On the Spatial Dynamics of a Network Spike in Neuronal Cultures

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Introduction

- There exists a short-term (~100 ms), repetitive, spontaneous **synchronization of network spiking activity** in planar neuronal networks grown *in vitro* from initially dissociated cortical or hippocampal neurons [1]. Such networks are called **neuronal cultures** while a single synchronization event is called a **network spike (NS)** or a population burst.
- The **stationary regime** of a NS activity in neuronal cultures is thought to be related to epilepsy therefore both the origin and the properties of such a regime is a subject of intensive studies.
- In a recent article [2] it was shown experimentally that **spatial dynamics** of a typical NS is **inhomogeneous**: there exist a few occasional local sources, or **nucleation centers**, from which the synchronous spiking activity propagates in the neuronal culture as **traveling waves**. The number and spatial locations of such sources are unique and steady for the specified culture of excitatory neurons, and these quantities vary over the different cultures.
- By generalizing the NS simulation model [3] to the case of a **spatially-dependent** network topology, we show that nucleation centers of a NS occur in simulations at certain conditions.

Network Model

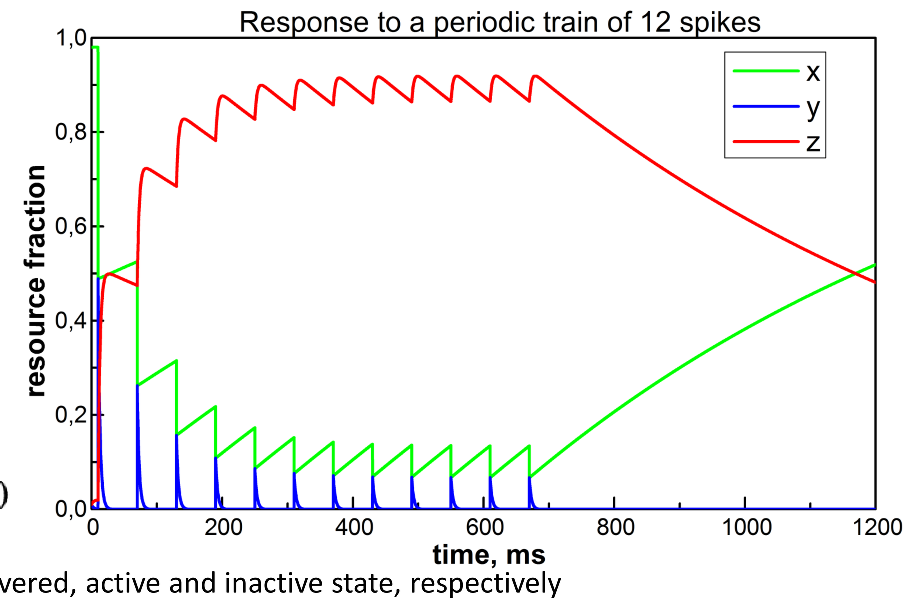
Neuron model: Leaky Integrate-and-Fire(LIF)[4]

Synapse model: Tsodyks-Uziel-Markram (TUM) model [3] of short-term synaptic plasticity

$$I_{syn}(t) = A \cdot y(t)$$

$$\begin{cases} \dot{x} = z/\tau_{rec} - u\cdot x\cdot\delta(t-t_{spike}), \\ \dot{y} = -y/\tau_I + u\cdot x\cdot\delta(t-t_{spike}), \\ \dot{z} = y/\tau_I - z/\tau_{rec}, \end{cases}$$

