EE 746 : Neuromorphic Engineering

Assignment 3: Neuronal Dynamics with plastic synapses and axonal delays

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Note: The codes for all the Neuron models are available *here*.

Problem 1: Representing synaptic connectivity and axonal delays

(We did the assignment in Python)
a) We used a 2D matrix to represent the cell. Elements of which contain the connection information and the Synapse joining the 2 neurons.

$$Fanout = \begin{bmatrix} [0 & 1] \\ [0 & 1] \\ [0 & 1] \end{bmatrix}$$

$$W = \begin{bmatrix} [3000 & 3000] \\ [3000 & 3000] \\ [3000 & 3000] \end{bmatrix}$$

$$\tau \text{ (in ms)} = \begin{bmatrix} [1 & 8] \\ [5 & 5] \\ [9 & 1] \end{bmatrix}$$

b) Case 1:

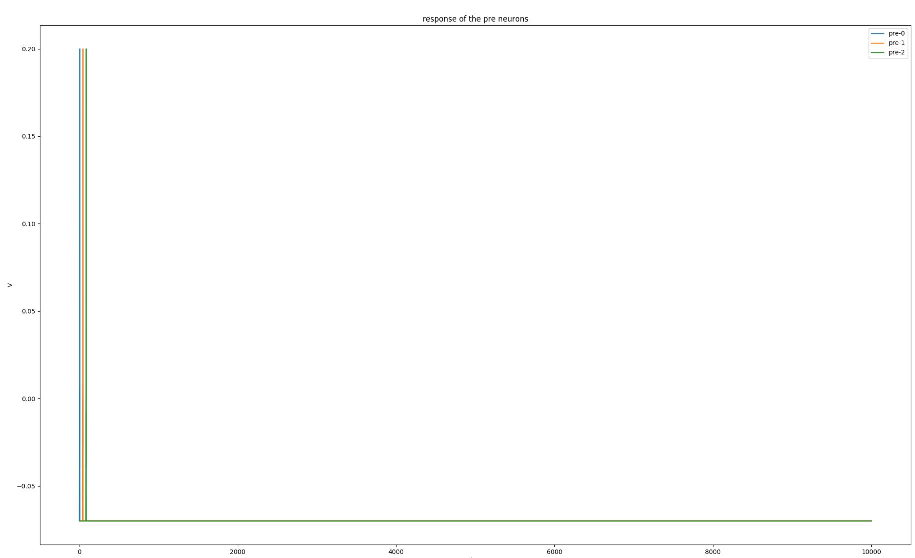

Figure 1: Response of the pre_neurons

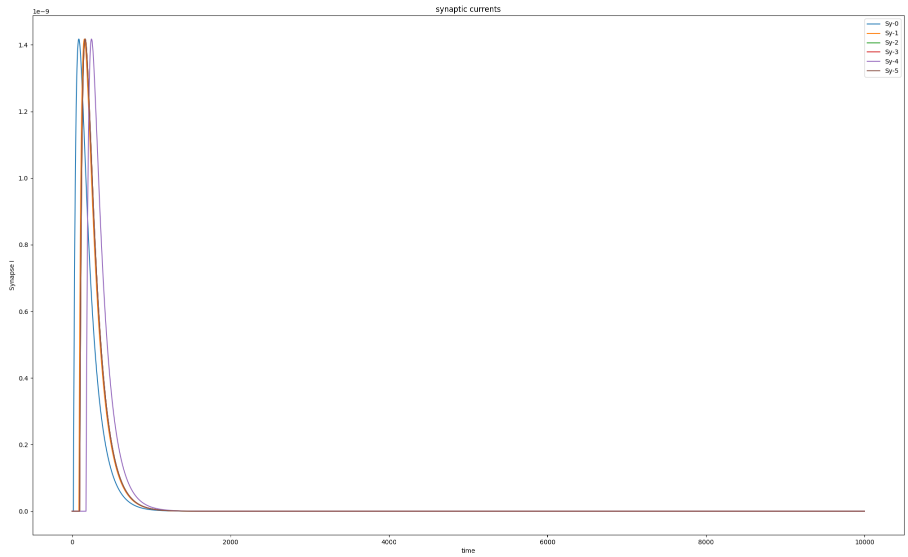

Figure 2: Synaptic currents, here we have $3 * 2 = 6$ synapses

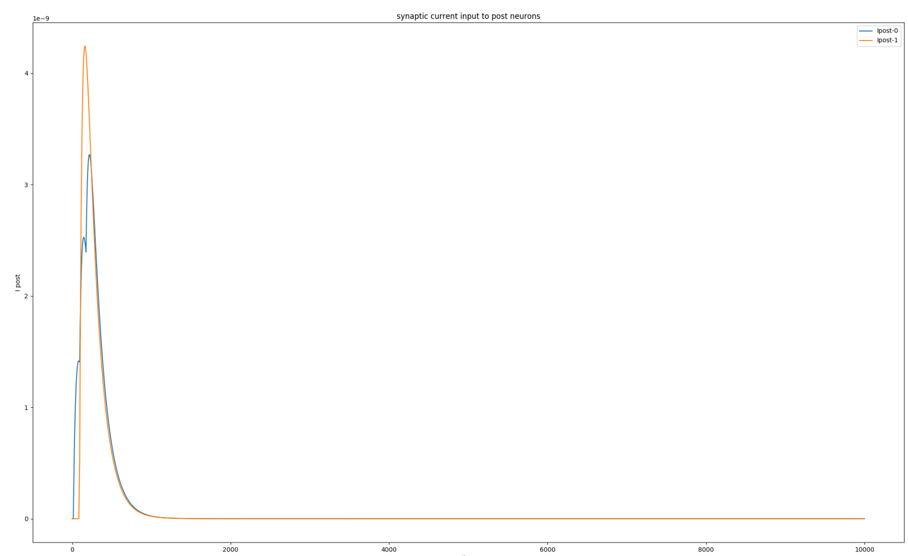

Figure 3: Current inputs to post_neurons from the synapses

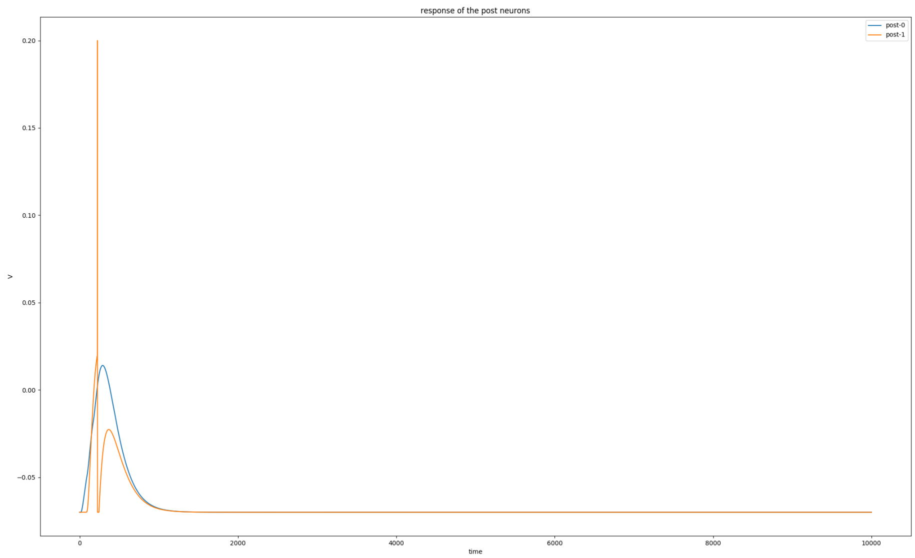

Figure 4: The neuron emitting a spike as closely spaced stimulus are present

b) Case 2:

