International Workshop

«Spatio-Temporal Structures in Ensembles of Interacting Oscillators»

(Chimera States — 2016)

PROGRAM

AND

BOOK OF ABSTRACTS

September 14–16, 2016

Saratov National Research State University, Saratov, Russia

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(Chimera states — 2016)

September 14–16, 2016

Radiophysics and Nonlinear Dynamics Chair,
Saratov National Research State University,
Saratov, Russia

Program

September 14, Wednesday

			Chairman: V.S. Anishchenko
	10:00 — 10:10	**Opening Ceremony**	
1	10:10 — 10:50	E. Schöll TU Berlin	Chimera patterns in Van der Pol networks: Influence of fractal topologies and self-adaptive control
2	10:50 — 11:20	T.E. Vadivasova SSU, Saratov	Chimeras in a ring of linear oscillators with nonlinear local unidirectional coupling
	11:20 — 11:50	**Coffee Break**	
3	11:50 — 12:20	J. Sawicki TU Berlin	Chimera states in hierarchical networks of Van der Pol oscillators
	12:20 — 14:00	**Lunch Time**	

			Chairman: T.E. Vadivasova
4	14:00 — 14:40	A. Zakharova TU Berlin	Coherence-resonance chimeras: a bridge between chimera states and coherence resonance
5	14:40 — 15:10	G.V. Osipov UNN, N. Novgorod	Transient spatiotemporal patterns in a reaction-diffusion-mechanics system
	16:00	**Excursion**	

September 15, Thursday

			Chairman: E. Schöll
6	10:00 — 10:40	V.S. Anishchenko SSU, Saratov	Chimera state realization in chaotic systems. The role of hyperbolicity
7	10:40 — 11:10	N.I. Semenova SSU, Saratov	Transition from synchronization to desynchronization in coupled logistic maps
	11:10 — 11:40	**Coffee Break**	
8	11:40 — 12:10	G.I. Strelkova SSU, Saratov	Amplitude and phase chimera states and cross-correlations in a ring of nonlocally coupled chaotic systems
	12:10 — 14:00	**Lunch Time**	

			Chairman: G.I. Strelkova
9	14:00 — 14:30	L. Tumash TU Berlin	Stability analysis of long-living transient amplitude chimeras
10	14:30 — 15:00	V. Semenov SSU, Saratov	Spatio-temporal phenomena is a single time-delay system: coherence-incoherence transition and noise-induced effects
	18:00	**Cultural Program**	

September 16, Friday

			Chairman: A.P. Chetverikov
11	10:00 — 10:30	A.V. Shabunin SSU, Saratov	Multistability in ensembles of phase oscillators with long-distance couplings
12	10:30 — 11:00	A.V. Slepnev SSU, Saratov	Peculiarities of chimera states formation in an ensemble of non-locally coupled Anishchenko–Astakhov self-sustained oscillators
	11:00 — 11:30	**Coffee Break**	
13	11:30 — 12:00	I. Shepelev SSU, Saratov	Chimera regimes in a two-dimentional network of cubic maps with nonlocal coupling
14	12:00 — 12:30	K.S. Sergeev SSU, Saratov	Steady states and transient processes in a chain of interacting non-oscillating elements
	12:30 — 14:15	**Discussion and Closing Ceremony**	
	14:15 — 15:30	**Lunch Time**	
	16:00	**Cultural Program**	

Amplitude and phase chimera states and cross-correlations in a ring of nonlocally coupled chaotic systems

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We explore the bifurcation transition from coherence to incoherence in an ensemble of nonlocally coupled logistic maps. It is shown that two types of chimera states, namely, amplitude and phase, can be found in this network. We reveal a bifurcation mechanism by analyzing the evolution of space-time profiles and the coupling function with varying coupling coefficient and formulate the conditions for realizing the chimera states in the ensemble. The regularities are established for the evolution of cross-correlations of oscillations in the network elements at the bifurcations related to the coupling strength variation. We reveal the features of cross-correlations for phase and amplitude chimera states. It is also shown that the effect of time intermittency between the amplitude and phase chimeras can be realized in the considered ensemble.

