes. From a distributed systems perspective, opportunistic networking applications are a simple practical example for systems where dynamic social contact patterns crucially affect processes like information diffusion or synchronization. We introduce recent advances in the analysis of data from such dynamic networked systems and introduce abstractions that facilitate analytical results about information diffusion in dynamic complex networks [27], [28]. By this, we demonstrate that the *temporal* dimension of biological and social systems is - apart from the *topological* dimension - an important driving factor of complexity that needs to be taken into account in the design of self-organizing systems.

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