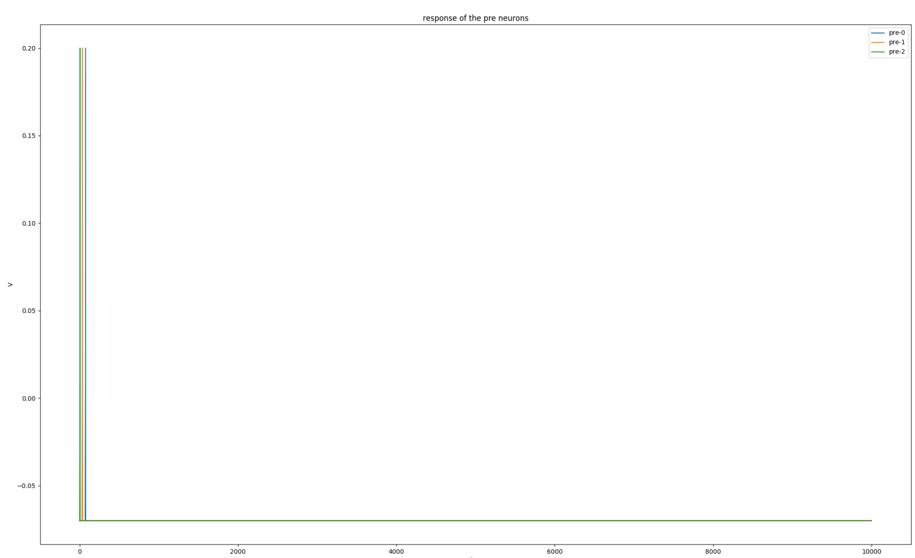

Figure 5: Response of the pre_neurons

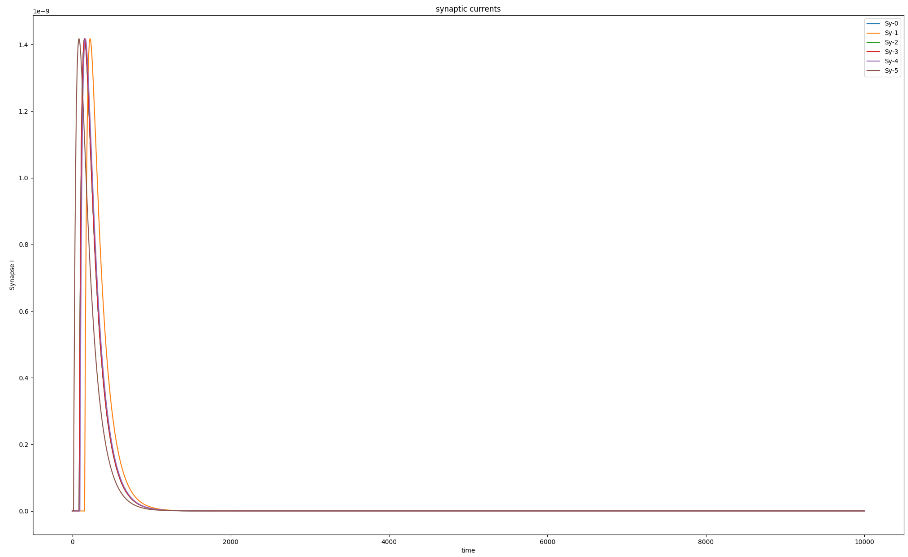

Figure 6: Synaptic currents, here we have $3 * 2 = 6$ synapses

Figure 7: Current inputs to post_neurons from the synapses

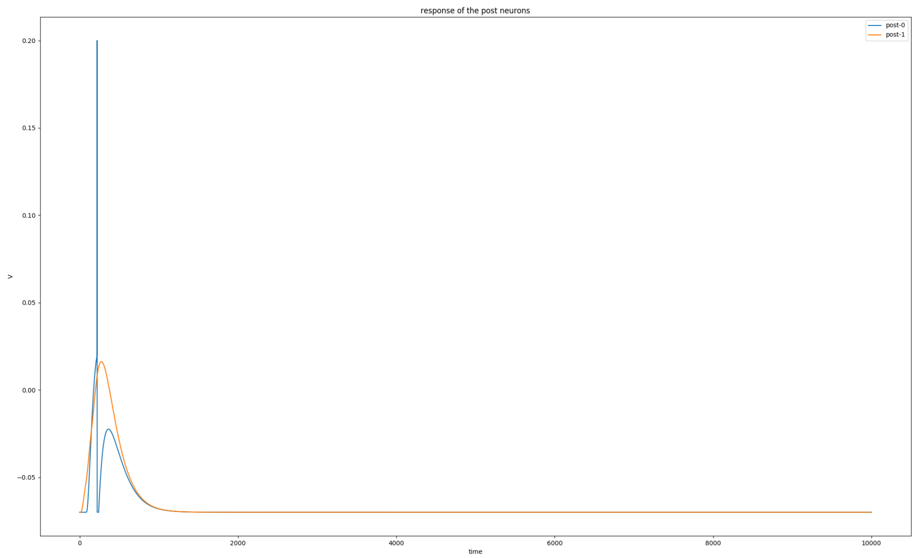

Figure 8: Response of the post_neurons

Problem 2: Dynamical Random network

a)