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Transient spatiotemporal patterns in a reaction-diffusion-mechanics system

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The reaction-diffusion-mechanics models are the models used to describe self-consistent electromechanical activity in a cardiac muscle. Such models couples two mechanisms of signal spreading in the tissue: the slow (reaction-diffusion) spreading of electrical excitation and the fast (almost instantaneous) spreading of mechanical deformations. This coupling may significantly modify the electrical excitation spreading and corresponding contractile activity with emergence of new spatiotemporal structures and patterns, which modification is not yet completely understood even in the one-dimensional case of a single muscle fiber. We propose clear convenient model which allows one to study the electromechanical activity of such a fiber in relation to the mechanical parameters of fiber fixation (such as stiffness of tissue fixation and the applied mechanical load, which can be easily controlled in experiments). Using this model, we determine and analyze the physical origin of the primary dynamical effects which can be caused by electromechanical coupling and mechanoelectrical feedback in a cardiac tissue.

On the basis of the reaction-diffusion-mechanics model with the self-consistent electromechanical coupling, we have numerically analyzed the emergence of structures and wave propagation in the excitable contractile fiber for various contraction types (isotonic, isometric, and auxotonic) and electromechanical coupling strengths. We have identified two main regimes of excitation spreading along the fiber: (i) the common quasi-steady-state propagation and (ii) the simultaneous ignition of the major fiber part and have obtained the analytical estimate for the boundary between the regimes in the parameter space. The uncommon oscillatory regimes have been found for the FitzHugh—Nagumo-like system: (i) the propagation of the soliton-like waves with the boundary reflections and (ii) the clusterized self-oscillations. The single space-time localized stimulus has been shown to be able to induce long-lasting transient activity as a result of the after-excitation effect when the just excited fiber parts are reexcited due to the electromechanical global coupling. The results obtained demonstrate the wide variety of possible dynamical regimes in the electromechanical activity of the cardiac tissue and the significant role of the mechanical fixation properties (particularly, the contraction type), which role should be taken into consideration in similar studies. In experiments with isolated cardiac fibers and cells, these parameters can be relatively easily controlled, which opens a way to assess electrical and mechanical parameters of the fibers and cells through analysis of dynamical regimes as dependent on fixation stiffness and external force. In real heart, high blood pressure and hindered blood flow play similar role to the applied external force and increased fixation stiffness. Our results provide a hint of how such global (i.e., associated with the large areas of the heart tissue) parameters can affect the heart electrical and contraction activity.

Chimera states in hierarchical networks of Van der Pol oscillators

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Chimera states are complex spatio-temporal patterns that consist of coexisting domains of coherent and incoherent dynamics. We analyse chimera states in networks of Van der Pol oscillators with hierarchical coupling topology. We investigate the stepwise transition from a nonlocal to a hierarchical topology, and adapt various quantifications to establish a link between the existence of chimera states and the compactness of the initial base pattern of a hierarchical topology; we show that a large clustering coefficient promotes the occurrence of chimeras. Depending on the level of hierarchy and base pattern, we obtain chimera states with different numbers of incoherent domains. We investigate the chimera regimes as a function of coupling strength and nonlinearity parameter of individual oscillators. The analysis of a network with larger base pattern resulting in larger clustering coefficient reveals two different types of chimera states and highlights the increasing role of amplitude dynamics.

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[1] S. Ulonska, I. Omelchenko, A. Zakharova, and E. Schöll (2016), arXiv:1603.00171v1.

Chimera patterns in Van der Pol networks: Influence of fractal topologies and self-adaptive control

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Chimera states consist of coexisting domains of spatially coherent and incoherent dynamics in systems of nonlocally coupled oscillators, and they have recently been discussed in diverse classical and quantum systems [1]. We show that a plethora of novel chimera patterns arise if one goes beyond the Kuramoto phase oscillator model and considers coupled amplitude and phase dynamics. For the Van der Pol oscillator [2] we find various multi-chimera patterns. Of particular current interest is the influence of complex network connectivities other than simple ring topologies. To test the robustness of chimera patterns, we study small-world and fractal (hierarchical) topologies [3, 4]. This is of relevance in neuroscience since there exists evidence that the connectivity in the brain has a fractal structure.

