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Stochastic resonance in spatiotemporal on–off intermittency

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Abstract

Stochastic resonance is investigated in a generic system with spatiotemporal on–off intermittency: a chain of coupled logistic maps with a time-dependent control parameter, driven by a spatiotemporal periodic signal. Spatiotemporal correlation function between the periodic signal and the output signal, reflecting the occurrence of laminar phases and chaotic bursts, has a maximum as a function of the mean value of the control parameter. For a given period and length of the periodic signal the height of this maximum can be increased by choosing an optimum coupling strength between maps. It is argued that the obtained result can be interpreted as an example of noise-free (dynamical) stochastic resonance in a system with spatiotemporal intermittency.

1. Introduction

Stochastic resonance (SR) is a phenomenon occurring in systems driven by a combination of a periodic signal and noise, in which the strength of a periodic component of a suitably defined output signal is maximum for optimum nonzero noise intensity [1–3]. Nonlinear systems exhibiting SR comprise, e.g., bistable [4,5], dynamical excitable [6], and nondynamical threshold-crossing systems [7]. A separate class of systems with SR is formed by chaotic models in which, instead of external noise, the internal chaotic dynamics can be tuned to maximize the periodic component of the output signal. This is achieved by varying a control parameter, and the corresponding phenomenon is called noise-free (dynamical) SR [8–15]. In recent years, SR has been intensively studied in spatially extended stochastic systems driven by signals periodic in time [16–21] as well as both in time and space [22–25]. In particular, arrays of coupled elements exhibiting SR have been investigated, in which it has been shown that optimum values of both coupling and noise exist, such that the maximum strength of the periodic component of the output signal can be significantly increased in comparison with that from a single uncoupled element. For the optimum noise and coupling the periodicity of the input signal is best reflected in the dynamics of elements forming the array. For example, in a chain of bistable elements driven by the signal periodic in time and uniform in space the occupation of the two states of individual elements oscillates almost periodically in time. This leads to strong enhancement of the periodic component of the output signal from individual elements, as well as to maximum spatiotemporal synchronization among the chain elements, and between the chain elements and the input signal [16]. Similarly, in a chain of coupled threshold elements driven by the signal periodic both in time and space, the output signals from the elements are highly correlated with the input signal [25]. The above-mentioned effects are known under a general name of array-enhanced SR.

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In this paper we make a step towards the extension of the investigation of SR in spatially extended systems to the case of noise-free SR in systems with spatiotemporal chaos. An important step on the route to turbulence in spatially extended systems is spatiotemporal intermittency [26–31]. By studying noise-free SR in low-dimensional systems it was shown [11] that the laminar and chaotic phases in temporally intermittent signals can play a role analogous to two states in generic bistable models for SR [1–5]. It is so since the mean duration of at least one of them, the laminar phase, depends sensitively on the control parameter. Thus, if the output signal is defined so that it reflects the occurrence of the two phases in the time series for the system variables, the control parameter can be optimized so that the output signal reproduces well the effect of the periodic modulation of the system dynamics by the input signal. The purpose of the present paper is to show that, similarly, it is possible to observe noise-free SR in spatially extended systems with spatiotemporal intermittency. As an example a model exhibiting spatiotemporal on–off intermittency (OOI) [30] is considered. In low-dimensional chaotic systems this kind of intermittency is characterized by quiescent laminar phases, during which the measured variable is almost constant, separated by large chaotic bursts [32–41]. Similarly, spatiotemporal OOI is characterized by a mixture of quiescent laminar phases and chaotic bursts both in space and time [30,31]. The model for spatiotemporal OOI is a simple coupled map lattice (CML) which in our case enables analytic estimation, in the limit of vanishing coupling, of selected quantities characterizing SR. The problem of SR in spatiotemporal OOI can be interesting from the experimental point of view, since it was suggested that spatiotemporal OOI is amenable to observation in systems where the breakdown of spatiotemporal synchronized chaos takes place [31]. We also argue that qualitatively similar results for noise-free SR can be obtained in other systems and for other kinds of spatiotemporal intermittency.