$$\dot{u} = -u/\tau_{facil} + U\cdot(1-u)\cdot\delta(t-t_{spike})$$

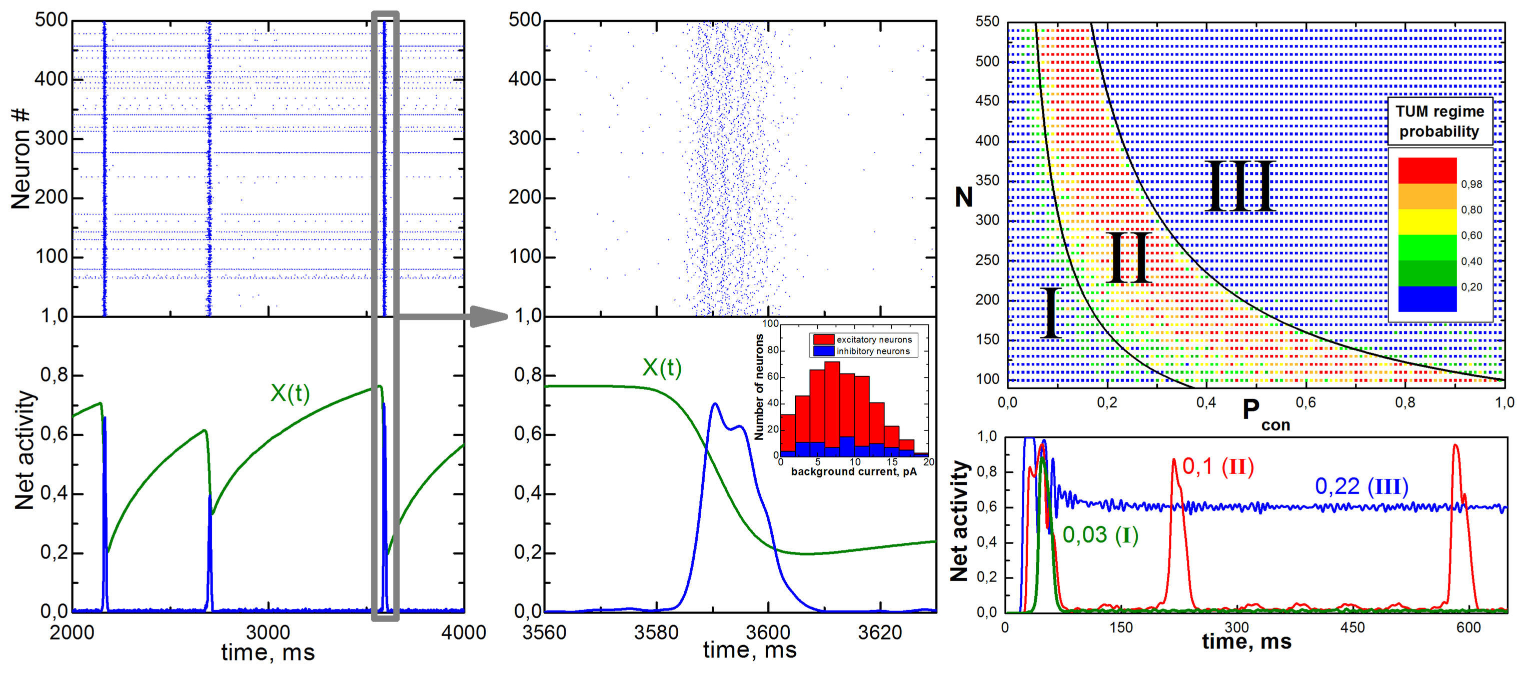


A is a maximal amplitude of synaptic current
x, y, z are fractions of synaptic resource in recovered, active and inactive state, respectively
τ_{rec}, τ_{facil}, τ_I are relaxation constants
τ_{rec}, τ_{facil} ~ 1 s, τ_I ~ 1 ms

Network topology model:

a) Binomial topology

- For **binomial networks** (with probability P_{con} of connecting any two different neurons) of **N excitatory** neurons with normally distributed **background currents**, repetitive NSs (**TUM-regime**) occurred only in a narrow range of **$N*P_{con}$ = 30-90** outgoing connections per neuron.
- This result was used as a **condition** for generating **spatially-dependent** network topology.



b) Spatially-dependent topology [5]:

