PHENOMENOLOGICAL SIMULATION STUDY OF NEURONAL ACTIVITY SYNCHRONIZATION IN 110 ELEMENTS NETWORK

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The phenomenon of activity synchronization in biological neural network is considered. Simulation of neurons dynamics in the 6-layer neural network with 110 elements in different regimes: regular spikes, chaotic spikes, regular and chaotic bursting, etc was performed. Izhikevich’s phenomenological model that displays different types of activity inherent for real biological neurons was used for simulation. Space-time diagram for the entire network and raster plots for the whole structure and for each layer separately were built for visual inspection of neural network activity synchronization. Synchronization coefficients based on cross-correlation times of action potentials for all neurons pairs were calculated for the whole neural system and for each layer separately.

Keywords: neuron networks, simulation, Izhikevich’s model, neuron dynamics, spikes, bursts, synchronization, the raster plot, space-time diagram.

INTRODUCTION

Studying the neural activity dynamics is of great interest for neuroscientist and specialists in physical and mathematical modeling. Many questions about functioning mechanisms of attention, division of unconscious and conscious mental processes and influence of emotions remain unclear. Are there general principles of information processing in the brain? If so, how are they reflected in the electrical activity of different structures? Do experimentally measured data of neurons activity correspond to principles mentioned above or these data are artifacts generated by specific experimental conditions? Getting answers to these questions depend largely on the theoretical understanding of the experimental data. Physical, mathematical and computer simulation of electrophysiological processes in biological objects is one of the important and promising areas of research.

According to the experimental results on animals synchronization of neural activity plays an important role in different mental processes [1], like the binding of different visual features into a single overall image by visual cortex. Mathematical simulation is the main tool for study of neurons synchronization.

Realistic (Hodgkin and Huxley based [2]) and phenomenological (Kuramoto [3], FitzHugh-Nagumo [4], etc) models are used for investigation of neural networks’ dynamics. Large computer resources requirement [5] for realistic simulations is the main reason that large amount of phenomenological models exist. So it is necessary to choose the phenomenological model of the neuron, which is able to reproduce the real cells dynamics without detaliization of physical processes that lie at its basis [6].

In present paper we perform numerical simulation study of neurons activity synchronization in cortical column by Izhikevich’s model [7].

MATERIALS AND METHODS

Structure of cortex columns. Cerebral cortex is the main element, which takes part in almost all physiological processes. It is a hierarchical system of neural networks - cortical columns. Powell, along with colleagues showed that the number of neurons in vertical, that goes through the thickness of the cortex, i.e. a cylinder with a diameter of 30 microns, is surprisingly constant and equals 110. [8] Cortex has six layers, contains from 10 to 14 billion neurons. It may be considered as a hierarchical system of neural networks - cortical columns. This structure of cortex offers the possibility to construct representations of complex objects.

In this work we consider the neural structure in the form of column, which consists of six layers of neurons. At each layer each neuron is connected to all neurons of its layer and to all neurons of the next layer lower in the hierarchy. The scheme of this structure is shown in fig. 1.

Six layers of columns are numbered by roman digits from top to bottom. The upper layer contains very few neurons and the deepest layer has the largest number of
neurons. Topology of connections between neurons is one of the most significant factors that influence information transformation and flows in the network.

**Mathematical model of biological neuron.** The model of neuron we used was proposed in 2001 by Eugene Izhikevich [7]. It is two-compartment model that contains an additional requirement for cell membrane discharge:

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + I,$$

$$\frac{du}{dt} = a(bv - u),$$

where $v$ and $u$ are the dimensionless membrane potential and membrane potential recovery variables respectively; $a$, $b$, $c$ and $d$ – dimensionless parameters. The variable $u$ simulates the activation of ionic $K^+$ currents and the deactivation of ionic $Na^+$ currents and provides negative feedback to $v$. Variable $I$ simulates external currents.

This model can reproduce all twenty types of real biological activity of neurons depending on the values of four model parameters [9]. On the subjective opinion of models’ author, the only one drawback of this model is a partial discontinuity of discharge dynamics of membrane potential when reaching the threshold.

Estimates of computing resources usage for most models presented in [10, 11]. Simulation of one neuron 1 ms dynamics using the Euler first-order fixed-step method by Izhikevich’s model requires 13 floating point operations. This number of operation is one of the best for all models that can reproduce all kinds of neurons activities.

**Synchronization analysis.** Usually synchronization is defined as setting of common rhythm in different natural processes. It is assumed that synchronization of oscillatory activity in sensory-motor cortex may provide integration and coordination of information flows that control the muscle contraction during movements and respiration rhythm [1]. It is proved that synchronization is responsible for the generation of the pathological tremor in Parkinson’s disease [12]. Synchronization of cerebral cortex parts may lead to epileptic activity.