2. The model

We study a one-dimensional chaotic CML, which is a generic model for spatiotemporal OOI [30] modified by inclusion of the input spatiotemporal periodic signal

$$\begin{aligned} x_{n+1}^{(i)} &= (1-w)f\left(x_n^{(i)}, a_n^{(i)}\right) + \frac{w}{2}\left[f\left(x_n^{(i-1)}, a_n^{(i-1)}\right) + f\left(x_n^{(i+1)}, a_n^{(i+1)}\right)\right], \\ a_n^{(i)} &= [a_0 + A\sin(\omega n - ki)]\xi_n^{(i)}, \quad i = 0, 1, \ldots, L-1, \\ f(x, a) &= ax(1-x). \end{aligned} \tag{1}$$

Here, $x_n^{(i)} \in (0,1)$ denotes the state of the lattice unit with spatial coordinate i at time step n, L is the lattice length, w is the coupling strength, $a_n^{(i)}$ is a time- and space-dependent control parameter, A is the amplitude of the input spatiotemporal periodic signal with frequency $\omega = 2\pi/T$ and wave vector $k = 2\pi/\lambda$. The variables $\xi_n^{(i)} \in (0,1)$ denote any chaotic process constrained to the unit interval. Hence, the system given by Eq. (1) can be treated as a $2L$-dimensional chaotic system with dynamics described by the variables $x_n^{(i)}$, $\xi_n^{(i)}$, $i = 0, 1, \ldots, L-1$. It possesses an invariant subspace $x_n^{(1)} = x_n^{(2)} = \cdots = x_n^{(L)} = 0$, and the variables $\xi_n^{(i)}$ describe the dynamics within this subspace, while the measured variables $x_n^{(i)}$ are perpendicular to this subspace. The existence of such invariant subspaces is a necessary condition for the occurrence of OOI, which appears due to the loss of the transverse stability of such a subspace with the rise of the control parameter.

For $A = 0$ a single uncoupled map $x_{n+1} = a_0\xi_n x_n(1 - x_n)$, which is equivalent to assuming $w = 0$ in Eq. (1), shows transition to OOI as a_0 is increased above a certain threshold a_c whose value depends on the probability distribution of ξ_n. For $a_0 > a_c$ chaotic bursts appear which are connected with fast departure of the phase trajectory from the invariant subspace $x_n = 0$, and laminar phases during which the system evolves in the vicinity of the invariant subspace. This transition is associated with the loss of the transverse stability of the invariant manifold $x_n = 0$, due to the change of sign of the transverse Lyapunov exponent $\lambda_\perp$ from negative to positive [32,33]. The latter exponent can be obtained as a time average of the eigenvalues of the logistic map at the fixed point $x = 0$ for a given value of ξ_n, i.e., $\lambda_\perp = \langle \ln(a_0\xi_n)\rangle$; the time average can be replaced by an equivalent average over the probability distribution of ξ_n. If $a_0 < a_c$ there is $\lambda_\perp < 0$ and the variable x_n converges to zero for large n, while if $a_0 > a_c$ there is $\lambda_\perp > 0$ and the variable x_n departs on average from the invariant manifold. In the latter case, the sequence of laminar phases, during which $x_n \approx 0$, and large chaotic bursts appears due to the confining nonlinearity of the logistic map which also provides a mechanism of reinjection of the variable x_n towards the invariant manifold; an example of the time series with OOI is shown in Fig. 1. By analogy, the CML (1) with $0 < w < 1$ exhibits spatiotemporal OOI [30]. The OOI threshold $a_c \leqslant e$ depends both on the probability distribution of ξ_n and the coupling strength w, and if $a > a_c$ each map shows a sequence of laminar phases and bursts, typical of OOI. Laminar phases and bursts can be also seen in space if the variables $x_n^{(i)}$,

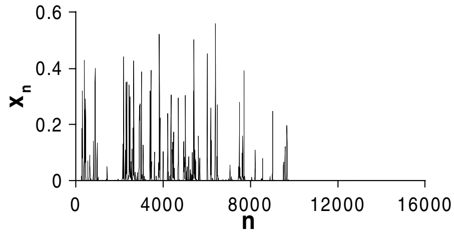

Fig. 1. Time series showing on–off intermittency from a single uncoupled map in Eq. (1) with $a_0 = a_c + 0.05$, $A = 0$, $w = 0$; the variable ξ_n is assumed as random variable with uniform distribution on the interval (0, 1).

