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Modelock-avoiding synchronisation method

H.-A. Tanaka and A. Hasegawa

A simple synchronisation method avoiding the modelock phenomenon has been realised using dynamic network coupling. Two-dimensional arrays of millimeter-wave power-combining and beam-scanning control systems are considered as an application of the method. The effect, limitations and robustness of the proposed method are investigated numerically.

Introduction: Networks of interconnected oscillators emerge in a wide range of engineering issues. Examples are known in millimetre-wave power-combining and beam-scanning control systems [1], a novel VLSI clocking [2], and Josephson junction arrays, where implementation of two-dimensional (2D) synchronous arrays has been a technical challenge since a number of oscillators are packed in a limited space and are required to oscillate in unison. As opposed to one-dimensional (1D) linear arrays of oscillators, planar arrays of oscillators can sometimes exhibit 2D phase-lagged stable synchronous patterns called modelock or travelling (spiral) waves. This modelock has been a notorious hazard since it hampers the desired in-phase synchronisation of the oscillator arrays.

In a 2D array of voltage-controlled oscillators (VCOs) for VLSI clocking [2], modelock is avoided by adding a special phase detector (PD) the response of which decreases monotonically beyond a phase difference of $\pi/2$ to each VCO. However, in solid-state circuits such as MESFET oscillators for millimetre-wave generation, the interaction between oscillators is due to the 'injection-locking' mechanism and the resulting synchronisation characteristics (corresponding to the PD response) come from the intrinsic nonlinearity of the oscillator. Thus, in such cases avoiding modelock by tuning the synchronising characteristics may not be straightforward (if not impossible), as opposed to the case of the VLSI clocking circuit.

In this Letter we propose an alternative synchronising method that avoids modelock by introducing dynamic coupling with only on–off switches to the array (see Fig. 1). The basic idea comes from the observation that nonregular (percolation-like) 2D networks of oscillators attain the in-phase synchronisation state by destruction of the 'core' of the spiral wave pattern (centre of the modelock). Systematic numerical simulations are carried out to consider the effectiveness of the method for possible applications to millimetre-wave power-combining and beam-scanning control systems. The limitations and robustness of the method are also investigated.

Phase dynamics in 2D oscillator arrays: We assume here a weak coupling between adjacent oscillators, and sufficiently uniform oscillator characteristics. Under such conditions, a systematic derivation of the phase equation for oscillators can be made (e.g. see [1]), which eventually takes the following form:

$$\dot{\theta}_i = \omega_i + \Delta\omega_m \sum_j \sin(\Phi + \theta_j - \theta_i) \quad (1)$$

where θ_i and ω_i represent the oscillation phase and free-running frequency of the ith oscillator, respectively. $\Delta\omega_m$ is interpreted as the locking range of each oscillator which is assumed to be small and the same for all oscillators. The phase lag Φ reflects signal delay, which cannot be neglected for the case of radiative coupling. However, if the coupling is made by one-wavelength waveguides, Φ is assumed to be 0 and we focus on this case. The above discussion is valid for any network topology. For the 2D oscillator array with switched coupling as shown in Fig. 1, (1) can be modified to the following phase equation

$$\dot{\theta}_i = \omega_i + \Delta\omega_m \sum_j S_i S_j \sin(\Phi + \theta_j - \theta_i) \quad (2)$$

where the additional parameter S_i takes $1/0$ depending on the on/off states of the switch between the ith oscillator and the coupling network. The summation $\sum_j$ is taken for adjacent (jth) oscillators to the ith oscillator. Here, we assume each switch independently takes the on/off states alternatively for a time span T_{on}/T_{off}, respectively. It is clear that if all switches are on, (2) reduced to (1). Conversely, if all switches are off, (2) becomes $\dot{\theta}_i = \omega_i$, which implies that all oscillators are free-running. Between these two extremes, we have intermediate states where any two oscillators with $S_i = 1$ are connected by the network and a certain amount of oscillators with $S_i = 0$ are disconnected from the network, forming a percolation-like, global network of interacting oscillators.