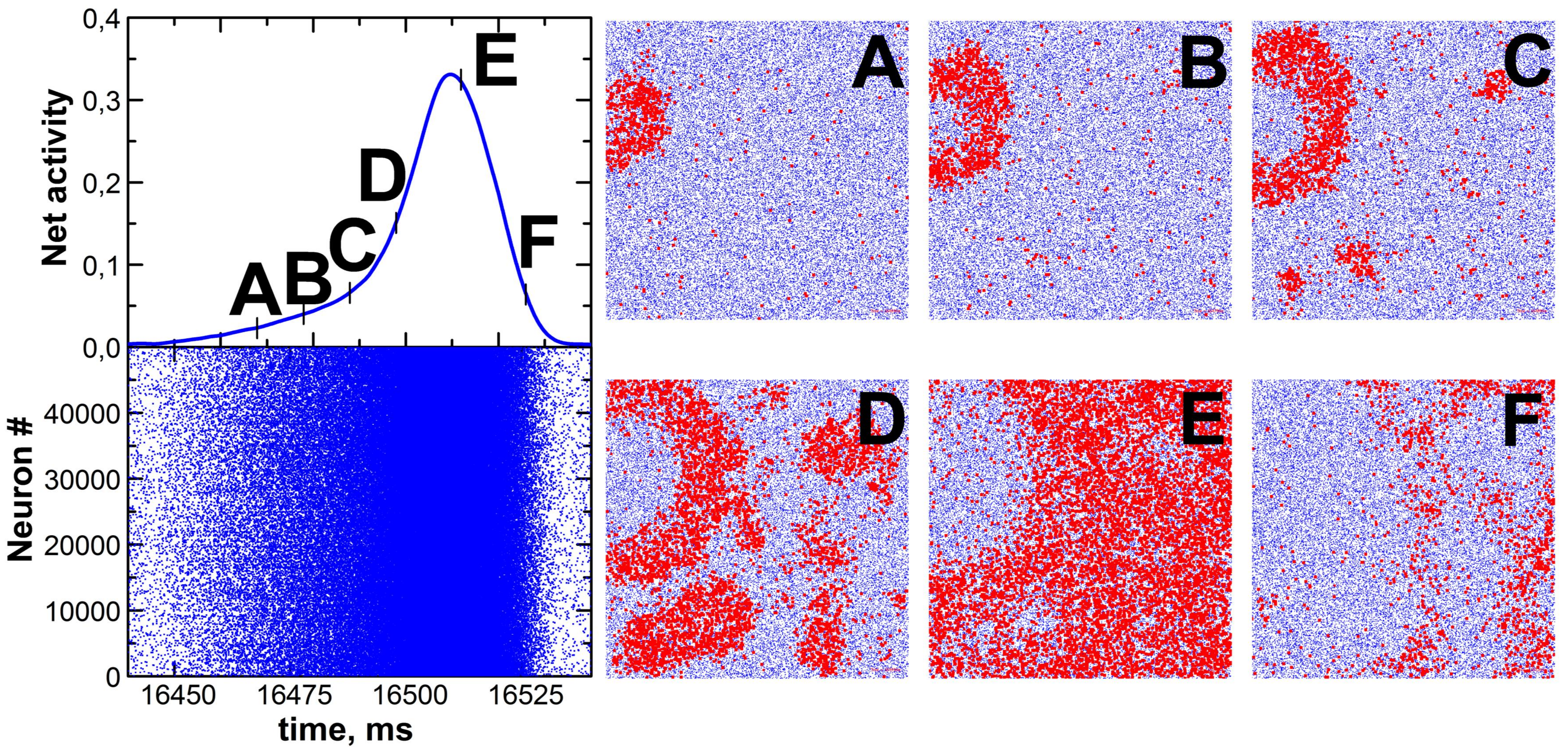
$$p_{con}(r_{ij}) = e^{-r_{ij}/\lambda}$$