Researching the synchronization in large neuron ensembles is a significant problem because there is no sufficient knowledge in this area and only the presence of some known phenomena provides necessary information.

Network dynamics is traditionally visually represented by the raster plot (Fig. 3) - the graph, on which vertical axis corresponds to the number of a neuron in the network, the horizontal axis is a time and points color is values of membrane potential. Such raster plot allows to visually assess the synchronization in the network. Weak synchronization is presented by a chaotic set of points. Strong synchronization is described by points ordered on a vertical lines. Each line represents a short period of time, during which most of the neurons in the network generated a discharge, thereby providing synchronous activity of the system. However, for the quantitative analysis of the network synchronization degree visual display on a raster plot is not enough. Reviewing the raster plot may give the impression that the oscillations are synchronized, but most of the neurons in the network do not generate action potential and therefore such oscillations in the network cannot be considered to be synchronous. Therefore, to characterize oscillations the coefficient $(k)$ of network synchronization was calculated.

Normalized cross-correlation of different neurons pairs’ signals was used to calculate synchronization coefficient [13]. At first the oscillation frequency $f_i$ for each of $n$ neurons in the network is computed as the inverse of the average inter-spike time interval. Then the average oscillation frequency for the whole network is computed as:

$$f_{net} = \frac{\sum_{i=1}^{n} f_{i}}{n}$$

The whole time interval, for which the synchronization coefficient is computed, is divided into $K$ equal intervals with duration $\tau = \alpha / f_{net}$ (see Fig. 2, dashed line). At each K-segment spikes for neurons pairs were determined in a binary format: $X(i)=1$ - if $i^{th}$ neuron generates a spike in this interval, and $X(i)=0$ - if the spike is absent (respectively $Y(i)=1$ and $Y(i)=0$ for other neuron). Then for each pair of $i^{th}$ and $j^{th}$ neurons the synchronization coefficient is determined as:
The coefficient of synchronization $k$ of the whole network is found by averaging the coefficients $k_{ij}$ of all pairs of neurons.

$$k_{ij}(\tau) = \frac{\sum_{l=1}^{k} X(l)Y(l)}{\sqrt{\sum_{l=1}^{k} X(l)^2 \sum_{l=1}^{k} Y(l)^2}}$$

RESULTS AND DISCUSSION

For simulation we considered neural network structure of 110 elements with different states: regular spikes, chaotic spikes, regular and chaotic bursting, etc. It is homogeneous and fully connected neural network, whose hierarchical structure is close to the cortical column. It consists of six layers: the first layer has nine neurons, the second - eleven, the third - eleven, the fourth - fifteen, the fifth - seventeen, the sixth – forty seven neurons. At each layer each neuron is connected to all neurons of its layer and to all neurons of the next layer lower in the hierarchy (fig. 1). Simulation is performed with model parameters suggested by models’ author [7]: $a=0.02$, $b=0.2$, $c=-55$, $d=2$ and time of discretization $dt=0.01\text{ms}$. Raster plots for each neural layer were maximally increased in scale to be visible. Special software was developed for calculation of neuron synchronization in cortical column and its layers. Parameter $\alpha$ is chosen to be 0.25.

The coefficient of synchronization $k=0.284$ for the whole neural network was computed, and for the visual synchronization analysis the raster plot was constructed (fig. 3).

Then the neural dynamics of whole network system on each layer was analyzed. The sixth layer receives the synaptic current from the lower cortical columns because it is the deepest layer of neural structures. Neural activity at lower layer has the form – class 2 excitable (fig. 4).

The primary information which comes to the sixth layer is processed by neurons of this layer. Then it is grouped in a sequence of pulses and transmitted to higher layers. Coefficient of synchronization for neurons of the sixth layer of neural network is $k=0.577$ and for this layer the raster plot was constructed (fig. 5).
The behavior of the membrane potential of neurons in the next, the fifth, layer differs significantly from the lower layer and looks like - mix mode: irregular tonic bursting and spiking (Fig. 6).

In this layer spiking sequences came from the sixth layer are transferred into "a sequence of sequences" – bursting activity. Coefficient of synchronization for neurons of the fifth layer of neural network is $k=0.241$ and for this layer the raster plot of neural activity was constructed (fig. 7).

The fourth-layer dynamics is not significantly different from the previous layer - irregular double spiking and regular tonic bursting (Fig. 8). So "sequences of sequences," which came from the lower layers, are transferred into combination of more structured pulses will go to higher levels of cortical hierarchy. Coefficient of synchronization for neurons of the fourth layer of neural network is $k=0.213$ and for this layer the raster plot of neural activity was constructed (fig. 9).

