Chasing chimeras: control of complex networks

Professor Eckehard Schöll and **Dr Anna Zakharova** are studying the complex, rich, and ever-relevant dynamics of coupled networks of oscillators. From models of the brain, through socio-economic models, to the electrical power grid: being able to predict and even control the behaviour of such networks is crucial in the modern world. The observation of intriguing states called chimeras, where some regions of the network oscillate coherently together while others are incoherent, suggests a tantalising pathway to understanding and controlling these networks across a huge range of applications in natural physical, chemical, biological, and technological systems.

Professor Schöll and Dr Zakharova of Technische Universität Berlin (Berlin Institute of Technology) and their collaborators are researching how we can characterise different networks, and understand their dynamical responses. We see rich and varied dynamical behaviour in networks owing to non-linearities in their intrinsic dynamics and in the way the nodes are coupled together: a slight change at one part of the network can grow or shrink rapidly and even chaotically, with huge consequences. Various biological, socio-economic, and physical systems, as well as technological communication and supply systems, can be well-modelled by complex networks. Understanding the dynamics of these mathematical objects is a crucial, highly interdisciplinary field with a huge range of applications.

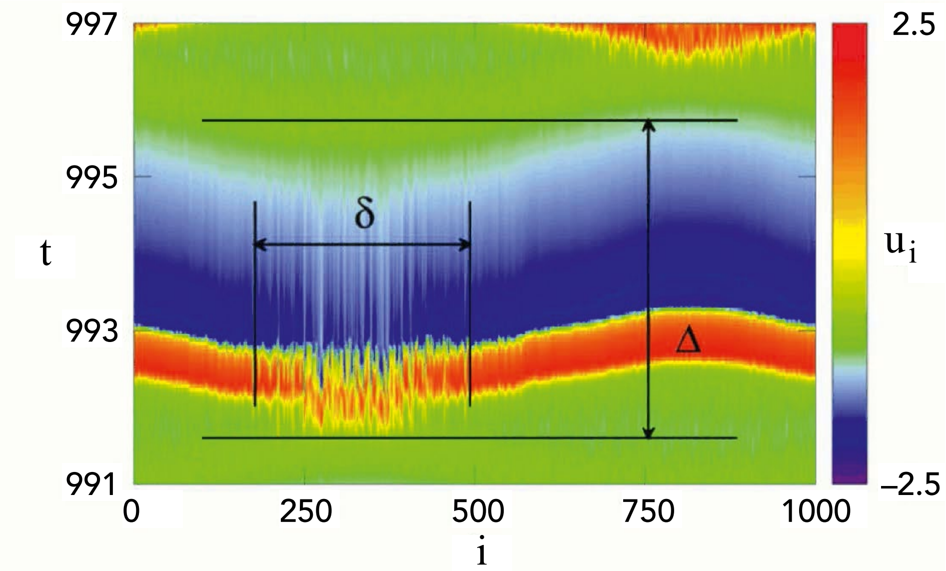
BRAIN-POWER

A network consists of a certain number of elements, called nodes, and the connections (links) between them. The classic example – and the reason so-called neural networks are used for artificial intelligence – is the human brain. Each neuron is an individual cell, similar to a node in the network: the complex possibilities for connections between neurons, called synapses, explain how we perceive the world. The process of learning is similar to constructing a weighted network: over time, some connections get reinforced, while others fade.

Networks can be subject to random fluctuations: for example, consider our power network, the electrical grid of supply and demand. In the case of a power grid – especially as more and more renewable energy sources are integrated, resulting in random fluctuations of the generator power – control using smart technologies is key, but to control networks, we must first understand them and learn how to predict their behaviour. Prof Schöll constructs mathematical models of networks and investigates their dynamics.

