3 Dynamical Synapses

A marked feature of synaptic transmission between neocortical neurons is a pronounced frequency dependence of synaptic responses to trains of presynaptic spikes. The task of this assignment is to investigate the effects of short-term synaptic plasticity on the population rate of a number of LIF neurons using NEST.

The model which is considered for this task consists of 500 input neurons with stochastic spikes. This input population is connected to a population of 1000 LIF neurons via dynamical synapses (Fig. 1). By measuring the population rate of the latter population, the effects of short-term plasticity are examined.

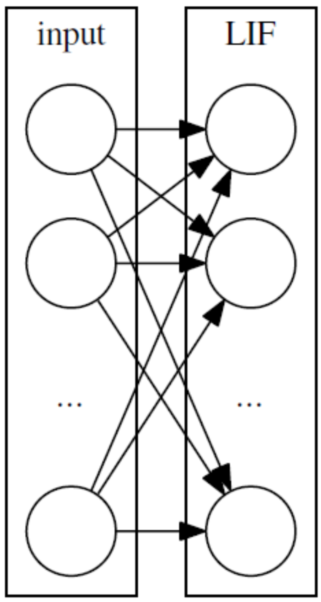

Figure 1: Network architecture.

In this task, in order to understand the nature of the dynamic transmission which varies for different classes of neurons, the phenomenal model by Markram-Tsodyks-Pawelzik is considered. It allows to describe facilitation and depression within the same synapse. By which various number of phenomena that affect the probability that a presynaptic action potential opens postsynaptic channels can be measured and analysed. The state of the synapse is updated every time a spike is transmitted. The weight of each connection of the time of the n-th presynaptic spike is given by:

$$A_n = A\, u_n R_n \,, \tag{1}$$

where A is the absolute synaptic efficacy (i.e, the maximum weight), u_n describes the current utilization of synaptic resources, and R_n describes the current availability of synaptic resources. These are updated from some starting values for a delay of Δt since the last spike using

$$u_{n+1} = U + u_n(1 - U)\exp\left(-\frac{\Delta t}{F}\right) \tag{2}$$

where U governs the increase of synaptic efficacy per spike and F is the time constant for facilitation, and

$$R_{n+1} = 1 + (R_n - R_n u_n - 1)\exp\left(-\frac{\Delta t}{D}\right) \tag{3}$$

where D is the time constant for depression.

Population rate

The population rate of a population of N neurons in some time period $[t - \Delta t, t]$ is given by

$$A(t) = \left\langle \frac{1}{\Delta t} \cdot \frac{N_{spikes}(t - \Delta t, t)}{N} \right\rangle \tag{4}$$

where $N_{spikes}(t_0, t_1)$ is the number of spikes which occurred between t_0 and t_1. The brackets $\langle\cdot\rangle$ denote averaging over multiple trials.

Considering all the initial setup such as to connect the target LIF interneurons from input neurons (where according to point processes the input neurons generating the spikes). Below are the plots through which their respective behaviour is being discussed.

Task 3a

Fig 2 illustrates the trial-averaged postsynaptic population rate by evoking a series of action potentials from the presynaptic population of neurons. The positive change in population rate signifies that there is a positive change in amplitude of postsynaptic neurons and thus the facilitation. Basically, the strength of the synapse is related to the amplitude of the postsynaptic response. Well, inside the pre-synaptic terminals, there are vesicles filled with neurotransmitter. Now to go back to steady state or to ready to use state into the vesicles, is characterized by F, facilitating time constant, an exponential approach. In this model, there's always a certain number of vesicles in the state ready to use, ready to be released. And with each spike, out of those that are not yet in the state ready to be released at the next spike arrival. This gives an idea that the larger the F, the quicker the vesicles move from normal state to ready to use state or vice versa. This also provides an idea that quicker it releases the neurotransmitters and come to steady state the quicker it can recruit the spikes that are coming in as a result that there is an increased change for F = 0.376s in the population rate compared to F = 0.1. To tell it in mathematical point of view as, per the equation (1), (2) and (3). The more the spikes are generated in the presynaptic terminal the more the resources u_n is utilized resulting to which the behaviour, increase in the synaptic conductance i.e $A_n > A_{n-1}$ which is nothing but facilitation. F = 0.376s or F = 0.1s is greater than D = 0.045s where D is almost closer to '0' which means Rn is near close to a value of '1' and F has a positive contribution towards the utilization of synapse resources u_n.

