Instabilities in Cortical Networks with Embedded Synfire Chains

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What is a synfire chain ?

Historical context (Abeles, 1982)

Experiment: *in vivo* recordings of neurons spiking time.

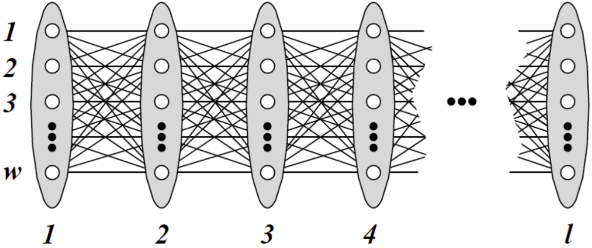
Goal: examine correlation between spiking times of distinct neurons.

Result: **evidence of repeated precisely timed firing patterns**, over "too long" time span for classic explanation.

$\rightarrow$ introduction of synfire chains (SFCs).

Historical context (Abeles, 1982)

Synfire chain: chain of pools of neurons linked in a feed-forward fashion.



Synfire wave: near-synchronous volley of spikes propagating along a synfire chain.

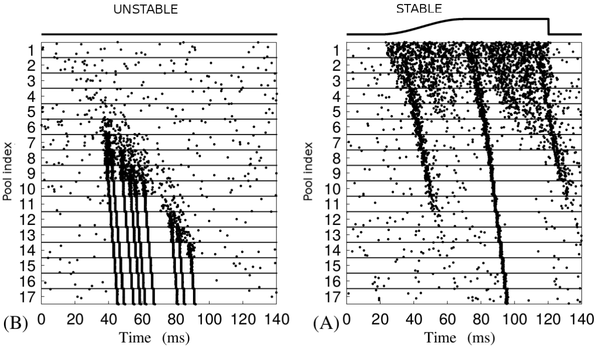
Motivation today

Main motivations to study SFCs today:

- **compositionality:** multiple SFCs could be dynamically linked and activated to form complex cognitive representations.
- **biologic plausibility:** SFC structures could emerge during cortical development from STD learning rules. Several studies carried out but still inconclusive.

Key properties of SFCs

- stability of synfire wave propagation – only above minimum pool size;
- stability of the ground state of the SFC – *i.e.* no spontaneous birth of waves, only below maximum pool size;



Key properties of *embedded* SFCs

More realistic models embed SFCs in a network.

The embedding network and the waves in the SFCs interact
$\rightarrow$ additional key properties:

- stability of low AI rate of stochastic firing of embedding network;
- regulation of the number of co-active waves;
- embedding capacity – trade-off between number of pools possibly embedded and number of co-active waves possibly existing.

Those properties were examined for our model.

A high capacity embedding model (Trengove et al. 2013)

Our network model is based on Trengove's (2013) embedding model of synfire chain superposition network (SFCSN).

Key features of the model:

- inhibitory shadow pools;
- intra-link transmission delay variability;
- instantaneous conductance-based synapses.

Results:

- higher embedding capacity;
- regulation of the number of waves.

NB: simulations done only for stable region of the parameter space

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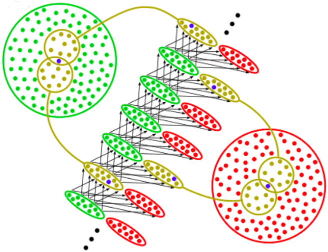
Model and methods

Network model



- two populations of excitatory (green) and inhibitory (red) neurons;
- pools randomly drawn from them;
- each pool linked to the next in all-to-all fashion;
- single cyclic chain.

NB1: each neuron has on average C_E excitatory and C_I inhibitory synaptic inputs.
NB2: each neuron belongs to numerous pools.
NB3: no ongoing external input other than pulse packets.

Neuron model

Model neurons: leaky integrate-and-fire neurons, with conductance-based **non-instantaneous** synapses.

$$I^{x}_{syn}(t) = [V_x - V(t)] \sum_{i,j} \boldsymbol{\Theta(t - t_{i,j}) G_x \exp[-(t - t_{i,j})/\tau^{x}_{syn}}]$$

Trengove et al. (2013) had **instantaneous** synapses, this is the difference!

$$I^{x}_{syn}(t) = C[V_x - V(t)] \sum_{i,j} \boldsymbol{g_x \delta(t - t_{i,j})}$$

This change was suggested to remove the need for intra-link transmission delay variability for regulation of number of waves, and for increased biological realism.

Mean field analysis

We explored the new model across parameter space *via* **numerical simulations**, and gave a **mean field approach** of the equilibrium states.

Total mean firing has a stochastic and a wave component

$$\nu = \nu_W + \nu_S$$

Wave spiking: due to the arrival of a pulse packet.
Stochastic firing: due to **background input** – *i.e.* all other inputs.