A second focus of recent research are chimeras in small networks. Chimeras are generally difficult to observe in small networks due to their short lifetime and erratic drifting of the spatial position of the incoherent domain. We propose a control scheme which can stabilize and fix the position of chimera states in small networks by symmetric and asymmetric self-adaptive feedback control [5]. Like a tweezer, which helps to hold tiny objects, our control has two levers: the first one prevents the chimera collapse, whereas the second one stabilizes its lateral position. The control scheme might be useful in experiments, where usually only small networks can be realized.

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[1] E. Schöll, S. H. L. Klapp, and P. Hövel: *Control of self-organizing nonlinear systems* (Springer, Berlin, 2016).

[2] I. Omelchenko, A. Zakharova, P. Hövel, J. Siebert, and E. Schöll: *Nonlinearity of local dynamics promotes multi-chimeras*, Chaos **25**, 083104 (2015).

[3] I. Omelchenko, A. Provata, J. Hizanidis, E. Schöll, and P. Hövel: *Robustness of chimera states for coupled FitzHugh-Nagumo oscillators*, Phys. Rev. E **91**, 022917 (2015).
[4] S. Ulonska, I. Omelchenko, A. Zakharova, and E. Schöll: *Chimera states in hierarchical networks of Van der Pol oscillators*, arXiv:1603.00171 (2016).
[5] I. Omelchenko, O. Omel'chenko, A. Zakharova, M. Wolfrum, and E. Schöll: *Tweezers for chimeras in small networks*, Phys. Rev. Lett. **116**, 114101 (2016).

Chimera state realization in chaotic systems. The role of hyperbolicity

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We study dynamical properties of one-dimensional ensembles of identical chaotic oscillators with nonlocal coupling. Such systems can demonstrate the transition from complete chaotic synchronization to spatiotemporal chaos when the coupling coefficient decreases. This transition is called the "coherence – incoherence" transition and, for certain networks, is accompanied by the appearance of chimera states. Our studies have shown that chimera states are observed in ensembles of oscillators which are characterized by non-hyperbolic chaotic attractors. These oscillators can be exemplified by the logistic map, the Henon map, the Roesller oscillator, the Anishchenko–Astakhov oscillator and others. As follows from our studies, the ensembles of oscillators with hyperbolic (quasi-hyperbolic) chaotic attractors cannot show chimera states. These systems include networks of the Lozi maps, tent maps, and Lorenz-type oscillators. They demonstrate the "coherence-incoherence" transition through the regime of so-called "solitary states" but the chimera states are not observed.

In our work we introduce the basic models for individual elements of the ensembles indicated above, namely, the two-dimensional Henon map and two-dimensional Lozi map. The first map describes the typical properties of oscillators with non-hyperbolic chaotic attractors, while the second one – with hyperbolic attractors. In our report we substantiate the hypothesis about the role of hyperbolicity in the appearance of chimera states. Particularly, the "coherence-incoherence" transition is explored in a ring of non-locally coupled Lorenz oscillators. In a single Lorenz system, the transition from a hyperbolic to non-hyperbolic chaotic attractor can be realized when the system parameters are varied. It is shown that in an ensemble of Lorenz oscillators in the regime of hyperbolic chaos, the transition from coherence to incoherence is observed through the regime of solitary states (there are no chimera states). If all the individual Lorenz oscillators are in the regime of non-hyperbolic chaos, then the chimera states can emerge.

The research results are described in detail in the paper [1].

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[1] N. Semenova, A. Zakharova, E. Schöll, and V.S. Anishchenko: *Does hyperbolicity impede emergence of chimera states in networks of nonlocally coupled chaotic oscillators*, Europhys. Lett. **112**, 40002 (2015).

Transition from synchronization to desynchronization in coupled logistic maps

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Dynamics of networks (ensembles) with local and global coupling have been thoroughly studied. Many interesting regimes have been found in such systems [1, 2]. In the present work we analyse the networks of the identical chaotic oscillators with nonlocal coupling. We analyse the ring of nonlocally coupled logistic maps in chaotic regime. It is known that such system can demonstrate reach dynamics from spatial coherence or incoherence to chimera states [3]. In the present work we make a shot at finding of impact of nonlocal coupling on the ring dynamics. In the furtherance of this aim we variate the coupling parameters and obtain which regimes are caused by nonlocal coupling and which one depends on dynamics of partial elements.