Thus, implies in this case $A_n \rightarrow \; A\,u_n$. And having had F = 0.376s and F = 0.1s, it is likely to be increased facilitation for F = 0.376s compared to F = 0.1s because u_n, utilization factor is relatively more for F = 0.376s compared to F = 0.1s that informs more number of signal transmissions for F = 0.376s compared to F = 0.1s.

The stable values are different because by principle the postsynaptic neuron amplitude or population rate saturates after certain amount of facilitation/depression and then adapts to latest one until no signal is provided following to which it goes to recovery mode. The rate of change of population for F = 0.376s as it is greater than F = 0.1 the saturation point differs to each other. Hence, the result.

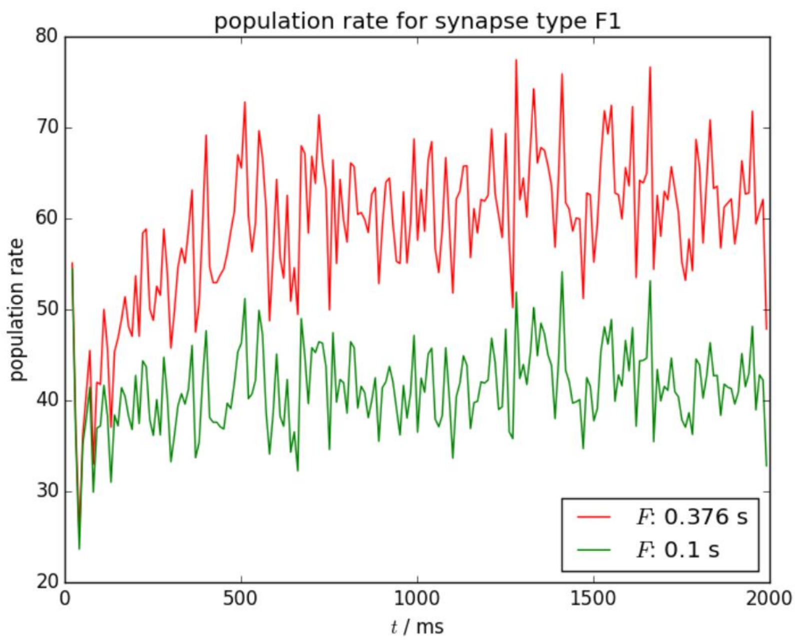

Figure 2

Task 3b

This model works just the way it is explained in Task 3a but, in analogous with a fact that not all vesicles are in the state ready to use. In the state (ready to use) they are close to the membrane so that they can open the arrival of the signal and spill out the neurotransmitter. So, amongst the total number of vesicles that are around, some sit just inside the cell useless and the certain fraction is ready to use. Now in a steady state, transmitter molecules are forced back into the vesicles, vesicles will dock the membrane, goes to ready to use state and is characterized by D, depression time constant, an exponential approach to go back to steady state or to ready to use state. Here the synaptic conductance is controlled by a factor of number of resources available vs number of spikes that are arriving through dendrites to pre-synaptic terminal. As a result, in this case it is always a reduced response. Mathematical view is the more the spikes are generated in the presynaptic terminal the more the resources R_n is enabled as a result by the tsodyks deductions it tends to become $R_n < R_{n-1}$ implies $A_n < A_{n-1}$and also u_n tends to become which results in constant utilization of synaptic resources causing nothing but depression.