$i = 0, 1, \ldots, L-1$ are measured at any fixed time step n. For strong coupling, long-range spatial correlations between maps appear.

From the above discussion follows that in the case of an uncoupled map the dynamics in the direction transverse to the invariant subspace $x_n = 0$ is determined by that within the invariant subspace, modelled by the variable ξ_n. Just above the intermittency threshold the mean duration of laminar phases much exceeds that of the chaotic bursts. The chaotic process ξ_n has a characteristic time scale beyond which its autocorrelation is negligible. By making $a_0 - a_c$ sufficiently small, the typical time between bursts can be made long in comparison with the correlation time of ξ_n. Thus, just above the intermittency threshold, we are concerned with the time scales between bursts much longer than the correlation time of ξ_n. Hence, in generic models for low-dimensional OOI based on the parametrically driven logistic map [32–35] the chaotic process ξ_n with properties described above is approximated as white noise with uniform distribution on the interval (0, 1). It follows that the qualitative properties of OOI (scaling laws for the probability distribution of lengths τ of laminar phases $P(\tau) \propto \tau^{-3/2}$ and their mean duration $\langle\tau\rangle \propto (a_0 - a_c)^{-1}$, etc.) close to the intermittency threshold obtained from such generic models are universal. In fact, for low-dimensional chaotic systems with OOI it was verified both via numerical simulations [32] and experimentally [38–41] that the properties of OOI are independent of the details of the dynamics within the invariant subspace. Deviations from the universal scaling laws are possible [36,37], but it seems that they require conditions which are seldom fulfilled in real systems with OOI. Similarly, in the generic model for spatiotemporal OOI the variables $\xi_n^{(i)}$ are assumed as white noises uncorrelated in space and time [30]. The qualitative properties of spatiotemporal OOI obtained from this model seem also to be universal, as was verified via numerical simulations in Ref. [31].

On the basis of the above discussion, following Ref. [30,32–35], henceforth we assume that $\xi_n^{(i)}$ in the model (1) are random numbers with uniform distribution on the interval (0,1), uncorrelated in time and space. Although then they become stochastic variables, they in fact represent a part of the chaotic dynamics of the system. The properties of the model are quite universal for modelling spatiotemporal OOI. Thus the name noise-free (dynamical) SR for phenomena connected with the transmission of the periodic signal by the CML (1) is still appropriate.

Before going to numerical simulations and analytic theory, let us discuss qualitatively the possibility of the occurrence of SR in the system (1). The mean duration of laminar phases (in time in a single map, and both in time and space in the CML) decreases with $a_0 - a_c$, and the bursts become more frequent. In other words, when the control parameter increases, the probability of the occurrence of a chaotic burst also increases, while decrease of the control parameter causes that the probability of the occurrence of a laminar phase increases. Thus, if the control parameter is modulated periodically with amplitude $A > 0$, and if the output signal reflects the occurrence of laminar phases and bursts, there should be an optimum value of a_0 close to a_c for which the output signal should have a maximum periodic component. The mechanism of noise-free SR is thus related to the periodic changes in the stability of the invariant manifold due to the modulation of the control parameter, and to the confining nonlinearity of the logistic map which enables the occurrence of chaotic bursts. In fact, noise-free SR was observed in systems with temporal OOI [11–14]. In this paper we show that the CML (1) is also a proper model to observe noise-free SR in a spatially extended system.

3. Methods of analysis

We define the spatiotemporal output signal from the system (1) as $y_n^{(i)} = \Theta\left(x_n^{(i)} - x_{\rm thr}\right)$, where Θ denotes the Heaviside step function, $\Theta(z) = 1$ if $z \geqslant 0$ and $\Theta(z) = 0$ if $z < 0$, and $x_{\rm thr} \ll 1$ is a threshold which enables distinction between the laminar phases and bursts. To characterize SR, measures based on the power spectral density of the output signal are usually applied, e.g., the signal-to-noise ratio [2,4] or signal power amplification [2,5]. However, especially in spatially extended systems with periodic input signal [19,22,25], or in systems with aperiodic input signal [42], SR is often characterized using cross-correlation functions between the input and output signal. Following the latter tendency, as a measure of SR we use the normalized spatiotemporal input–output correlation function