CHIMERAS: PART-ORDER, PART CHAOS

Key to understanding network behaviour is analysing the interplay of network topology – the way that the network's nodes and the connections between them are arranged – and dynamics, as well as the influence of random fluctuations and time delay in the connections. A ring of connected nodes is an example of a simple topology, but this topology interacts with random fluctuations in the network to produce a huge variety of different states. A class of states that Prof Schöll is especially interested in are called chimeras. The chimera in Greek mythology was a fire-breathing monster composed of incongruous parts: a lion's head, a goat's head, and a serpent's head; in networks, chimeras are similar mixtures of incongruous dynamical behaviour. In a chimera state, a network has regions that are highly synchronised (coherent



A graphic illustration (space-time plot) of a coherence resonance chimera. The time evolution (vertically) of the excitation of 1000 neurons (horizontally) is colour-coded, showing an incoherent part (indicated by a horizontal double arrow) and a coherent part.

or ordered) and regions that are highly desynchronised (incoherent), side-by-side. A useful mathematical model is a set of coupled oscillators – you might think of a network of masses on springs connected together, with oscillations in one part of a network triggering reaction across all connected nodes. In this case, a chimera state may involve some of the oscillators vibrating together, in synchrony, while others oscillate in an uncorrelated, desynchronised way. These states exhibit spontaneous symmetry breaking.

Some brain activity may be explicable via chimeras. For example, Prof Schöll in collaboration with a Russian group noted that in a neural network brain model, stimulating the network with random noise could result in the formation of coherence-resonance chimeras. In other words, the brain network could end up spontaneously synchronising in some regions, while failing to synchronise in others. Since the complete synchronisation of the network is often associated with pathological brain function like epilepsy, understanding how it arises or breaks down via chimera states could be crucial to understanding neurological disorders, in particular, epileptic seizures. Moreover, unihemispheric sleep is well known in some mammals like dolphins and in migratory birds, enabling them to sleep (and rest) with one half of their brain, while staying awake and alert with the other half. This could also be explained by a chimera state, since the synchronised and desynchronised states correspond to sleep and awakeness, respectively.

A RARE BEAST: CHIMERAS IN THE LAB

One of the key problems for researchers investigating chimeras was that they could not construct experimental setups where chimeras could be observed in the lab. One of the types of network that can display chimera properties are coupled maps; this is a time-discrete system of equations intended to model the chaotic behaviour of a physical system.

Prof Schöll and his collaborators in the US were able to demonstrate an experimental setup that allowed them to observe the dynamics of a system with nonlocal couplings in excellent agreement with the theoretical prediction. This was achieved using a spatial light modulator (SLM), which alters the polarisation properties of an optical beam. By changing the properties of the SLM, which affects the polarisation of light by introducing a phase shift which can then be measured, they were able to experimentally realise different types of coupling. This setup laid the groundwork for future experimental results which can probe chimera behaviour in the real world.

One of the most promising applications of complex networks is the study of the brain, or technological interdependent systems

Q&A

Q&A with Prof Schöll and Dr Zakharova

Do you think we are moving closer to a more generalised understanding of the richness of complex networks?

If we wish to understand the richness of complex networks, we should take not only dynamics and topology into account, but also random fluctuations and time delays, which naturally occur in real-world systems, as well as systematically investigate more complex network topologies. One of the recent trends in the network science – multilayer approach – is a promising step towards generalising our knowledge on complex networks. In multilayer networks, the nodes are distributed in different layers according to the type of the relation they share. For example, in a neuronal network, the neurons can form different layers depending on their connectivity through a chemical link or by an ionic channel.

What insights into the function of the brain can we gain through a greater understanding of more complex neural networks?

Most of the biological systems including the brain (neural networks), but also cellular networks, are not only extremely robust but also highly adaptable. Disclosing the nature of complex interdependencies in neural networks can enable us to find a compromise between robustness and adaptability, and also for the construction of man-made networks such as power grids and transportation systems. With regards to chimera patterns, a deeper understanding of these hybrid states can help with disclosing the mechanisms of unihemispheric sleep and epileptic seizures.

What is the role of topology in determining how networks interact with their surroundings? Do you think that we can construct networks with favourable topologies for control?

