MS4 Networks

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Dynamics of Multilayer Networks

Session abstract:

Dynamics of complex networks is a central issue in nonlinear science with applications to different fields ranging from physical and biological to technological and socio-economic systems. The interplay of network topology with naturally arising delays and random fluctuations results in a plethora of spatio-temporal synchronization patterns. In particular, multilayer networks where the nodes are distributed in different layers offer better representation of the topology and dynamics of real-world systems in comparison with one-layer structures. One of the most promising applications of the multilayer approach is the study of the brain, where the neurons can form different layers depending on their connectivity through a chemical or electrical synapses, or technological interdependent systems, i.e., those systems in which the correct functioning of one of them strongly depends on the status of the others. For instance, multilayer networks with interconnected layers naturally occur in transportation systems and electrical power grids. The intriguing dynamics of multiplex networks includes relay synchronization and partial synchronization patterns like chimera states.

A1) Coherence-incoherence patterns in multiplex networks.

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We investigate the occurrence of coherence-incoherence patterns in multiplex networks where the nodes are distributed in different layers according to the type of the relation they share. For instance, in the case of a neuronal network the neurons can form different layers depending on their connectivity through a chemical link or by an ionic channel. The prime objective of multiplex networks is to study multiple levels of interactions where functions of one layer get affected by the properties of other layers. In the present work we particularly aim to understand the impact of multiplexity on emergence of chimera state in which the system splits into coexisting domains of spatially coherent (synchronized) and incoherent (desynchronized) dynamics.

A2 Pattern formation in spatially-distributed multiplex networks

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Only taking into consideration the interplay between processes occurring at different levels of real spatially-distributed networks provide the complete information about their efficiency and robustness. We study the interaction of the hierarchical structure and the spatial connectivity between nodes with the help of a multiplex network approach. For this purpose, we use both real data and percolation modeling. We found that a spatially-distributed geo-network imposes its own ranking to the hierarchical network, while the latter redistributes the shortest paths between nodes in the spatial layer. The comparison with the regular scale-free network reveals that the observed effects are intimately connected with the spatially distributed nature of the real structure. More specifically, the effect of redistribution of shortest paths refers to the absence of direct connections between the main hubs of the network. Additionally, we investigate the dynamical properties of the given networks and reveal the effect of long-range inter-layer connections on synchronization.

A3) Relay synchronization in multiplex complex networks

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Very recently, relay and remote synchronization have captured the attention of researchers. This form of synchronization is observed when two units of a network (identical or slightly different) synchronize despite not being directly linked due to the intermediation of a relay mismatched unit. The phenomenon has been experimentally detected in lasers and circuits, but where remote synchronization is of outstanding relevance is in the brain: the thalamus acts as a relay between distant cortical areas through the thalamo-cortical pathways, playing the role of a coordination hub.

Complex structures and neuronal dynamics are implicated in this process involving higher order relay paths, that transfer the information through multiple-step relay chains. Recently, remote synchronization has been addressed in the context of complex networks, revealing the important role of network structural and dynamical symmetries in the appearance of distant synchronization, as it was already suggested by the observation of zero-lag delays between mirror areas of the brain. Nevertheless, the interplay between symmetry, dynamics and multi-layer structure remains still mostly unexplored.

In our work we have extended the concept of relay synchronization to the case of a multiplex network, showing that the intermediation of a relay layer can lead to inter-layer synchronization of a set of paired layers, both topologically and dynamically different from the transmitter. The phenomenon can be extended to indefinitely higher order relay configurations, provided a mirror symmetry is preserved in the multiplex. The coherent state is very robust to changes in the dynamics, topology, and even to strong multiplex disconnection. In this latter scenario, we proved that the low degree nodes in the synchronized outer layers are responsible for resilience of the synchronous state, while hubs can be safely de-mutiplexed. Finally, we experimentally validated our results in a multiplex network of three layers of electronic oscillators. Our results provide a new path for starting the study of the role of symmetries in setting long distance coherence in real systems.

A4) Partial relay synchronization in multiplex networks

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Multiplex networks are often used to represent real-world systems. An interesting phenomenon within this topology is relay (or remote) synchronization between parts of one layer and its counterpart in a second layer which are not directly connected. A simple realization of such a system is a triplex network where a relay layer in the middle acts as a transmitter between two outer layers. We study the influence of time delay in the inter-layer coupling on the partial synchronization of chimera states, complex patterns of coexisting coherent and incoherent domains. We demonstrate that three-layer structure of the network allows for synchronization of coherent domains of chimera state in the first layer with its counterpart in the third layer, whereas the incoherent domains are desynchronized. By varying the topology of the relay layer, we study its influence on the remote synchronization in outer layers. Our results can be applied for secure communication and modelling of neuronal dynamics.