$$C = \frac{\langle\langle y_n^{(i)} A \sin(\omega n - ki)\rangle\rangle}{\sqrt{\langle\langle A^2 \sin^2(\omega n - ki)\rangle\rangle \left[\langle\langle (y_n^{(i)})^2\rangle\rangle - \langle\langle y_n^{(i)}\rangle\rangle^2\right]}}, \tag{2}$$

where double angular brackets mean averaging over time and space, and in Eq. (2) the fact that the spatiotemporal average of the input signal is zero was taken into account. The appearance of noise-free SR in the system (1) is characterized by a maximum of the curve C vs. a_0. The spectral measures, like the signal power amplification, reach maximum value when the output signal power at the frequency of the input signal is maximum, independently of the phase shift between the input and output signal. In contrast, the correlation function C is maximum when the output signal is periodic with the same frequency and phase as the input signal. Thus, so that the function C was at a maximum, not only the periodicity of the input signal must be best reflected in the dynamics of the CML, but also the chaotic bursts should appear most probably when the input signal is at a maximum, without a significant shift in time.

Assuming periodic boundary conditions, the time averages in Eq. (2) evaluated over different lattice units are equal due to the system symmetry, i.e., $\langle y_n^{(i)}\rangle = \langle y_n^{(j)}\rangle$ for any i, j, etc. Thus the function C is equal to the cross-correlation function between the input and output signal from any lattice unit i

$$C = C^{(i)} = \frac{\langle y_n^{(i)} A \sin(\omega n - ki)\rangle}{\sqrt{(A^2/2)\left[\langle (y_n^{(i)})^2\rangle - \langle y_n^{(i)}\rangle^2\right]}}. \tag{3}$$

In Eq. (3) the angular brackets denote the time average, and the spatiotemporal average of the input signal was evaluated as $A^2/2$ in the continuous-time approximation, valid for small ω. Using Eq. (3) for the numerical evaluation of the full correlation function (2) requires long simulations. Thus, in practice, C is obtained by first evaluating $C^{(i)}$ for all lattice units, with averages calculated over several periods of the input signal T, and then performing spatial averaging

$$C = \frac{1}{L}\sum_{i=0}^{L-1} C^{(i)}. \tag{4}$$

4. Theoretical analysis in the limit of vanishing coupling and small signal frequency

For $w \to 0$ and in the adiabatic limit $\omega \to 0$ the function C vs. a_0 can be estimated semi-analytically. For this purpose let us note that under the influence of the slow periodic modulation of the control parameter the probability that the lattice unit i at time step n exhibits burst, i.e., that $y_n^{(i)} = 1$, becomes slowly time-dependent; this probability will be denoted as $p^{(i)}(n)$. Taking into account that $y_n^{(i)} = (y_n^{(i)})^2$, using the continuous-time approximation, and replacing the time averages in Eq. (3) with averages over the (time-dependent) probability distribution for $y_n^{(i)}$, it is straightforward to obtain

$$\begin{aligned} \langle y_n^{(i)} A \sin(\omega n - ki)\rangle &= T^{-1}\int_0^T p^{(i)}(t) A \sin(\omega t - ki)\,\mathrm{d}t, \\ \langle (y_n^{(i)})^2\rangle = \langle y_n^{(i)}\rangle &= T^{-1}\int_0^T p^{(i)}(t)\,\mathrm{d}t. \end{aligned} \tag{5}$$

As mentioned in Section 3, due to the system symmetry, the index i can be dropped, and $i = 0$ can be used in further calculations without loss of generality.

The idea behind the adiabatic approximation is to obtain the time-dependent probability of burst $p(t)$ in the presence of the periodic signal from the time-independent probability of burst in the absence of the periodic signal. The latter probability is assumed to be a known function of the control parameter a_0. For the slowly varying periodic signal this can be achieved by replacing in this function the control parameter by its time-dependent value, $a_0 \to a_0 + A \sin \omega t$ [4]. For a single map without periodic driving, and with ξ_n being a random number with uniform distribution on (0,1), the mean duration of laminar phases just above the OOI threshold obeys the scaling law $\langle\tau(a_0)\rangle \approx e^2/[2(a_0 - a_c)]$, with