$$\tau_{delay}^{ij} = \tau_{delay} + \frac{r_{ij}}{v_{spike}}$$

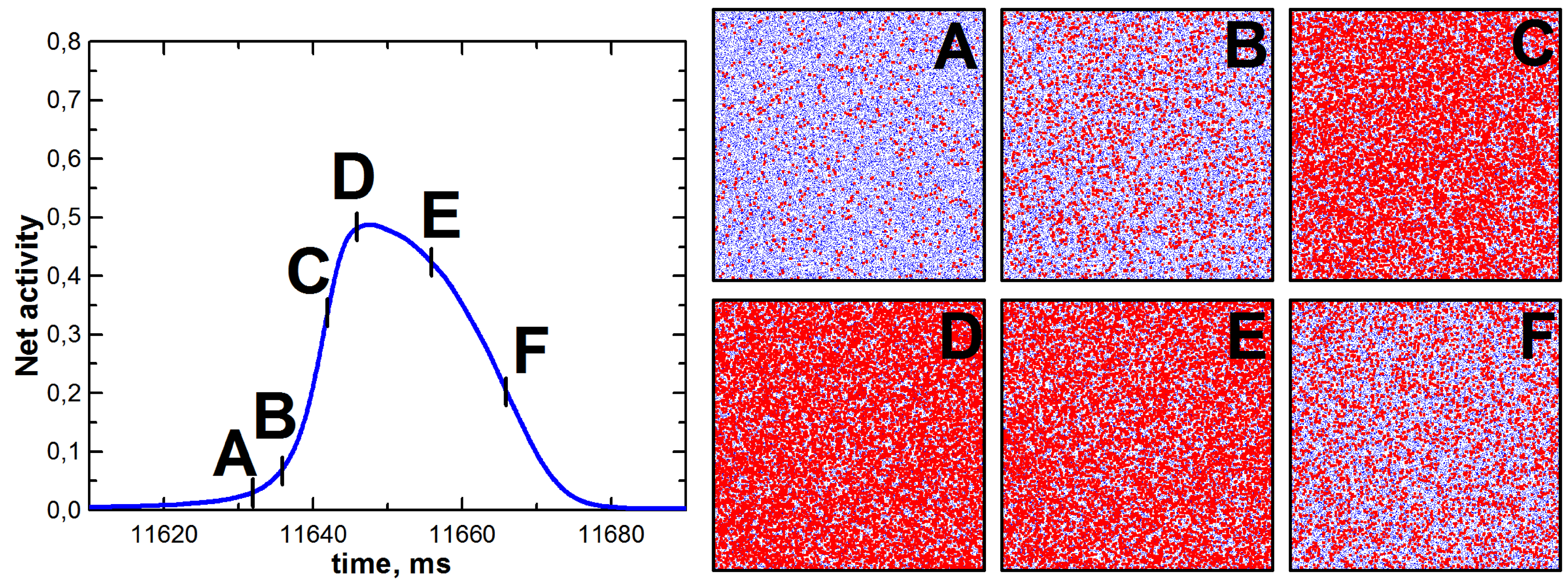
Simulation results

The emergence and spread of a **NS** in the planar neural network consisting of 50 thousand LIF-neurons (80% excitatory, 20% inhibitory) randomly **(a, b, c)** and regularly **(d)** distributed over the square of unit area, when the activity of inhibitory neurons was blocked.

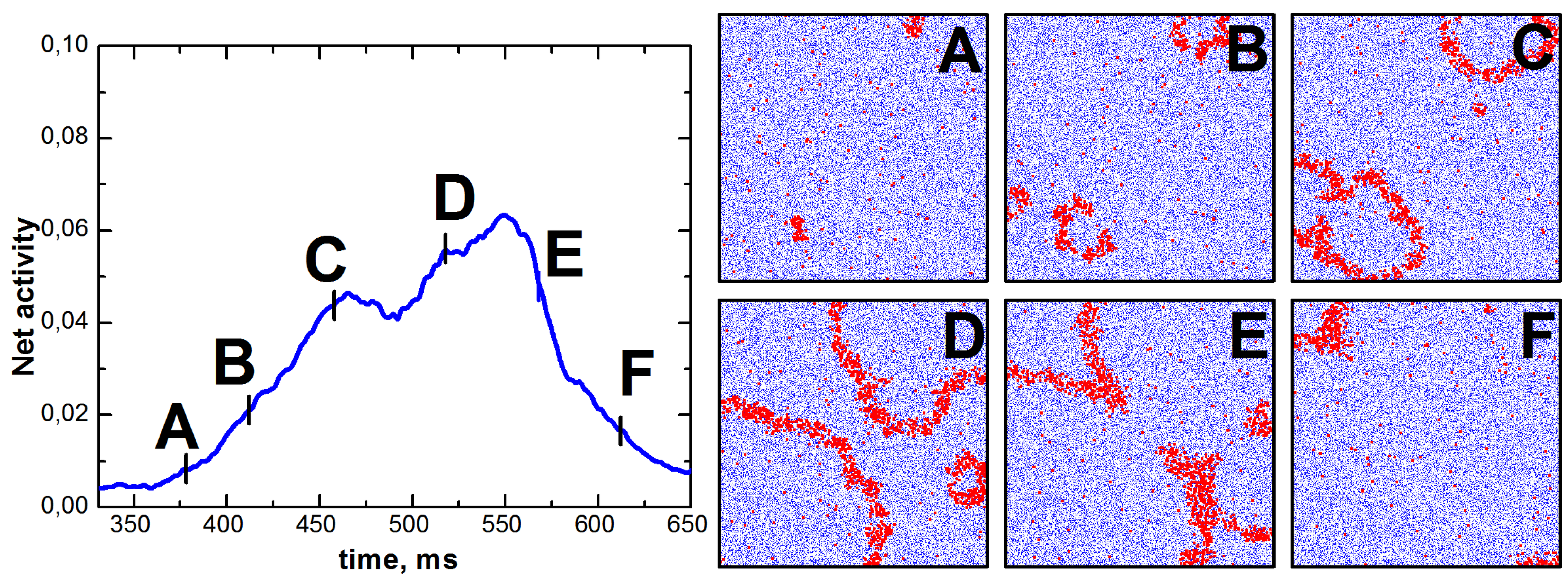
a) $p_{con}(r) = exp(-r/\lambda)$, where r is **distance** between neurons, $\lambda = 0.01$.