System under study is the ring of nonlocally coupled logistic maps:

$$x_i^{t+1} = (1-\sigma)f(x_i^t) + \Phi_i^t. \tag{1}$$

where t is the discrete time, $i = 1, 2 \ldots N$ is the index of oscillator, $f(x)$ is the logistic map $f(x) = ax(1-x)$, $\Phi_i^t = \frac{\sigma}{2P} \sum\limits_{j=i-P; j\neq i}^{i+P} f(x_j^t)$ is coupling term. The last one shows impact of $2P$ neighbours on i-th oscillator. Here σ is the coupling strength, P is the number of neighbours on the either side of i-th oscillator.

In the present work we vary the coupling strength σ and study its impact on temporal and spatio-temporal dynamics in system (1). The main results are following. During the transition from complete synchronization to coherence we obtain a new regime which we call fractional synchronization. The amplitude and phase chimera states have been found in the process on transition from coherence to incoherence. We study their special aspects in temporal and spatial dynamics and corresponding dynamics of the coupling term.

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[1] Afraimovich V. *Some Topological Properties of Lattice Dynamical Systems* Lecture Notes in Phys. **671**, p. 153–179 (2005).

[2] Nizhnik Leonid P., Nizhnik Irina L., Hasler M. *Stable Stationary Solutions in Reaction-diffusion Systems Consisting of a 1-d Array of Bistable Cells* Int. J. Bifurcation Chaos **12**, 2, p. 261–279 (2002).

[3] Omelchenko I., Maistrenko Yuri, Hövel P., Schöll E. *Loss of coherence in dynamical networks: spatial chaos and chimera states* Phys. Rev. Lett. **106,** p. 234102. (2011).

Spatio-temporal phenomena is a single time-delay system: coherence-incoherence transition and noise-induced effects.

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It is well-known that the certain effects revealed in ensembles of coupled oscillators or spatially extended systems can be tracked down in a purely temporal dynamics of the single time-delay systems [1–4].

In the present work a variety of spatio-temporal phenomena including regular dynamics, spatio-temporal chaos, chimera states, and solitary states are shown by numerical simulation in a nonlinear oscillator model with negative time-delayed feedback. A scenario for the transition from complete coherence to complete incoherence via solitary states has been identified when the nonlinearity parameter of the oscillator is varied. The control of the dynamics by external periodic forcing is demonstrated. It has been shown that chimera states with controllable characteristics, e.g., a desired number of incoherent clusters can be induced by using external periodic driving. A generalized form of synchronization with the driving signal leads to Arnold tongues of multi-chimera states when the driving frequency obeys a resonance condition, independently of initial conditions. We have also shown that noise can play a constructive role for controlling the chimera state. Noisy modulation of the external forcing amplitude can induce chimeras in regimes where they do not exist without noise. The noise-induced formation of chimera states is accompanied by an increase of the peak of the power spectrum at the resonance frequency, followed by a decrease upon further increase of the noise intensity similar to stochastic resonance. Such non-monotonic behavior as a function of noise intensity is also found in the signal-to-noise ratio.

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[1] F. T. Arecchi, G. Giacomelli, A. Lapucci, and R. Meucci, Phys. Rev. A **45**, R4225 (1992).
[2] G. Giacomelli and A. Politi, Phys. Rev. Lett. **76**, 2686 (1996).
[3] G. Giacomelli, F. Marino, M. A. Zaks, and S. Yanchuk, Europhys. Lett. **99**, 58005 (2012).
[4] L. Larger, B. Penkovsky, and Y. Maistrenko, Phys. Rev. Lett. **111**, 054103 (2013).

Steady states and transient processes in a chain of interacting non-oscillating elements

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We study one of models of dynamics of a chain of active non-oscillating elements interacting via nonlinear bonds. Nonlinear negative friction of elements is considered to be of a Rayleigh type. For this reason each isolated particle may be treated asymptotically as a Rayleigh oscillator with zero frequency.