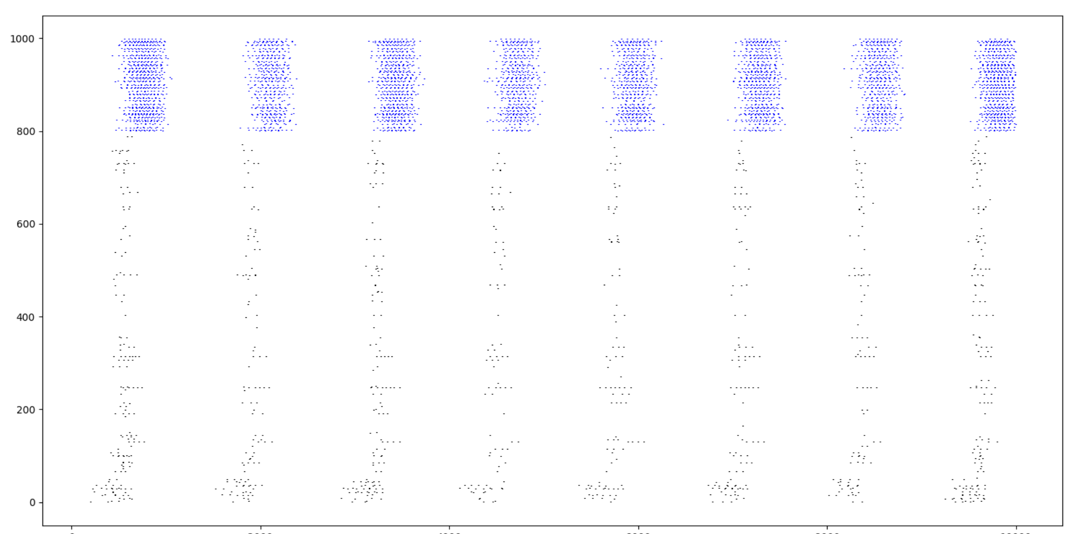

Figure 9: Raster plot for $N = 500$, $T = 1000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons.

b)

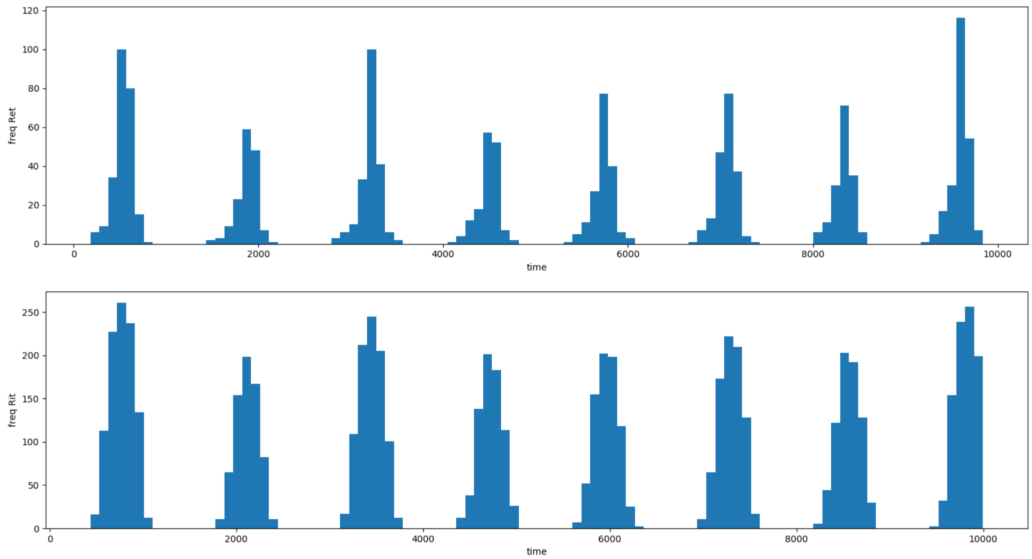

Figure 10: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, the oscillating pattern

c) As can be seen in the raster plot and histograms there seems to be an oscillating pattern in the firing, this can be explained by the fact that, 1) inhibitory spikes are post neurons only for excitatory pre neuron, this makes them more prone to firing. 2) The pattern can also be accounted to formation of different groups in the network and each group spiking similarly. The groups are characterized by matching axonal conduction delays between neurons. [1]

Also, when we inject current due to poisson spike train voltage input to a few excitatory neurons in the network, it naturally initiates significant spiking in the other excitory neurons connected to the initial ones. Thereafter, we see a steep rise in the total number of spikes in the excitatory neurons. Similar argument holds for the inhibitory neurons excited by excitatory neurons pre-connected to them. However, after a point of time the influence of inhibitory neurons starts affecting the overall spiking to reduce and ultimately go to nil. This explains the first peaky response in Figure 10 for both, $R_e(t)$ and $R_i(t)$. Further, the poisson spike generated current input is still active on the initial 25 excitatory neurons. Thus restarting the process as explained above. Hence, an oscillatory pattern is seen in the total number of spikes in excitatory as well as inhibitory neurons over time.