The reason why when $r_{input} = 20\ Hz$ undergoes greater depression when compared to $r_{input} = 10\ Hz$ can be understood by the formula (1), $A_n = A\ u_n R_n$, ∀A = 100/r_{input}. Which tells that when r_{input} is greater the ability to produce a desired synaptic transmission is lesser because the maximum weight is divided by a larger number. That conveys having had the respective amount of resources available R_n the absolute synaptic efficacy is divided by a greater number which decreases the weight of each connection. As we could see because of the value of D = 0.706s and F = 0.021s, $A_n \rightarrow\ A\ UR_n$. Just because there is a decrease in the weight of a connection which is caused by increase in the spikes i.e $r_{input} = 20\ Hz$ the depression is more compared to $r_{input} = 10\ Hz$. Hence, the observation. And then after a saturation point it adapts to its later amplitude or population rate.

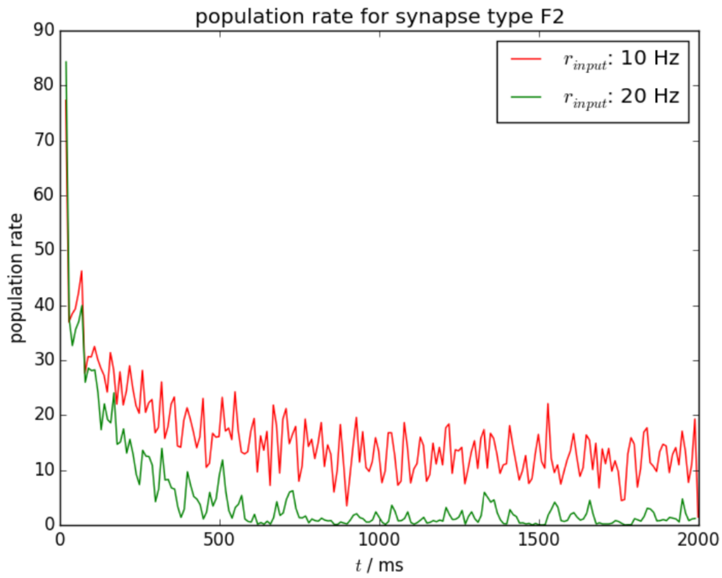

Figure 3

Task 3c

As discussed in task 3a, about the working principle of the facilitation. Here the facilitation for $r_{input} = 20\ Hz$ is greater than $r_{input} = 40\ Hz$ for the reason of the influence that it makes in amplitude or population rate which can be verified by the formula $A_n = A\, u_n R_n$, ∀A = 100/r_{input}. Here it clearly justifies lesser the r_{input}, higher the value of A_n that conveys maximum utilization of resources resulting in a greater synaptic conductance compared to the value with $r_{input} = 40\ Hz$. Hence the behaviour.