Both cases of local and nonlocal coupling are considered. In the first case each element is coupled to two nearest neighbors only. In the second one each element interacts with two next-to-next neighbors as well.

In chains which appertain to considered class of models dissipative solitons may be excited. Combinations of different number of those uniformly distributed solitons are steady-state modes of the chain. However the numerical simulations show us that when starting from random initial conditions density peaks (i. e. solitons) are unevenly distributed. Such states are unstable but transition from the unstable state to a stable one may take a long time.

The duration of a transient process depends substantially on values of parameters. Numerical researches demonstrate that a transient time grows exponentially with a number of elements of a chain. Dependence of the transient time on both strength of bond between neighbor elements and nonlocal coupling are studied. Furthermore the mechanism of solitons excitation and spatial structures (such as solitonic clusters) formation statistics are investigated by means of computer simulation. Influence of noise on steady states and metastable states is considered as well.

The study was performed in the framework of the grant from the Russian Science Foundation (No. 16-12-10175).

Multistability in ensembles of phase oscillators with long-distance couplings

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We consider multistability in an ensemble of N identical phase oscillators with non-local diffusive couplings:

$$\dot{\theta}_i = \sum_{d=1}^{L} \gamma(d) \left[\sin\left(\theta_{i+d} - \theta_i\right) + \sin\left(\theta_{i-d} - \theta_i\right)\right] \quad (1)$$

Here θ_i is a 2π- periodic dynamical variable in the i-th cell $(i = 1, ..., N)$, $\gamma(d)$ is the coupling strength, which depends from distance d, while L is the maximum distance of the interaction. Since the boundary condition is periodic, all operations with spacial indexes are performed in modulus N.

Variables θ_i can be associated with instant phases of harmonic oscillations in some system of “full-scaled” oscillators: $X_i(t) = \cos\left(\Omega t + \theta_i(t)\right)$. Consequently, stationary solutions $\theta_{i0} = i\Delta\theta$ of the PO equations, can be considered as *traveling waves* observed in chains of periodic self-sustained oscillators. Stability properties of the traveling waves regimes as well as their basins of attractions are the subject of the study.

The work extends classical research published in paper [1], where stability conditions for traveling waves in chain of phase oscillators, whose strength of interaction monotonically decreases with the distance, were obtained analytically. Here we investigate how the Ermentrout criterion works in cases which are beyond the limitations used in [1].

The work was supported by the Russian Ministry of Education and Science (Project No. 1008).

[1] L. Ren, G.B. Ermentrout: *Phase locking in chains of multiple-coupled oscillators.* Physica D **143**, 56 (2000).

Chimera regimes in a two-dimentional network of cubic maps with nonlocal coupling

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Complex spatiotemporal structures, which are known as chimera states, are studied in a two-dimensional network of cubic maps. The system under study is described by following equations:

$$
\begin{aligned}
&x_{n+1_{i,j}} = x_{n+1_{i,j}} = (\alpha x_{n_{i,j}} - x^3_{n_{i,j}}) \cdot \exp\left(\frac{x^2_{n_{i,j}}}{\beta}\right) + \sum_{k=i-R}^{i+R} \sum_{p=j-R}^{j+R} (x_{n+1_{k,p}} - x_{n+1_{i,j}}),\\
&x_{i+N,j} = x_{N,j}, \qquad\qquad (1)\\
&x_{i,j+N} = y_{i,N},
\end{aligned}
$$

where α and β are the control parameters of the cubic map, σ is the coupling strength. Coupling between the network elements is nonlocal, i.e. each element is coupled with all neighbors in the limit of radius R. The boundary conditions are periodic for both directions.

One of the important features of the cubic map describing a single unit is bistable behavior. The map can demonstrate bistability with periodic or chaotic attractors in two wells or combined chaos depending on parameter values. We have chosen the values of α and β in a combined chaotic regime near a threshold of its appearance. In this case, the network (1) demonstrates a lot of different regimes with changing coupling strength. Incoherent chaos, global synchronization, partial synchronization with one-well location or with switching between two wells are observed. Among possible regimes are different structures, coexisting clusters with coherent and incoherent dynamics of units. Such structures are known as chimera structures [1–5].