$a_c = e = 2.718\ldots$ [32]. In contrast, we observed that the mean duration of bursts τ' close to a_c is almost independent of the control parameter and increases only far from the OOI threshold. The time-independent probability of burst for a given a_0 is then $p = \{\tau'/[\langle\tau(a_0)\rangle + \tau']\}\Theta(a_0 - a_c)$, where the Heaviside function emphasizes the fact that bursts appear only if $a_0 > a_c$. Thus in the adiabatic approximation we find the time-dependent probability of burst as

$$p(t) = \frac{\tau'\Theta(a_0 + A\sin\omega t - a_c)}{\tau' + e^2/[2(a_0 + A\sin\omega t - a_c)]}. \tag{6}$$

After inserting Eq. (6) into (5) the integrals can be evaluated numerically, and the theoretical curve C vs. a_0 can be obtained by inserting the result into Eq. (3). The curve shows maximum at a_0 slightly above a_c, as expected. This supports the numerical finding, presented below, that noise-free SR can appear in the CML (1).

At this point it should be noted that, although there are two distinct phases in the output signals from the lattice units in the system (1), their mean durations do not depend on the control parameter in a symmetric manner. In contrast, at the onset of OOI the laminar phases are usually longer and interrupted by shorter chaotic bursts. This makes the dynamics of the system under study intermediate between that in bistable [1–5] and dynamical excitable [6] models for SR, the latter being characterized by the output signal in the form of a pulse train, with short pulses of constant duration.

5. Numerical results and discussion

Numerical simulations of Eq. (1) were performed with periodic boundary conditions, L/λ being an integer power of two, $L = 512$, $A = 0.05$, $x_{\rm thr} = 0.001$, and other parameters varied. Let us first consider the case of signal periodic in time ($\omega \neq 0$) and uniform in space ($k = 0$). The numerical curves C vs. a_0 for various frequencies ω and coupling strengths w are shown in Fig. 2. The occurrence of maxima in these curves shows that noise-free SR in the system appears. For comparison, in Fig. 2(c) also the theoretical curve C vs. a_0 for $w = 0$ is shown, obtained from Eqs. (3)–(6) with numerically measured value of τ' close to the onset of intermittency. It can be seen that although Eq. (6) is valid only in the vicinity of the OOI threshold, the theoretical results for uncoupled lattice units and slowly varying periodic signal are comparable with the numerical ones.

For any fixed w the numerically evaluated correlation function increases with the modulation period T and saturates in the adiabatic limit of slowly varying signals $\omega \to 0$. It should be noted that the adiabatic limit is attained only for very long modulation periods; e.g., comparing Fig. 2(b) with Fig. 2(c) it can be seen that even for $T = 1024$ the correlation function has not saturated yet. This is typical of SR in systems with OOI: also in a model for noise-free SR in temporal OOI it was observed that the adiabatic limit was attained only for very long periods of the signal modulating the control parameter [12]. For any ω there is an optimum coupling strength $w > 0$ for which the height of the maximum of the correlation function reaches its supremum value. The effect of coupling is strong: the height of the maximum of C can be significantly increased in comparison with that in a single uncoupled map (i.e., in the CML with $w = 0$). This is an example of array-enhanced noise-free SR. For optimum w, and for a_0 corresponding to the maximum of the respective (for given w) correlation function, the periodicity of the input signal is best reflected in the output signal by the location