Inference of Networks

Session Abstract:

The inference of the architecture of networks from experimental data is key for the understanding of many real-world dynamics in science, technology and engineering. A fundamental approach is to estimate directed links between network nodes by analyzing signals measured at individual nodes. We here revisit the application of bivariate nonlinear interdependence measures that aim to detect directed links by analyzing all possible pairings of signals. As an alternative approach we present the separate analysis of multiple simultaneous signals. This generates multiple networks, and the dynamics of the original system is represented as a biased random walk on a resulting multiplex system. We furthermore present analytical approaches to validate the output of such network inference methods. Given the inferred vertex degree distribution and probabilities of false positive and false negative errors, this approach allows one to calculate analytically the vertex degree distribution of the original network. Once derived and validated, results from network inference can help to shape and constrain mathematical models of real-world dynamics. These models in turn allow one to predict the networks' reaction to interventions and perturbations, as we illustrate for the emergence of seizure dynamics in epilepsy patients.

B1) Networks from multi-channel dynamics

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Methods exist to construct network representations of dynamical systems from time series. But these work well only for scalar time series. We propose an extension of these ideas to the situations when one has access to multiple simultaneous variables. One obvious solution is to apply the standard scalar techniques to each variable independently thereby generating multiple networks and the dynamics of the original system is represented as a biased random walk on resulting multiplex system. A natural question, which we hope to address, is whether this multiplex approach has any advantage over the (admittedly more mechanical) multi-variate time series approaches which would represent the collective time series dynamics as a single network.

B2) Inferring of directed networks using rank based connectivity measures

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The study of network dynamics is an important tool to characterize real-world systems in natural and social science as well as engineering [1]. The topology of the network is a decisive feature which along with the properties of individual nodes determines the behavior of the dynamics. Oftentimes, however, the topological structure of the system is not accessible. It is therefore important to infer the network topology by analyzing signals measured from the nodes. Here, we use a rank-based nonlinear interdependence measure originally developed for pairs of signals in reference [2]. This measure not only allows one to measure the strength but also the direction of the coupling. In application to multi-variate signals, one can estimate the matrix of directed couplings between pairs of network nodes. Our results derived from mathematical model systems show that this approach allows us to infer the underlying topology of the system for intermediate coupling strengths. For both very weak coupling and almost synchronizing couplings, in contrast, we get false negative and false positive errors. We furthermore show an application to multichannel electroencephalographic (EEG) recordings for epilepsy patients. Our study provides further evidence for the advantage of this measure compared to other data-driven approaches [3, 4] which cannot determine the direction of coupling.

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B3) Network models of seizures to understand epilepsy surgery

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Epilepsy is characterised by the repeated occurrence of seizures, which are periods of pathological brain activity that arise spontaneously from a predominantly healthy functional state. Large-scale brain networks are recognised as important for the generation of seizures (ictogenesis), and we can therefore use network models of state-switching dynamics to understand ictogenesis. An important application for such models is to understand the effects of treatments. In epilepsy surgery, for example, regions of brain tissue are removed with the aim of reducing the occurrence of seizures. However, surgery is not always effective, and the reasons why it may not work are incompletely understood.

To address this, we developed a model-based framework to quantify the effect that perturbations have on the dynamics of brain networks. This allows to characterize nodes based upon their mechanistic contribution to the emergence of seizure dynamics (i.e. their node ictogenicity, NI). Studying NI in networks of different topologies, we find that for scale-free and rich-club networks there exist specific nodes that are critical for seizure generation and should therefore be removed, whereas for small-world networks the strategy should instead focus on removing sufficient brain tissue. In order to explore the consequence of these findings we analysed intra-cranial EEG recordings from patients who had undergone epilepsy surgery. We found rich-club structures within their functional networks, suggesting the existence of critical nodes. We found that postsurgical seizure occurrence was improved when a greater proportion of the rich club was removed, in agreement with our theoretical predictions.

B4) Analytical approach to reconstruct the vertex degree distribution

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Networks are one of the most frequently used modelling paradigms for dynamical systems. Investigations towards synchronization phenomena in networks of coupled oscillators have attracted considerable attention, and so has the analysis of chaotic behaviour and corresponding phenomena in networks of dynamical systems to name just a few.