Our report is devoted to the study of chimera states in the two-dimensional network (1). Various kinds of chimeras have been found. They are both already known chimera regimes, such as amplitude and phase chimeras located in one of the two wells ([4, 5]), and new chimera structures combined of parts located in the two wells. One of the new structures is a so-called "switching chimera" including the clusters of units irregularly located in the two wells. The regime diagram has been plotted on the (R, σ) parameter plane.

The study was supported by RFBR (research project No. 14-52-12002) and the Russian Science Foundation (grant No. 16-12-10175.

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[1] Y. Kuramoto, D. Battogtokh: *Coexistence of coherence and incoherence in nonlocally coupled phase oscillators*, Nonlinear Phenom. Complex Syst. **4**, 380–385 (2002).

[2] M.J. Panaggio, D.M. Abrams: *Chimera states: Coexistence of coherence and incoherence in networks of coupled oscillators*, Nonlinearity **28**, R67 (2015).

[3] I. Omelchenko, Y. Maistrenko, P. Hövel, E. Schöll: *Loss of coherence in dynamical networks: Spatial chaos and chimera states*, Phys. Rev. Lett. **106**, 234102 (2011).

[4] A. Zakharova, M. Kapeller, E. Schöll: *Chimera death: Symmetry breaking in dynamical networks*, Phys. Rev. Lett. **112**, 154101 (2014).

[5] S.A. Bogomolov, G.I. Strelkova, E. Schöll, and V.S. Anishchenko: *Amplitude and phase chimeras in an ensemble of chaotic oscillators*, Tech. Phys. Lett. **42**(7), 763–766 (2016).

Chimeras in a ring of linear oscillators with nonlinear local unidirectional coupling

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One of important problems concerning chimera states is the type of coupling in ensemble when such structures can arise. Until now, it was assumed that chimeras exist only in ensembles with nonlocal character of interactions. However, this assumption is not exactly right. In some special cases, chimeras can be realized for local type of coupling [1, 2, 3]. The existence of a virtual chimera in the systems with delayed feedback [4] and the analogy of oscillator with delayed feedback and one-dimensional spatially extended system suggests that chimeras can emerge in a ring of oscillators with local coupling at least in a case of unidirectional character of interaction of units. The results of numerical simulations, which prove this assumption, are presented in this report.

The ensemble of linear oscillators in form of a ring with local nonlinear coupling are studied. The equations of the model are as follows:

$$\dot{x}_j = -\alpha x_j - \omega_0^2 y_j + \sigma f(x_{j-1}) + \gamma(x_{j-1} + x_{j+1} - 2x_j), \quad \dot{y}_j = x_j, \quad (1)$$

$$f(x) = \frac{B}{1 + A\sin^2(x+\varphi)}.$$

Here x_j and y_j are the dynamical variables of units, $j = 1, \ldots, N$ is an oscillator number, $N = 300$ is the number of units in the ring, α and ω_0 are the dissipation coefficient and the natural frequency, respectively. The frequency was fixed as $\omega_0 = 1$. Two types of local interactions are taken into account in (1). The first type is a nonlinear unidirectional coupling given by the nonlinear function $f(x)$ with intensity σ. The parameters of nonlinearity are fixed, $A = 4.7$, $B = 4$, $\gamma = 0.4$. The second type is a dissipative coupling with the coefficient γ. The equations (1) were integrated numerically. Space-time plots, snapshots, temporal realizations in fixed spatial points were applied for diagnostic of the regimes. Initial conditions were chosen as random or periodic with an additional random part.

The numerical studies have shown an example of a chimera regime, appearing in the ensemble (1). It is evidence that the local character of interaction does not exclude the possibility of formation of such complex structures as chimeras. Moreover, the elements of the studied ensemble are the simplest linear oscillators with large dissipation. The nonlinear unidirectional coupling plays in this case the main role in the chimera formation. The system demonstrates the property of roughness as the form of nonlinearity is changed or the diffusive coupling is added. Chimeras exist in a large area of values of unidirectional coupling coefficient and dissipation parameter of the oscillators, and they become impossible as the dissipation decrease too small or the diffusive component of coupling increases too large.