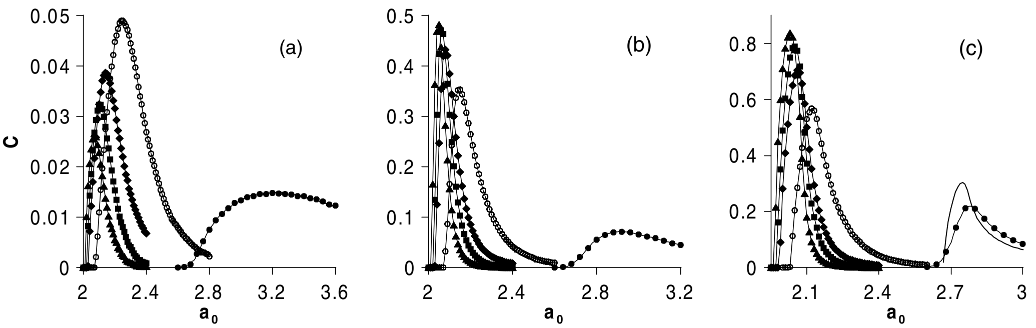

Fig. 2. Correlation function C_1 vs. a_0 for the system (1) with $k = 0$ and (a) $T = 128$, (b) $T = 1024$, (c) $T = 65536 = 2^{16}$. Symbols represent numerical results for $w = 0$ (dots), $w = 0.1$ (circles), $w = 0.4$ (squares), $w = 0.8$ (triangles), $w = 1.0$ (diamonds) (curves connecting points are guides to the eyes); solid line in (c) represents theoretical estimation from Eqs. (3)–(6) with $\tau' = 15$. Note different scales on axes in (a)–(c).

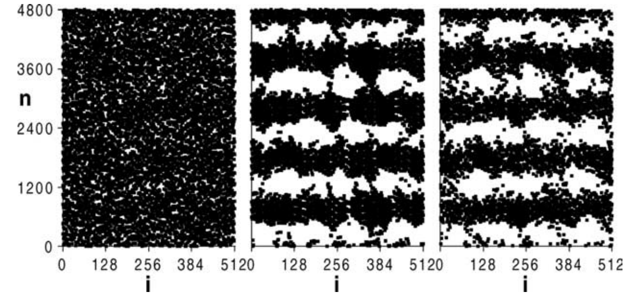

Fig. 3. Spatiotemporal diagrams for the system (1) with $k = 0$, $T = 1024$, and, from left: $w = 0.0$, $a_0 = 2.91$ (smaller than optimum w, a_0 corresponding to maximum C); $w = 0.9$, $a_0 = 2.05$ (optimum w, a_0 corresponding to maximum C); $w = 1.0$, $a_0 = 2.06$ (larger than optimum w, a_0 corresponding to maximum C). Black points denote burst phases ($y_n^{(i)} = 1$), white points denote laminar phases ($y_n^{(i)} = 0$).

of laminar phases and bursts in time and space. This is illustrated in Fig. 3 by means of spatiotemporal diagrams. For the coupling strength w other than optimum the visibility of the input signal in the output one is deteriorated, even though a_0 is at the value corresponding to the maximum of the respective correlation function. This is particularly noticeable in the limit of small coupling (cf. Fig. 3 (left) for $w = 0$).

Next, let us consider the case of signal periodic also in space ($k = 2\pi/\lambda \neq 0$). If $T \gg \lambda$ the input signal is, in fact, periodic only in space and almost constant in time, thus we deal with the case of spatial SR in a system with spatiotemporal chaos (the phenomenon of spatial SR in stochastic systems was considered in Ref. [22,23]). For any λ, ω and w the curves C vs. a_0 have maxima, which shows that SR with spatiotemporal signal [25] appears in the CML (1). The agreement between the numerical and theoretical curves C vs. a_0 for $w = 0$ and small ω turns out to be as good as previously in Fig. 2(c) (not shown). The height of the maximum of the numerical curve C vs. a_0 is shown in Fig. 4 as a function of λ and w for different periods T. For any fixed T and λ there is an optimum coupling strength $w > 0$ for which the height of the maximum of the correlation function reaches its supremum value. This shows that SR with spatiotemporal signal can be enhanced due to proper coupling, in analogy with what is known in stochastic systems [25,43]. In Fig. 4 (right) it can be seen that in the adiabatic limit $\omega \to 0$ the supremum value of the height of the maximum of C appears for $k \to 0$, i.e., for spatially uniform signals. A similar observation was made in stochastic spatially extended systems, in which SR is usually a weaker effect in the case of spatially nonuniform periodic signals [24]. However, it is interesting to note that in the nonadiabatic regime (the cases with $T = 128$ and $T = 1024$ in Fig. 4 (left and middle)) the supremum value of the height of the maximum occurs for $k > 0$, i.e., SR is stronger for spatially nonuniform signals. This is probably related to long-range spatial and temporal correlations between strongly coupled maps in spatiotemporal OOI, but this problem requires further investigation. The precise location of the supremum as a function of λ and w turns out to depend on the choice of the burst threshold x_{thr} and is shifted towards larger λ with increasing period