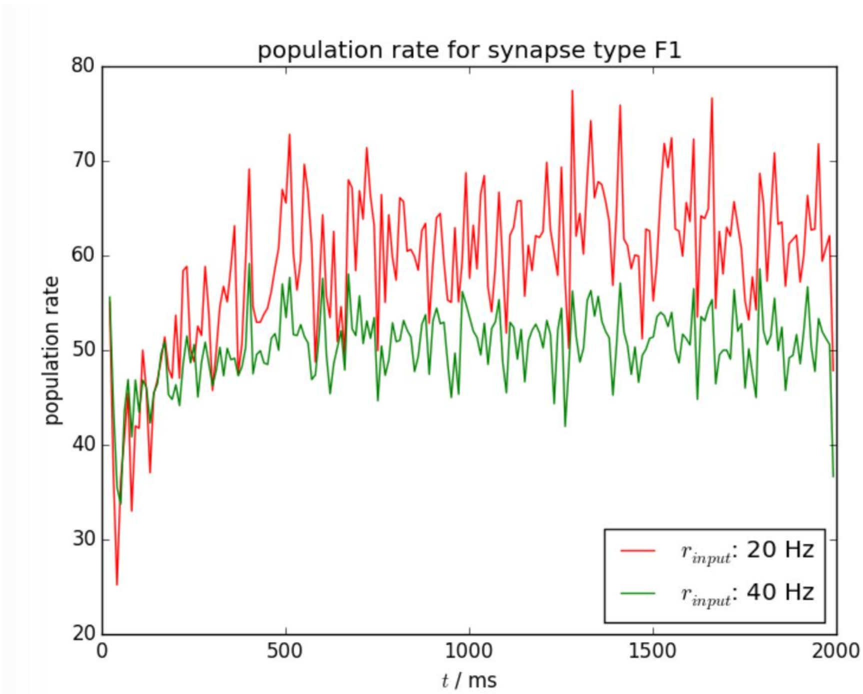

Figure 4

Task 3d

This task is to derive the synaptic weight for long constant rate input.

Rewriting the definition of equation (1), gives

$$A_n = A\, u_n R_n$$

$$\rightarrow \quad A_n = \left(\frac{100}{r_{input}}\right) u_n R_n \tag{5}$$

Where the Absolute synaptic efficacy A was set to $\left(\frac{100}{r_{input}}\right)$.

Thus, fixed points u_n and R_n for A_n yields to

$$u_{n+1} = U + u_n(1-U)\exp\left(-\frac{1}{F * r_{input}}\right) \tag{6}$$

$$R_{n+1} = 1 + (R_n - R_n u_n - 1)\exp\left(-\frac{1}{D * r_{input}}\right) \tag{7}$$

The resulting equations say if it is considered for 100 presynaptic spikes and also the parameters and its values from the first three tasks to find coherence with the behaviour of synaptic weights. Following are the results that are obtained.

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Task 3a
Synaptic weight for rate input: 20 , U: 0.16 , D: 0.045 , F: 0.376 for spikes 100 is  2.33159779026
Synaptic weight for rate input: 20 , U: 0.16 , D: 0.045 , F: 0.1 for spikes 100 is  1.4058940531
Task 3b
Synaptic weight for rate input: 10 , U: 0.25 , D: 0.706 , F: 0.021 for spikes 100 is  0.94821317485
Synaptic weight for rate input: 20 , U: 0.25 , D: 0.706 , F: 0.021 for spikes 100 is  0.28820912481
Task 3c
Synaptic weight for rate input: 20 , U: 0.16 , D: 0.045 , F: 0.376 for spikes 100 is  2.33159779026
Synaptic weight for rate input: 40 , U: 0.16 , D: 0.045 , F: 0.376 for spikes 100 is  0.931522889071
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And the same parameters if it is considered for 500 presynaptic spikes it could be observed the behaviour of synaptic weight has remained the same just as the previous considered number of presynaptic spikes case which is a clear indication that after a certain amount of spikes that are received whether it is a depression or facilitation, the weight or population rate still remains the same as long as there are no further spikes that are received.

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Task 3a
Synaptic weight for rate input: 20 , U: 0.16 , D: 0.045 , F: 0.376 for spikes 500 is  2.33159779026
Synaptic weight for rate input: 20 , U: 0.16 , D: 0.045 , F: 0.1 for spikes 500 is  1.4058940531
Task 3b
Synaptic weight for rate input: 10 , U: 0.25 , D: 0.706 , F: 0.021 for spikes 500 is  0.94821317485
Synaptic weight for rate input: 20 , U: 0.25 , D: 0.706 , F: 0.021 for spikes 500 is  0.28820912481
Task 3c
Synaptic weight for rate input: 20 , U: 0.16 , D: 0.045 , F: 0.376 for spikes 500 is  2.33159779026
Synaptic weight for rate input: 40 , U: 0.16 , D: 0.045 , F: 0.376 for spikes 500 is  0.931522889087
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