Here, we discuss another related challenge that originates from the fact that network inference in the Inverse Problem typically relies on statistical methods and selection criteria. When a network is reconstructed, two types of errors can occur: false positive and false negative errors about the presence or absence of links. We analyse analytically the impact of these two errors on the vertex degree distribution. Moreover, an analytic formula of the density of the biased vertex degree distribution is presented.

In the Inverse Problem, the aim is to reconstruct the original network. We formulate an equation that enables us to calculate analytically the vertex degree distribution of the original network if the biased one and the probabilities of false positive and false negative errors are given. When the dimension of the network is relatively large, numerical issues arise and consequently the truncated singular value decomposition is used to calculate the original network vertex degree distribution.

The outcomes of this work are general results that enable to reconstruct analytically the vertex degree distribution of any network. This method is a powerful tool since the vertex degree distribution is a key characteristic of networks.

Chimera States I

Session abstract (jointly for Chimera states I-III):

Chimera states in dynamical networks consist of coexisting domains of spatially coherent (synchronized) and incoherent (desynchronized) behavior. They are a manifestation of spontaneous symmetry-breaking in systems of identical oscillators, and occur in a variety of physical, chemical, biological, ecological, technological, or socio-economic systems. We focus on recent developments with future promising perspectives, for instance, chimera patterns in small networks, adaptive networks, complex coupling topologies like modular or hierarchical connectivity, coupled phase and amplitude dynamics, multiple delayed-feedback chimeras, coherence resonance chimeras, and control methods for stabilizing chimera states.

C1) An organising centre for chimera states in small networks

Peter Ashwin, Christian Bick
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Yuri Maistrenko
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This talk discusses some recent work on finding weak chimeras with partial frequency synchrony in coupled oscillator networks. This includes small networks of phase oscillators and inertial phase oscillators of Kuramoto type. In the latter case we investigate a codimension two symmetric heteroclinic bifurcation of three coupled Kuramoto oscillators with inertia, where the breakup of the invariant torus interacts with a synchrony breaking bifurcation. This bifurcation was first explored in numerical simulations by [Maistrenko et al. Physical Review E, 95(1):010203, 2017]. It apparently organizes a very wide range of weak chimeras and chaos in a neighbourhood of the bifurcation.

C2) Optimal design of the tweezer control for chimera states in small systems

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Chimera states are complex spatio-temporal patterns which consist of coexisting domains of spatially coherent and incoherent dynamics in systems of coupled oscillators. In small networks, chimera states usually exhibit short lifetimes and erratic drifting of the spatial position of the incoherent domain. A tweezer feedback control scheme can stabilize and x the position of chimera states [1]. We analyse the action of the tweezer control in small nonlocally coupled networks of Van der Pol and FitzHugh-Nagumo oscillators, and determine the ranges of optimal control parameters. We demonstrate that the tweezer control scheme allows for stabilization of chimera states with different shapes, and can be used as an instrument for controlling the coherent domains size, as well as the maximum average frequency difference of the oscillators [2].

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C3) Chaos and chaotic weak chimeras in minimal oscillator networks

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The emergence of collective dynamics is a fascinating effect in networks of interacting oscillators. We show that chaos and chaotic weak chimeras can arise even in very small networks of Kuramoto phase oscillators consisting of two populations. We analyze these solutions in terms of their symmetries and the bifurcations that lead to the emergence of chaos. Hence, weak chimeras with complicated dynamics can arise even in the smallest and simplest systems

C4) Quasiperiodic chimera states

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In this talk we will describe recent work on quasiperiodic chimera states in a one-dimensional model of nonlocally coupled phase oscillators. In the continuum limit such chimera states appear as quasiperiodic solutions (more precisely, as relative periodic orbits) of the corresponding Ott-Antonsen equation. We will show how to perform numerical continuation of these solutions and analyze their stability. Thereby we will focus on mathematical problems concerned with the solution non-smoothness and the presence of neutral continuous spectrum in the corresponding linearized problem.