The topology of the network has a significant impact on its dynamics, in particular in terms of stability, i.e. robustness to perturbations. For example, recent studies have shown that symmetries play a crucial role for the functionality of the networks. In our current research project, we aim to elaborate efficient control strategies based on the design of network structure, time delay schemes, and noise characteristics as main governing tools.

Who has been your greatest scientific and mathematical inspiration, and why?

Prof Schöll: As Isaac Newton said, "If I have seen further it is by standing on the shoulders of Giants". We are always inspired by our teachers and mentors, and I am personally deeply indebted to my PhD supervisors Peter T. Landsberg (Southampton) and Friedrich Schlögl (Aachen), and also, to the great theoretical physicist Hermann Haken who created the field of Synergetics, of which the complex behaviour of networks is one prominent example.

Dr Anna Zakharova: Professor Schöll has always inspired me with his enthusiasm, passion, hard work and dedication to science, as well as his exceptional ability to use the language of mathematics to describe physics. I am still fascinated by his dedication to simple paradigmatic models, which he uses for his research to uncover complex phenomena in non-linear systems and networks.

What progress has been made in experimentally observing and controlling chimeras?

The first experimental studies on chimera states were provided only ten years after their theoretical discovery. One of the reasons they remained undetected for a long time is that usually in experiments, only small networks can be realised. The two principal obstacles are the transient nature of chimeras that eventually collapse to the uniformly synchronised state, and the erratic motion of the incoherent domain. We have developed a control scheme which can stabilise and fix the position of chimera states in small networks. Therefore, this feedback control scheme, like a tweezer, might be especially useful in experiments.

Our research extended one of the recently suggested control techniques based on proportional control relying on the measurement of the global order parameter. On the other hand, Bick and Martens showed that the chimera position can be stabilised by a feedback loop inducing a state-dependent asymmetry of the coupling topology. However, the operation of the latter control scheme may become ill-posed for small system sizes like 20-30 oscillators; therefore, one needs to use a refined control in this case.

TAMING THE BEAST: CONTROLLING CHIMERAS

Prof Schöll and Dr Zakharova have examined the birth and death of chimera states in these mathematical systems. They discovered novel types of chimera behaviour for networks of coupled oscillators. The system transitioned from a state where chimera behaviour occurred not in the phase but in the amplitude of the oscillators (an amplitude chimera) to one where the oscillations were suppressed (chimera death.) By characterising this transition, Prof Schöll and Dr Zakharova hope to provide tools by which network builders can suppress oscillations in complex networks and still induce coherent and incoherent steady state parts. They showed that such a transition relies on a coupling that breaks the underlying symmetry.

By adding a feedback control loop into their mathematical model of complex networks, Prof Schöll and Dr Zakharova along with their collaborators were able to manifest some control over chimeras. "Our control is an interplay of two instruments: the symmetric control term suppresses the chimera collapse, and the asymmetric control term effectively stabilises its position." They hope that this control mechanism will allow for better experimental observations of chimera states, which could unlock a deeper understanding of how networks partially synchronise. An astonishing array of behaviour can be observed in these networks, and, as the world becomes ever-more interconnected, understanding this richness will be crucial for humanity's future development.

Detail

RESEARCH OBJECTIVES

Prof Schöll and Dr Zakharova's research investigates emergent phenomena and their control in complex networks. The goal is to investigate noise- and delay-induced nonlinear dynamics as well as complex deterministic effects and partial synchronisation patterns, like chimera states (which combine spatially coexisting synchronised and desynchronised domains) and explore their underlying mechanisms.

FUNDING

DFG (Center of Excellence on Control of Self-Organizing Nonlinear Systems, SFB 910)

COLLABORATORS

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BIO

Prof Schöll has had a broad and exciting career. He received PhDs in Mathematics at the University of Southampton (UK) in 1978 and in Physics at RWTH Aachen (Germany) in 1981, as well as an Honorary Doctoral degree from Saratov State University (Russia) in 2017. Since 1989, he has been a Professor of Theoretical Physics at TU Berlin. In addition, since 2011, he has been the founder and Chairman of the Collaborative Research Center SFB 910 "Control of Self-Organizing Nonlinear Systems".

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