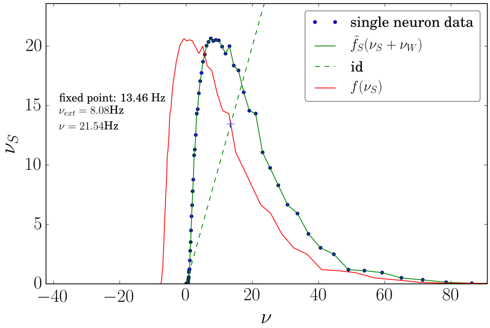
Stochastic firing of the network function of input rate: $f_S(C_E\nu, C_I\nu)$.
$\rightarrow$ **self-consistency** gives the equilibrium rate by **fixed-point** analysis of the **transfer function**:

$$\nu_S = f_S(C_E\nu, C_I\nu) = \tilde{f}_S(\nu_W + \nu_S)$$

Mean field analysis

The **transfer function** was estimated by simulating a **single neuron** receiving balanced input at rates $C_E \nu$ and $C_I \nu$.

Equilibrium **mean field** ν_S was obtained by a **fixed-point analysis** of the transfer function, for given g_I and ν_W values.



Given the ν_W found in a SFCSN simulation, one can **compare the mean field predictions** for ν and ν_S **with** those from **SFCSN simulations**.

Goals

Goals of the thesis

Look for possible instabilities in the parameter space plane generated by pool size and inhibition strength.

Pool size has an effect on wave propagation and spontaneous wave births.
$\rightarrow$ possible loss of **stability of ground state** of the SFC;

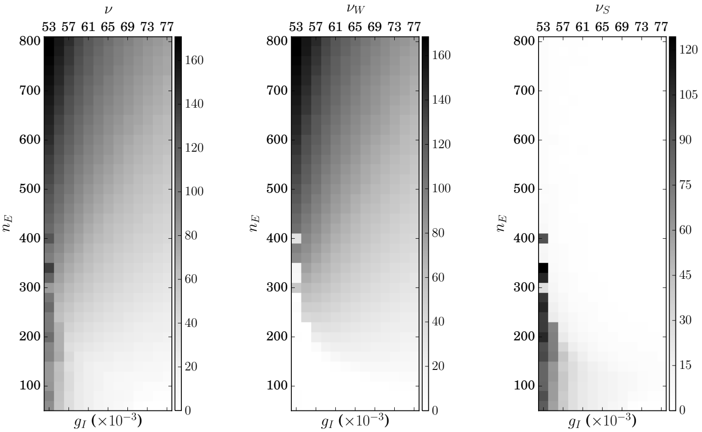
Low inhibition strength increases stochastic spiking
$\rightarrow$ possible loss of **low rate AI** stochastic spiking;

and shift I/E balance of background input
$\rightarrow$ waves more robust to background input
$\rightarrow$ possible loss of **self-regulation** of number of co-active waves.

Check necessity of intra-link transmission delay variability for self-regulation.

Results

2 regimes



2 regimes

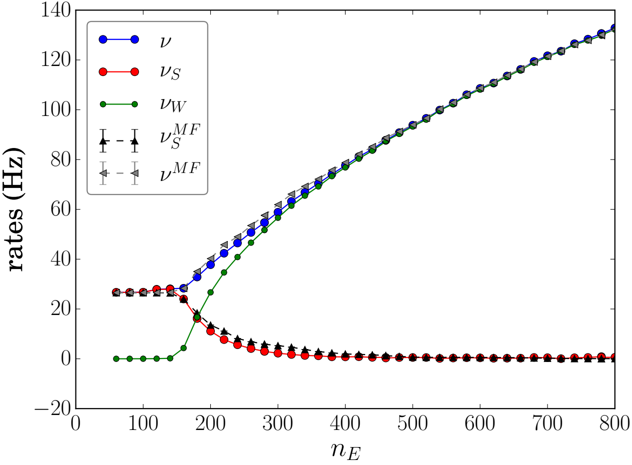


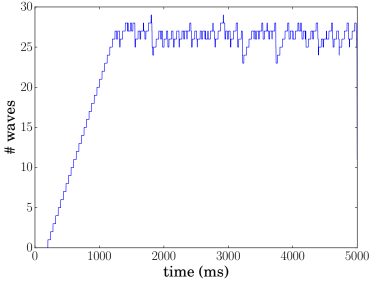
Figure : Equilibrium rates as a function of pool size, for $g_I = 0.059$.

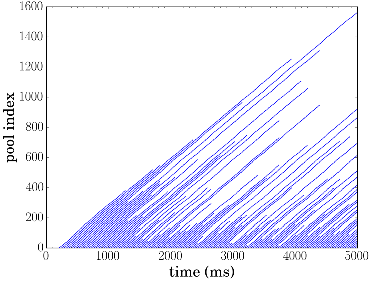
2 regimes

Synfire wave dominated (SFWD):

- stable wave propagation;
- stable low AI stochastic rate;
- regulation of number of waves.

This regime was already observed in Trengove et al. (2013).





