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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Saeed Osat

PhD Program: CDSE

Title of thesis: PERCOLATION ON COMPLEX NETWORKS AND ITS APPLICATIONS

Supervisor: Vladimir V. Palyulin, Skoltech

Name of the Reviewer: Sergei Nechaev

I confirm the absence of any conflict of interest	**Signature:**  **Date: 22-09-2021**

Reviewer's Report

Referee report for PhD thesis of Saeed Osat "Percolation on complex networks and its applications"

The work of Saeed Osat is devoted to the investigation of the question how the collective statistical behavior in complex distributed systems (in particular, multiplex networks) emerges under changing the control parameters. The general unified idea lying behind all works constituting the core of the Thesis is to probe the multiplex networks for the percolation transition.

I should honestly say that reading the Thesis I was pleasantly surprised by the solidness of posed questions, used tools and diversity of considered models. Saeed demonstrated very good possession of the methods of generating functions combined with exhaustive numerical investigations.

The Thesis of Saeed Osat consists of 6 original chapters (one chapter per one particular posed problem, arranged as a published paper) which are preceded by the introduction serving as a navigator through the Thesis. Each chapter begins with a clear explication of the personal contribution of Saeed Osat to the work. These chapters are: 1) "Emergence of power laws in noncritical neuronal systems", 2) "Generalization of core percolation on complex networks", 3) "Observability transition in multiplex networks", 4) "Characterizing the Analogy Between Hyperbolic Embedding and Community Structure of Complex Networks", 5) "Optimal percolation on multiplex networks", 6) "k-core structure of real multiplex networks". Despite all sections of the Thesis are important and emphasize different facets of

percolation on complex networks, I would like to highlight the sections 1), 4), 5) and 6), which provide elegant solutions of interesting and new questions. Let me summarize briefly the findings of these works.

In the chapter “Emergence of power laws in noncritical neuronal systems” authors have demonstrated that the degree distribution of the network underlying neural dynamics plays a fundamental role in the emergence of power-law distributions of avalanches (“cascades”) in their sizes. In the model under consideration, an avalanche starts with a single activated neuron and, at each time step, every one of the active neurons fires a signal that stimulates all of their neighbors. The avalanche of activities continues until no new neuron can be activated. This model is identical to the so-called independent cascade model, often considered in the context of opinion spreading in social networks. Considering a simplified model of neural dynamics on networks, authors have shown that, for some scale-free networks, avalanche sizes obey power-law distributions even in subcritical dynamical regime.

In the chapter “Characterizing the Analogy Between Hyperbolic Embedding and Community Structure of Complex Networks” it is shown that the community structure of a network under embedding into the hyperbolic disc is manifested in the “closeness” of angular coordinates. Authors performed a systematic analysis of several real world and synthetic networks and have demonstrated that networks which are “natural” for hyperbolic embedding (i.e. the loss function of embedding of the network into the hyperbolic disc is relatively small) typically are highly modular, in the sense that partitions found by community detection algorithms correspond to very large values of the modularity function and nodes within the same communities are likely to have similar angular coordinates.

In the chapter “Optimal percolation on multiplex networks” authors consider the problem of finding the minimal set of network nodes removal of which leads to the defragmentation of the multilayer network into non-extensive disconnected clusters. The solution to this problem is important for some practical questions, such as strategies of immunization in disease spreading, and influence maximization in opinion dynamics. Authors state that despite optimal percolation has received considerable attention in the context of isolated networks, however its generalization to multiplex networks has not yet been considered. The study is focused mostly on the characterization of the sets of “structured nodes” of a given multiplex network whose removal is crucial for the network defragmentation. It is shown that generally, multiplex networks have considerably smaller sets of structural nodes compared to the one of single-layer networks. Overall, the authors conclude that neglecting the multiplex structure may result in significant inaccuracy of predictions about the network robustness.

In the chapter “k-core structure of real multiplex networks” the authors state that multiplex networks are convenient mathematical representations for many real-world systems: biological, social, and technological systems of interacting elements, where pairwise interactions among elements have different flavors. Previous studies pointed out that real-world multiplex networks display significant interlayer correlations (degree-degree correlation, edge overlap, node similarities) which are able to make them robust against random and targeted failures of their individual components. Authors show that interlayer correlations are important also for the characterization of their k-core structure, namely, for the shell organization of nodes with an increasingly high degree. Understanding the k-core structures is important in the study of spreading processes on networks – for example for the identification of influential spreaders and emergence of localization phenomena. Authors made an important conclusion that if the degree distribution of the network is heterogeneous, then a strong k-core structure is well

predicted by significant positive degree-degree correlations, while if the network degree distribution is homogeneous, then strong k-core structure is due to positive correlations at the level of node similarities.

Overall, the Thesis of Saeed Osat provides diversity of important new results in the field of statistical physics of complex networks. It presents a number of interconnected questions which constitute the self-contained subarea in the sea of problems related to multiplex network statistics. The thesis is clearly written and highlights practical questions beyond the purely academic framework. Minor corrections, mainly concerning the style of presentation, do not influence my very high appreciation of the work. Without any doubts, Saeed Osat deserves the Degree of "Doctor of Philosophy" with the grade magna cum laude (very good) and his Thesis satisfies all relevant requirements.

Provisional Recommendation

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☐ ~~*I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*~~

☐ ~~*The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*~~