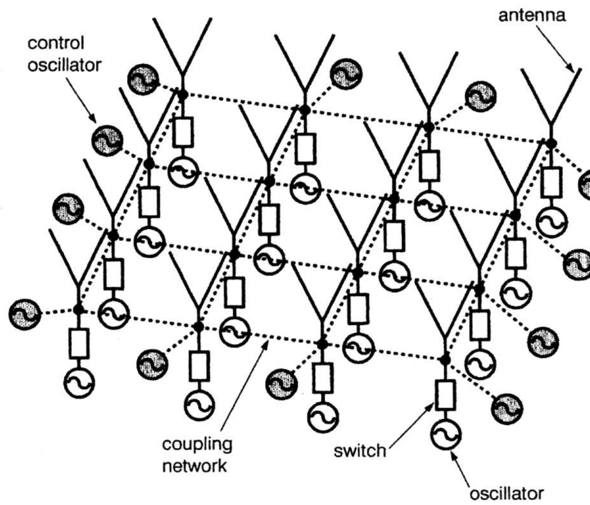

Fig. 1 *2D square array oscillators with switched couplings*

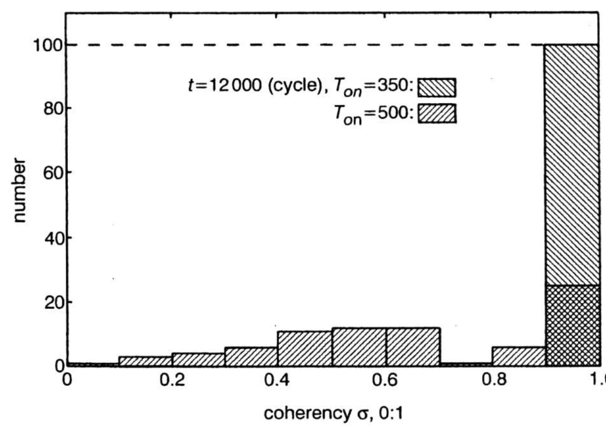

Fig. 2 *Coherency distribution of σ after 12 000-cycle oscillations*

We performed numerical simulations of (2) for two cases of $(T_{on}, T_{off}) = (350, 150)$ and $(T_{on}, T_{off}) = (500, 0)$, respectively, where 100 trials are made for 30×30 oscillator array networks with random initial oscillation phasers and switching states. The natural frequencies ω_i are chosen uniformly from [0.95, 1.05] at random. To measure the degree of phase synchronisation, the phase coherency σ is introduced as follows:

$$\sigma = \sum_{j=1}^{N} S_j \exp(i\theta_j) \Bigg| \Bigg/ \sum_{j=1}^{N} S_j \quad (3)$$

It is noted that $\sigma = 1$ corresponds to the in-phase synchronised state and the lower coherency σ indicates loss of in-phase synchrony. Fig. 2 shows the result of this simulation (after 12 000-cycle oscillations). A clear difference is observed between the case of $(T_{on}, T_{off}) = (500, 0)$ and the case of $(T_{on}, T_{off}) = (350, 150)$. The former has a widespread coherency distribution, which is due to the generation of modelock (sometimes several spiral coexist in the array.) Conversely, the latter has a sharp distribution below $\sigma = 1$, where no modelock remains and all (connected) oscillators exhibit in-phase synchronisation.

Such avoidance of modelock in switched array networks can be explained as follows. Figs. 3*a* and *b* shows typical examples for cases without control oscillators, and with control oscillators attached to the outside of the array, respectively. (For the latter case, driving frequencies ω_i of the control oscillators are gradually set to be low to high from the top to the bottom of the array shown in Fig. 3*b*.) In both cases of Figs. 3*a* and *b*, it is observed that (i) initially, (multiple) stable spiral waves exist (at this stage all switches are on), (ii) shortly after the switching is initiated, some cores of the spiral waves are destroyed or moved, (iii) the spiral waves continue to be destroyed, (iv) finally they are lost and a coherent pattern is stabilised, and (v) at this stage, we obtain completely coherent patterns by making all switches on again.

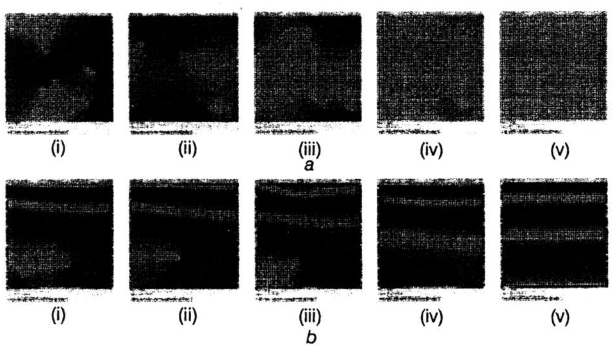

Fig. 3 *Synchronisation process to coherent patterns in 2D array oscillators*

a Without control oscillators
b With control oscillators

Discussion: In the above simulations of (2), the case of $\Phi = 0$ is considered. We also considered cases of $\Phi = 0.01\pi$ and 0.1π, modelling mismatches to one-wavelength interconnections. For the $\Phi = 0.01\pi$ case with 30×30 arrays, several per cent of the trials did not converge to the completely coherent state (at least for 12 000-cycle oscillations). 10×10 and 20×20 arrays are also simulated under the same conditions, and 100% convergence is obtained for $\Phi = 0.01\pi$. This implies that smaller arrays have better in-phase synchrony, and this is what the simulation in [3] reported. In the case of $\Phi = 0.1\pi$, none of 10×10, 20×20, and 30×30 arrays converged to the in-phase state, suggesting a certain upper limit of Φ beyond which the presented method is no longer effective.