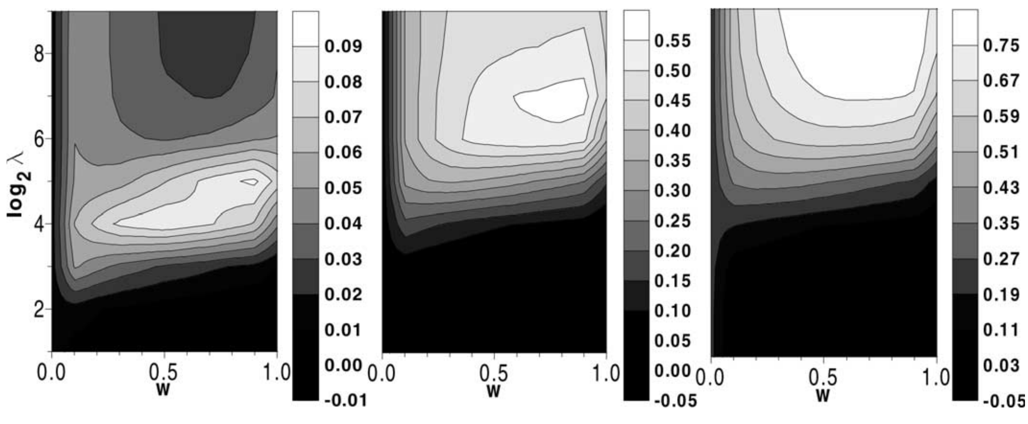

Fig. 4. Contour plots of the height of the maximum of the correlation function C_1 vs. a_0 as a function of w and λ for the system (1) with, from left: $T = 128$, $T = 1024$, $T = 65536$.

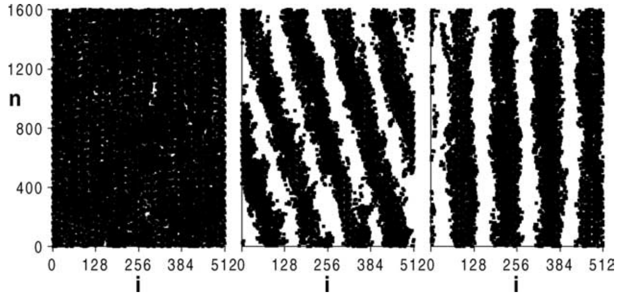

Fig. 5. Spatiotemporal diagrams for the system (1) $\lambda = 128$, and, from left: $T = 128$, $w = 0.1$, $a_0 = 2.24$; $T = 1024$, $w = 0.9$, $a_0 = 2.03$; $T = 65536$, $w = 0.6$, $a_0 = 2.03$; in all cases w is optimum and a_0 corresponds to maximum C for a fixed T.

T. As in the previous case, for any ω and for such w and a_0 for which the correlation function C reaches its supremum value, the periodicity of the input signal is best reflected in the output signal by the location of laminar phases and bursts in time and space (Fig. 5).

6. Conclusions

In this paper we extended investigation of SR in spatially extended systems to the case of noise-free SR in systems with spatiotemporal chaos in the form of spatiotemporal OOI. All kinds of SR and related effects, previously observed in spatially extended stochastic systems, were found also in the chaotic CML (1). They comprise SR with signal periodic only in time, only in space, and both in time and space, as well as enhancement of SR due to proper coupling between lattice units. The basic properties of noise-free SR in the system under study resemble those in spatially extended systems with stochastic dynamics. In particular, for a given length and period of the input signal, the control parameter and the coupling strength can be chosen in the optimum way so that the periodicity of the input signal is best reflected in the output signal by the location of the laminar phases and bursts. This leads to maximum correlation between the input and output signal.

Although our system is discrete both in space and time, it is known that the properties of SR in spatially extended noise-driven systems with discrete dynamics are in general analogous to those in systems with continuous time [21]. Moreover, for the appearance of SR in our system only intermittent dynamics in space and time with sensitive dependence of the mean duration of laminar and, possibly, chaotic phases on the control parameter is necessary. This is the case also in other kinds of sustained spatiotemporal intermittency, found, e.g., in numerical simulations and experimental observations of convection [27,28]. Thus our results also open a way to study noise-free SR in spatially extended systems with chaotic dynamics other than that typical of CML, and with other kinds of spatiotemporal intermittency.

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