Chimera States II

D1) Control of chimera states with minimal coupling modifications

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Chimera states are hybrid spatiotemporal patterns that spontaneously form in networks of identical coupled oscillators. In this fascinating phenomenon the elements that form the network split into two complementary groups, one with the oscillators almost synchronized and one displaying an erratic motion. It was proved that in finite size systems chimeras are chaotic transients coexisting with the stable synchronous solution. Furthermore the two groups drift along the network in time. The smaller is the network, the stronger are these instabilities. We focus on the control of chimera states in small networks of nonlocally coupled phase oscillators. We perform the control acting exclusively on the coupling structure of the network and we aim to find the minimal modification necessary to control chimeras. We first show how cutting all incoming links of one oscillator allows us to prevent the collapse of the chimera to the synchronous state and to generate chimeras from the synchronous state. This action corresponds to one oscillator of the network acting as a pacemaker. Secondly, we observe that the pacemaker attracts the incoherent group, thus preventing its drifting motion. Our analysis shows that we can control the position of the chimera also removing less links form the connectivity structure. Indeed, merely lowering the strength of just one link has a significant effect on the position of the chimera. The advantages of our control mechanism are its simple implementation and its independence from the parameters of the individual oscillators.

D2) Chimera States in Three Dimensional Networks

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We report the appearance of chimera and solitary states in three-dimensional (3D) Kuramoto model with inertia. In the case without inertia, two families of 3D chimera states were previously obtained: type I - oscillating chimeras, i.e., those without spiraling of the coherent region (coherent and incoherent balls, tubes, crosses, and layers in incoherent or coherent surrounding, respectively), and type II - spirally rotating chimeras, called scroll wave chimeras (rolls, Hopf link, trefoil, etc.) [1-2]. In the considered model with inertia, type II chimeras are found such as rolls, Hopf link and trefoil. However, in contrast to the pure phase equations, they can have coherent inner parts. Moreover, a new type of stable scroll wave chimera state - 3D torus was obtained from random initial conditions. For the model, we also report the appearance of different types of solitary states [3] and obtain their stability regions in the parameter space.

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D3) Chimera states in two dimensional networks with hierarchical connectivity

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Inspired by recent findings in the fractal morphology of the neuron axons network of the human brain, we study synchronization phenomena in a 2D network of Leaky Integrate-and-Fire (LIF) oscillators linked via hierarchical coupling schemes. We show that depending on the coupling strength a variety of chimera patterns is observed, such as multiple spots, stripe and grid chimeras, as well as travelling waves and subthreshold oscillations. Unlike in the case of nonlocal connectivity [1], when tuning the coupling strength to small values a spot chimera is formed with internal structure reminiscent of the fractal connectivity scheme. This is in agreement with previous results for 1D networks, where hierarchical connectivity also induces chimeras with stratified spatial arrangements [2,3].

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D4) Chimera patterns in ecological networks

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The chimera state is an intriguing and counterintuitive spatiotemporal state that has been in the centre of active research over the past decade. In this state the population of coupled identical oscillators spontaneously split into two incongruous domains: In one domain the neighboring oscillators are synchronized, whereas in another domain the oscillators are desynchronized. Recent experimental observations of chimera states have established their robustness in natural and man-made systems. The strong current interest in chimeras may be attributed to their possible connection with several phenomena in nature, like unihemispheric slow-wave sleep of dolphins and certain migratory birds, ventricular fibrillation, and power grid networks. Recently, chimera patterns have been found in models from SQUID metamaterials and quantum systems showing their omnipresence in the macroscopic as well as in the microscopic world.

In the present talk I will discuss various chimera patterns that arise in a network consisting of ecological oscillators. Considering a network of Rosenzweig--MacArthur oscillators we explore and demonstrate the influence of several nonlocal coupling schemes in inducing chimera states. I will discuss the possible transitions between the spatiotemporal patterns that arise due to the interplay of coupling strength and coupling topology. In particular we will consider a nonlocal coupling characterized by a rectangular kernel and establish the occurrence of chimera. Apart from that, we also consider a more realistic coupling topology, namely the distance dependent power-law coupling. In general, distance-dependent interaction is an ubiquitous form through which natural systems interact in physical and biological sciences. Therefore, it will be interesting to explore this particular form of interaction on the occurrence of chimera states.

D5) Chimera-like states in two interacting populations of heterogeneous quadratic integrate-and-fire neurons

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We analyze the dynamics of two globally coupled populations of quadratic integrate-and-fire (QIF) neurons [1]. The isolated QIF neuron is the canonical model for the class I neurons near the spiking threshold. Unlike typical models, which consider chimera states in systems of identical oscillators, here we analyze two populations of heterogeneous neurons. Each population contains both excitable and spiking neurons. However the populations are identical. The coupling within and between the populations is global and symmetrical. The neurons interact via synapses that take into account the finite width of synaptic pulses. Using a recently developed reduction method based on the Lorentzian ansatz [2,3], we derive a simple system of ordinary differential equations, which describe the macroscopic dynamics of the firing rates and mean membrane potentials in both neural populations. This macroscopic model enables us to perform a thorough bifurcation analysis of the system. As a result, we detect two types of chimera-like states. In one of them, the majority of neurons in one population are quenched, while in another population they spike synchronously. In the second type, the majority of neurons produce spikes in both populations, but with a different synchronization level.