2 regimes

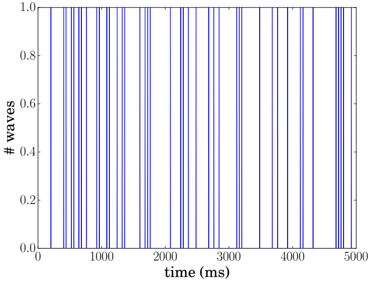
Stochastic spiking dominated (SSD):

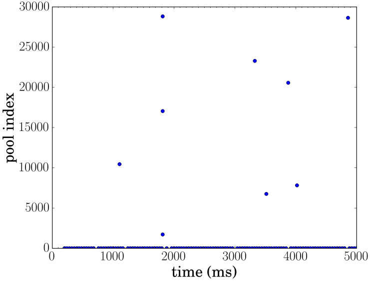
- no wave propagation;
- all spiking is stochastic;

Parameter space: low pool size and inhibition strength.

This is a new regime!

The SSD regime exists because of the **non-monotonic** transfer function that has a non-zero fixed point for almost zero external or wave input.
It is **self-sustained**.





SSD regime: stochastic firing is self-sustained!

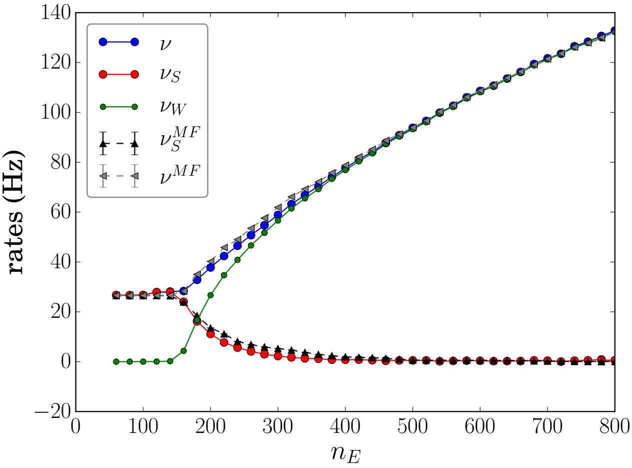
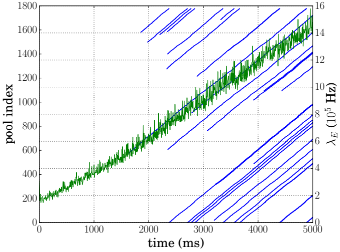


Figure : Equilibrium rates as a function of pool size, for $g_I = 0.059$.

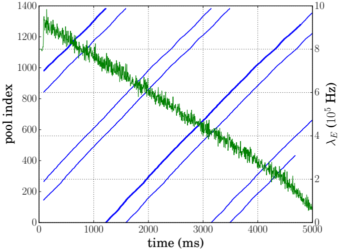
Spontaneous wave births

SFCN simulations exhibited spontaneous wave births, but only early in the simulations.

Necessary condition: high enough pool size and background input.



(a)



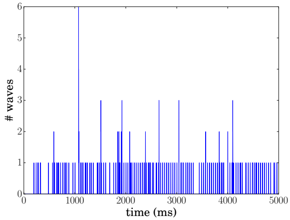
(b)

Figure : Ramping up (a) and down (b) experiments.

Zero intra-link delay spread

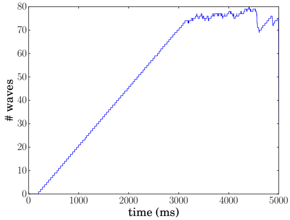
SFCSN simulations with zero intra-link delay spread showed a reduced region in parameter space for SSD regime.

Embedding capacity appears to be bigger.



(a) non-zero spread: SSD

$\rightarrow$



(b) zero spread: SFWD!

Figure : $n_E = 220$ and $g_I = 0.053$.

Conclusions

What we did

- studied a model of embedded synfire chains based on Trengove et al. (2013);
- used non-instantaneous synapses, however;
- numerically simulated the network;
- gave a mean field analysis of it.

What we found

2 distinct regimes, well described by the mean field analysis:

- a **functionally good regime similar** to Trengove et al. (2013): **synfire wave dominated** (SFWD);
- a **new regime** at low pool size and inhibition strength: **stochastic spiking dominated** (SSD) – no wave propagation possible, all spiking is stochastic.

The SSD regime is allowed by the non-monotonic transfer function of conductance-based non-instantaneous synapses.

What we found

Intra-link transmission delay **spread** is **not necessary for regulation** of the number of waves, and pushes the transition to the SSD regime further in parameter space.

Future work

For this study

Better understand spontaneous wave births – better targeted simulations protocols would help.

Further investigation of the zero intra-link delay effect on embedding capacity and phase diagram.

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For the SFC hypothesis

Build realistic cortical scale models that allow self-organised formation of SFCs structures.

Test SFC hypothesis *in vivo*, but need for better technical means.

Thank you for your attention!