For more effective synchronous network topologies, we performed simulations of (2) on triangular lattice networks under the same simulation protocol as that mentioned above. As opposed to the above square lattice cases, triangular lattices show better in-phase synchrony, e.g. 10×10, 20×20, and 30×30 oscillator arrays with a $\Phi = 0.1\pi$ phase delay have shown 100% in-phase synchrony.

Conclusions: Although a theoretical study has not been completed, systematic numerical simulations support the efficacy of the presented method for avoiding modelock. The required switches are expected to be realised using simple circuitry.

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Channel capacity of bit-interleaved coded modulation schemes using 8-ary signal constellations

S.Y. Le Goff

The object of the work described was to determine the 8-ary signal sets that maximise the coding gains achieved by power-efficient bit-interleaved coded modulation (BICM) schemes over an additive white Gaussian noise channel. To this end, the channel capacity limit of BICM for several 8-ary constellations has been evaluated. It is shown that the most suitable constellation for designing a BICM scheme depends on the desired spectral efficiency of the system.

Introduction: Bit-interleaved coded modulation (BICM) is a bandwidth-efficient coding technique made up of serial concatenation of binary error-correcting coding, bit-by-bit interleaving, and high-order modulation using Gray or quasi-Gray labelling [1]. BICM has proven to be a very power-efficient approach provided that state-of-the-art codes, such as turbo codes [2] or low-density parity-check codes [3, 4], are employed [5]. It is possible to design BICM schemes by employing any two-dimensional signal constellation. However, some recent studies have indicated that the choice of the signal set may have a strong influence on the error performance of the system [6]. In this Letter, we address the problem of finding the most suitable 8-ary constellations for designing BICM schemes, on additive white Gaussian noise (AWGN) channels, using the concept of capacity limit. The idea of evaluating capacity limits to find the best signal set comes from the fact that power-efficient BICMs usually employ state-of-the-art codes, and are thus capable of achieving near-capacity performance. As a result, the actual error performance of these BICMs can be predicted accurately by evaluating their capacity limits.

Capacity limit of BICM schemes using various 8-ary signal sets: Consider a 2^m-ary modulation modelled by a two-dimensional signal set S of size $|S| = 2^m$. Let $c = \{c_1, \ldots, c_m\} \in \{0, 1\}^m$ denote a set of m bits at the modulator input, and y the corresponding channel output. Based on some general results given in [1], we can demonstrate that, under the constraint of uniform-input distribution and assuming ideal (infinite-depth) bit-by-bit interleaving, the capacity C of a BICM system using 2^m-ary constellation is expressed over an AWGN channel as

$$C = E_{c,y}\left[m - \log_2 \frac{\left(\sum\limits_{s\in S} \exp\left(-\frac{d_{y,s}^2}{\sigma^2}\right)\right)^m}{\prod\limits_{i=1}^{m} \sum\limits_{s\in S_{i,c_i}} \exp\left(-\frac{d_{y,s}^2}{\sigma^2}\right)} \right] \quad (1)$$

where $E_{c,y}$ denotes expectation with respect to c and y. $d_{y,s}$ is the Euclidean distance between y and a signal $s \in S$, and s_{i,c_i} denotes the subset of the signals $s \in S$ the labels of which have the value $c_i \in \{0, 1\}$ in position $i \in \{1, \ldots, m\}$. Finally, σ^2 is the variance of complex zero-mean Gaussian noise. Capacity is here expressed in information bits per channel use, where a channel use corresponds to the transmission of a signal $s \in S$.

From (1), it is possible to evaluate the capacity limit of BICM for any two-dimensional constellation and thus determine the signal sets that maximise the coding gains achieved by power-efficient BICM schemes. In this Letter, the BICM capacity is evaluated for several 8-ary signal sets using Monte Carlo integration of (1). The 8-ary constellations that are considered in this work are 8-PSK, rectangular, (4, 4) with a ring ratio of 1.93, optimum, (1, 7), triangle, and 8-cross [7, 8]. All except the