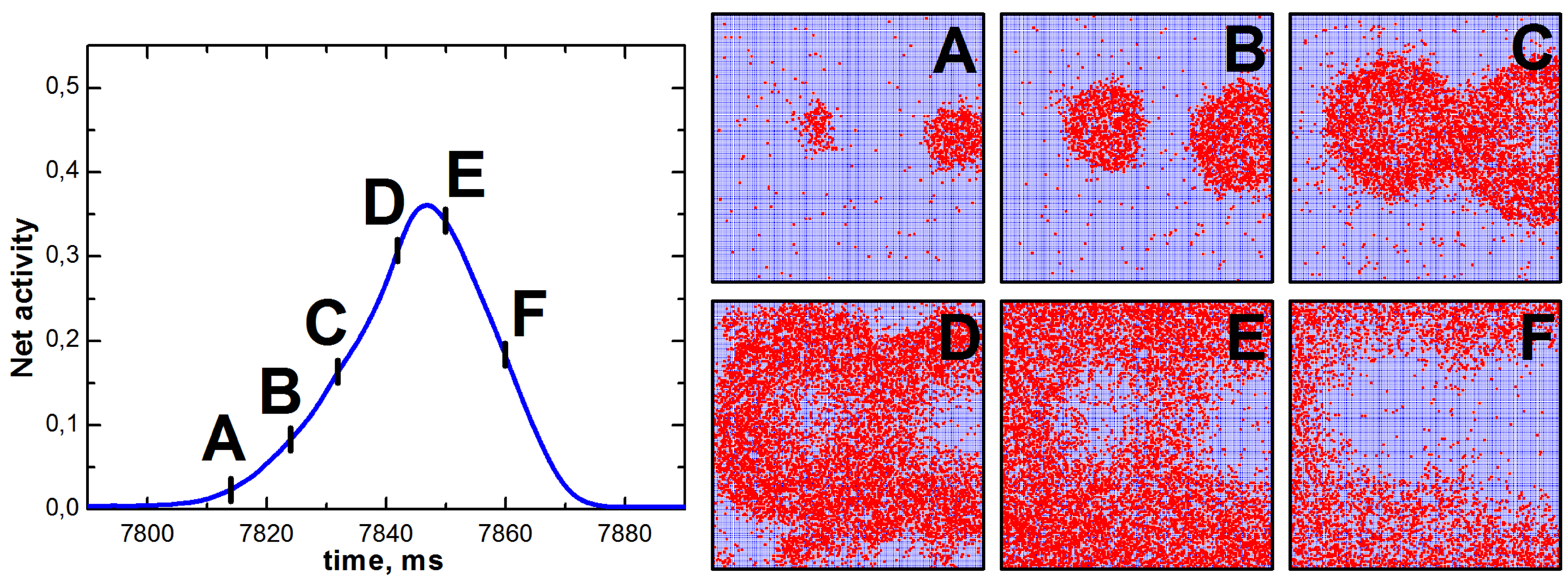
b) Spatially-independent connection probability $p_{con}(r) = const = 6.4*10^{-4}$ with the same average number of outgoing connections per neuron as in **(a)**.



c) $p_{con}(r) = \Theta(\lambda-r)$, where $\lambda = 0.014$ and $\Theta(x)$ is unit step function: $\Theta(x) = 1$, if $x \geq 0$, and $\Theta(x) = 0$ otherwise.



d) Network of 50 625 excitatory neurons **placed regularly in 225x225 nodes of a square lattice** with the lattice parameter a = 0.004. $p_{con}(r)$ is the same as in **(a)**.



Discussion

It is shown that

- spatial nucleation centers of a network spike appear if the **majority** of connections between neurons are the **local ones**,
- nucleation centers are **not nested** in fluctuations of **spatial density** of neurons,
- inhibitory neurons (i) **decrease** the average frequency of NS occurrence, (ii) **increase** the NS amplitude variability, the NS duration and the number of nucleation centers, (iii) **do not affect** essentially the degree (i.e., coefficient of variation) of periodicity of NSs and the level of spiking activity between the subsequent NSs.

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