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Chimera States III

E1) From Chimera States to Collective Chaos in Kuramoto Oscillator Networks

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Kuramoto oscillators are widely used to explain collective phenomena in networks of coupled oscillatory units. We consider a network of two interacting populations and explore the effects of heterogeneity in both coupling strengths and phase-lags, a setup which naturally arises in various biological and technological settings. This generic case of non-identical phase-lags allows for a variety of states with uniform and non-uniform synchronization. These states include in-phase and anti-phase synchrony, full incoherence (splay state) and chimera states which bifurcate into states with both populations desynchronized. Our findings elucidate previous experimental results involving a network of mechanical oscillators [PNAS, 110(26), 10563 (2013)]. Furthermore, we find the desynchronized states may undergo a period doubling cascade into collective chaos, which gives a positive answer to the conjecture by Ott and Antonsen [Chaos, 18, 037113 (2008)] that simple networks of two populations can exhibit chaotic dynamics. Unlike phase chaos, such chaotic mean field dynamics arise in both the continuum limit for identical and almost identical oscillators (as given by the Ott-Antonsen reduction) as well as for a wide range of finite-dimensional networks of identical oscillators whose dynamics are given by the Watanabe-Strogatz equations.

E2) Chimera States in Nonlinear Systems with Multiple Delayed Feedbacks

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Coherent-incoherent motions known as chimera states have recently sparked substantial interest in the nonlinear dynamics community. Recent findings show that chimera states may appear in a wide range of natural phenomena. In the present contribution, we exploit the analogy between delayed-feedback systems and symmetric networks of nonlinear oscillators in this context. We demonstrate the existence of two-dimensional chimera states created in a system consisting of two long delays, where one delay exceeds the other by two orders of magnitude. We present the first experimental demonstration of 2D chimera states in nonlinear delay systems and obtain an excellent agreement between numerical simulations and the experiment. Observed chimeras are highly robust, i.e. are stable with respect to the noise in the experimental setup and exist for a wide range of parameters. Results can potentially be applied in multiple areas including power grids, optical memory, and neuromorphic computing.

E3) Synchronization in multilayer networks showing chimera states

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Chimera states are an intriguing interplay of synchronous and asynchronous motion in networks of coupled oscillators. While chimera states were traditionally studied in one-layer networks, recent work studies interactions of chimera states across coupled layers in multilayer networks. It was shown that such couplings can induce generalized synchronization between chimera states across layers. This previous work, however, focused on multiplexed networks, for which the layers have the same number of oscillators and the inter-layer coupling connects individual oscillators in a pairwise and ordered topology. We here use a more general approach and study a two-layer network with a different number of oscillators in each layer and with different natural oscillator frequencies across the layers. For each layer we use the classical setting of a ring network of non-locally coupled identical phase oscillators in a chimera state. We couple the phases of individual oscillators in one layer to the phase of the mean field of the other layer. This coupling between the microscopic variables in one layer to a macroscopic variable in the other layer is done in both directions. Also in the presence of coupling both layers continue to exhibit chimera states. For a sufficient coupling, the phases of the mean fields lock, while their amplitudes remain uncorrelated. Hence, the macroscopic mean fields of networks in chimera states show phase synchronization, which was previously described for low-dimensional chaotic oscillators.

E4) Coherence-resonance chimeras. Impact of time-delayed feedback.

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We show that chimera behaviour can be observed in an ensemble of nonlocally coupled excitable systems in the presence of noise. This effect combines temporal features of coherence resonance and chimera states [1]. Moreover, we demonstrate that noise-induced chimera state can be controlled by time delayed-feedback [2]. Using time delay one can increase the range of parameter values where the chimera state occurs. Time-delayed feedback can induce a novel regime which we call period-two coherence-resonance chimera.

[1] N. Semenova, A. Zakharova, V. Anishchenko, and E. Schöll. Coherence-Resonance Chimeras in a Network of Excitable Elements. Phys. Rev. Lett. 117 (2016) p. 014102

[2] A. Zakharova, N. Semenova, V. Anishchenko, and E. Schöll. Time-delayed feedback control of coherence resonance chimeras. Chaos 27 (2017) p. 114320