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[1] A. Zakharova, M. Kapeller, and E.'Schöll: *Chimera death: Symmetry breaking in dynamical networks*, Phys. Rev. Lett. **112**, 154101 (2014).

[2] C.R. Laing: *Chimera in networks with purely local coupling*, Phys. Rev. E **92**, 050904 (2015).

[3] M.G. Clerc, et al: *Chimera-type states induced by local coupling*, Phys. Rev. E **93**, 052204 (2016).

[4] L. Larger, B. Penkovsky, and Y. Maistrenko: *Virtual chimera states for delayed-feedback systems*, Phys. Rev. Lett. **111**, 054103 (2013).

Peculiarities of chimera states formation in an ensemble of non-locally coupled Anishchenko–Astakhov self-sustained oscillators

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The model of an ensemble of non-locally coupled Anishchenko–Astakhov self-sustained oscillators is studied. The equations describing this model can be written as follows:

$$\begin{aligned}
\dot{x}_i &= mx_i + y_i - x_i z_i + \frac{\sigma}{2P}\sum_{j=i-P}^{i+P}(x_j - x_i),\\
\dot{y}_i &= -x_i + \frac{\sigma}{2P}\sum_{j=i-P}^{i+P}(y_j - y_i),\\
\dot{z}_i &= -gz_i + \frac{g}{2}x_i(x_i + |x_i|),
\end{aligned} \tag{1}$$

where m and g are the control parameters of elements, σ is the coupling strength, P is the coupling radius. A partial element demonstrates transition to chaos through a cascade of period-doubling bifurcations. The values of control parameters of the system (1) are fixed to be $m = 1.49$ and $g = 0.2$, that corresponds to the regime of developed chaos in a single oscillator.

The behavior of system (1) is considered while the coupling parameters σ and P are varied. The phenomenon of multistability consisted in the coexistence of standing waves, traveling waves and some other regimes for the same values of the system parameters is observed. The appearance of different types of chimera states from the standing and traveling waves is explored.

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Stability analysis of long-living transient amplitude chimeras

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Chimera states are characterized by a spontaneous break-up of a network of identical elements into coexisting domains of coherent (synchronized) and incoherent (desynchronized) dynamics. We study networks with coupled phase and amplitude dynamics. In contrast to classical phase chimeras, pure amplitude chimeras exhibit domains of coherent and incoherent dynamics with respect to the amplitude, but the phases are always regular and correlated. These states are long-living transients. In this work we investigate networks of Stuart-Landau oscillators with symmetry-breaking non-local coupling, in which amplitude chimeras can occur [1]. We verify the hypothesis that amplitude chimeras represent saddle-states in a high-dimensional phase space by calculating the Floquet exponents and the corresponding Floquet eigenvectors. In this way we can explain the dependence of the transient times upon coupling strength, coupling range and network size.

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[1] A. Zakharova, M. Kapeller, E. Schöll, Phys. Rev. Lett. **112**, 154101 (2014).

Coherence-resonance chimeras: a bridge between chimera states and coherence resonance

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We study an effect which combines coherence resonance and chimeras states in a network of nonlocally coupled excitable elements. We demonstrate that chimera behavior can be observed in a network composed of solely excitable units and not only in oscillatory systems and show that the presence of noise is a crucial condition for this case. Moreover, we uncover the constructive role of noise for chimera states and detect a novel type of coherence resonance, which we call *coherence-resonance chimeras* [1]. In these spatio-temporal patterns coherence resonance is associated with spatially coherent and incoherent behavior, rather than purely temporal coherence or regularity measured by the correlation time. Since we consider a paradigmatic model for neural excitability in a noisy environment, we expect wide-range applications of our results to neuronal networks in general.

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[1] N. Semenova, A. Zakharova, V.S. Anishchenko, and E. Schöll (2016), *Coherence-resonance chimeras in a network of excitable elements*, Phys. Rev. Lett. **117**, 014102 (2016).