On the second level the behavior of membrane potential of neurons becomes like mix mode: regular double tonic spiking and tonic bursting (Fig. 12). There are two higher levels of the cortical column, the second and the first that group all information from lower layers and transfer it to the sixth layer of other columns. Coefficient of synchronization for neurons of second layer of neural network is $k=0.195$ and for this layer the raster plot of neural activity was constructed (fig. 13).
Fig. 12. The neural activity of neurons at second layer of network.

Fig. 13. The raster plot for neurons from second layer of neural network, the synchronization coefficient is $k=0.195$.

On the first neural layer there is a kind of the neural activity - mix mode: single spiking and regular tonic bursting (Fig. 14). Coefficient of synchronization for neurons of first layer of neural network is $k=0.202$ and for this layer the raster plot of neural activity was constructed (fig. 15).

Fig. 14. The neural activity of neurons at first layer of network.

Fig. 15. The raster plot for neurons from second layer of neural network, the synchronization coefficient is $k=0.202$.

The diagram for visual study of synchronization coefficients was constructed (fig. 16). The X-axis represents the number of neural network layer, and Y-axis represents the synchronization coefficient.

Fig. 16. The diagram for synchronization coefficients on neural network layers.

The space-time diagram for visual studies of neural structure synchronization was constructed. The X-axis represents time in milliseconds, and the Y – axis represents the number of neural elements in the network, a gradient color on the scale characterizes potential value (fig. 17). One can easily observe a layered synchronization activity of studied neural structure. The synchronization time spikes occur in neighboring elements and then neighboring spikes group together.

Fig. 17. Space-time diagram for neural network with 110 elements.

CONCLUSION

Neurons activity in the cortical column model is changed from bursting to spiking activities when considering from the first to the sixth layer. Synchronization coefficient differs for different (from first to fifth) layers not more than 10%. Sixth layer is mostly synchronized and the second layer is less synchronized. The synchronization coefficient for the whole neural network does not exceed 30%, which corresponds to the normal physiological state of the cerebral cortex.
References


ФЕНОМЕНОЛОГИЧНЕ ДОСЛІДЖЕННЯ СИНХРОНІЗАЦІЇ НЕЙРОНАЛЬНОЇ АКТИВНОСТІ В МЕРЕЖІ ІЗ 110 ЕЛЕМЕНТІВ
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Розглянуто явище синхронізації нейронної активності мережевої структури. Проведено моделювання динаміки нейронної мережі 6-ти шарової структури із 110 елементів з різними режимами активності: регулярні спайки, хаотичні спайки, регулярні та хаотичні бюрсти, та інші. Для дослідження обрано модель Іжикевича, яка дозволяє відтворювати різні типи активності, притаманних реальним біологічним нейронам. Для візуальної оцінки синхронізації спайкової активності систему було побудовано просторово-часову діаграму для всієї мережі та растограми як для всієї структури так і для кожного шару окремо. Обчислено коефіцієнти синхронізації для всієї нейронної мережі і для кожного нейронного шару окремо. Метод розрахунку синхронізації базується на крос-кореляції часів потенціалів дії будь-яких пар нейронів

Ключові слова: нейронні мережі, моделювання, модель Іжикевича, нейронна динаміка, спайки, бюрсти, синхронізація, растограма, просторово-часова діаграма.

ФЕНОМЕНОЛОГИЧЕСКОЕ ИССЛЕДОВАНИЕ СИНХРОНИЗАЦИИ НЕЙРОНАЛЬНОЙ АКТИВНОСТИ НЕЙРОННОЙ СЕТИ ИЗ 110 ЭЛЕМЕНТОВ
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Рассмотрено явление синхронизации нейронной активности сетевой структуры. Проведено моделирование динамики нейросетевой шестилейнной структуры из 110 элементов с различными режимами активности: регулярные спайки, хаотические спайки, регулярные и хаотические бюрсты, и др. Для моделирования была выбрана модель Ижикевича, которая позволяет отображать различные типы активности, которые присущи реальным биологическим нейронам. Для визуальной оценки синхронизации спайковой активности системы были построены: пространственно-временная диаграмма для всей сети и растограммы как для всей сети так и для каждого слоя отдельно. Вычислены коэффициенты синхронизации для всей нейронной системы и для каждого нейронного слоя отдельно. Метод вычисления синхронизации основывается на кросс-корреляции времен потенциалов действия различных пар нейронов

Ключевые слова: нейронные сети, моделирование, модель Ижикевича, нейронная динамика, спайки, бёрсты, синхронизация, растограмма, пространственно-временная диаграмма.