MERC PhD Project Proposal

Title of the research project:

Structural properties and emergent dynamics of networks beyond pairwise interactions

Keywords (up to five)

- Complex networks
- Complex systems
- Emergent collective dynamics
- Synchronization

Supervisors (at least two from two different areas):

Supervisor 1 (name, contact details, homepage, area of expertise)

Prof. Dr. Stefano Boccaletti, CNR, Institute for Complex Systems, Florence, Italy
Mail: stefano.boccaletti@gmail.com Area of expertise: Statistical and nonlinear physics

Supervisor 2 (name, contact details, homepage, area of expertise)

Prof. Dr. Pietro De Lellis, University of Naples Federico II, Mail: pietro.delellis@unina.it
Area of expertise: Control and system engineering

Project description (max 5000 characters)

All beauty, richness, and harmony in the emergent dynamics of a complex system largely depend on the specific way in which its elementary components interact. The last twenty-five years have seen the development of the multidisciplinary field of Network Science, wherein a variety of distributed systems have been modelled as networks of coupled units.

There is, however, a fundamental limit in such a representation: networks capture only pairwise interactions, whereas the function of many real-world systems not only involves dyadic connections, but rather is the outcome of collective actions at the level of groups of nodes. Such multi-component interactions can only be grasped through either hypergraphs or simplicial complexes, which indeed have recently found a huge number of applications in social and biological contexts, as well as in engineering and brain science. They are indeed becoming increasingly relevant, thanks to the enhanced resolution of data sets and the recent advances in data analysis techniques, which (concurrently and definitely) have shown that such structures play a pivotal role in the complex organization and functioning of real-world distributed systems.

In this project, we aim to give solutions to a series of problems regarding the structure and dynamics of hypergraphs and simplicial complexes.

As for structure, the idea is to extend to hypergraphs and simplicial complexes the models, tools, and main structural measures that are used to characterize complex networks, from ranking to centrality and efficiency, from vulnerability to modularity, from betweenness to partitioning, as well as to give a fresh and rigorous framework for the study of directionality in hypergraphs.

As for dynamics, we will concentrate on the emergence of synchronization in networked systems. The aim of the project is to extend the formalism of the Master Stability Function to hypergraphs, for assessing the necessary conditions for the stability of different synchronous states, from complete synchronization to cluster synchronization. At the same time, the project will try to unveil all aspects regarding the delicate interplay between the properties of the underneath structure of connections and the collective dynamics featured by the hypergraph, with possible application for enhancement or control of synchronized states.
Relevance to the MERC PhD Program (max 2000 characters)

The project is openly multidisciplinary, as it involves methods and results from several areas of the physical sciences, namely nonlinear dynamics, statistical physics, and network science. Additionally, many of the main publications in the field have benefitted from approaches that are traditionally associated to other mathematical areas, such as topology, group theory and algebra. Thus, the number of disciplines involved is likely to be even greater.

Potential applications and beneficiaries are numerous. Complex Networks have found, indeed, a tremendous number of applications within the last twenty-five years, in fields as diverse as fields as diverse as transportation networks, phone call networks, the Internet and the World Wide Web, the actors’ collaboration network in movie databases, scientific co-authorship and citation networks, genetic, protein and metabolic networks, food-webs and ecological systems, meteorology, econophysics, neuroscience and personalized medicine.

Based on such an enormous success, it is easy to forecast that the results obtained in extending the studies on structure and dynamics to networked systems beyond pair wise interactions will be of essential value for a wealth of applications within the following years.

Moreover, the project relates directly to the areas of “systems and control theory”, “mathematical modelling and simulation of complex systems”, and “emerging properties and domino and cascade effects in complex and interdependent systems”, thereby squarely fitting within the MERC program.

Joint supervision arrangements

One of the supervisors of this project is based in Naples, and this guarantees a constant monitoring of the progresses made by the candidate in the the different projects. The first supervisor is working at the CNR, Institute of Complex Systems, in Florence. Therefore, weekly meetings will be organized with the main supervisor, and at least three visits to Naples will be made to ensure the best as possible supervision of the candidate.

During the period of stay abroad, regular meetings will be organized involving the PhD student the two supervisors and the senior scientists based at the University of Coventry and at the University of Maryland.

Location and length of the study period abroad (min 12 months)

The project foresees a total of 12 months where the candidate will collaborate with two groups in foreign Universities.

In particular,

1) A first 6 months period of stay will be realized in 2024 at the University of Coventry, in the UK, under the co-supervision of Prof. Dr. Charo del Genio. During this period, the candidate will advance in some open issues regarding hypergraph’s structure;

2) A second 6 months period of stay will be realized in 2025 at the University of Maryland at College Park (Maryland, USA), under the supervision of Prof. Dr. Louis Pecora. During this period, the candidate will interact with the renowned group of nonlinear and statistical physics of that University (where, besides Prof. Pecora, there are Prof. Michelle Girvan, Prof. Edward Ott and Prof. Rajarshi Roy), concentrating on the projects regarding hypernetworks’ collective dynamics.

The two Institutions have already agreed to host the candidate.

Please return this form via email by no later than 24th February 2023