Problem 3: Dynamics of smaller networks

a) For a smaller dynamical network, with similar statistical connectivity characteristics, we see that the network has a drastically different response as compared to that of a larger network as seen in Problem 2. Specifically, the plots for $R_e(t)$ and $R_i(t)$ show the trend of increasing and then saturating at a particular frequency with time as opposed to the oscillatory behaviour in Problem 2.

[1]Reference: *Polychronization: Computation with Spikes,* Eugene M. Izhikevich Eugene.Izhikevich@nsi.edu The Neurosciences Institute, 10640 John Jay Hopkins Drive, San Diego, CA 92121, U.S.A.

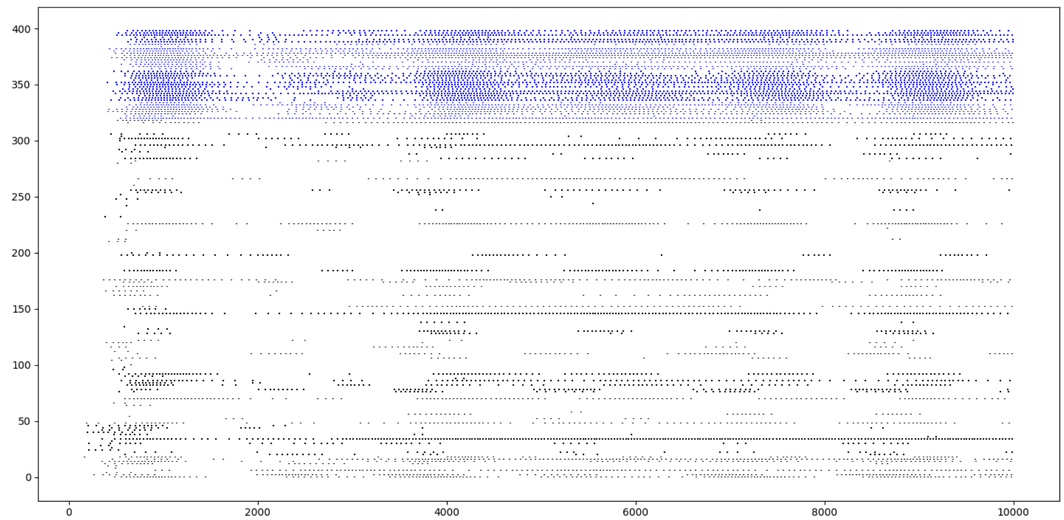

Figure 11: Raster plot for $N = 200$, $T = 1000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons. $|w_e| = |w_i| = 3000$

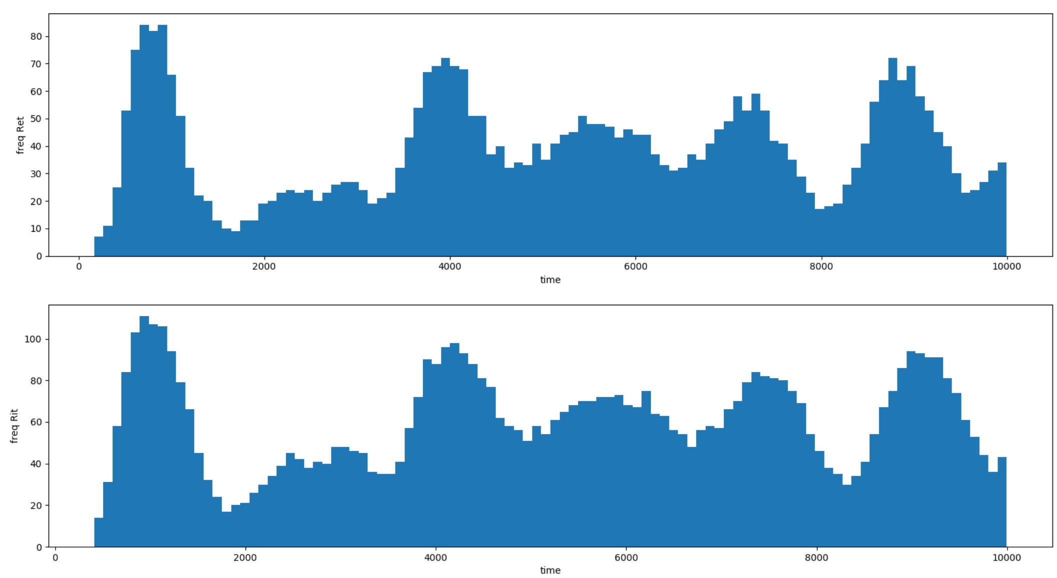

Figure 12: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, here there isn't an oscillatory pattern similar to that of Problem 2. $|w_e| = |w_i| = 3000$

b) For different values of weights we can see the following trend

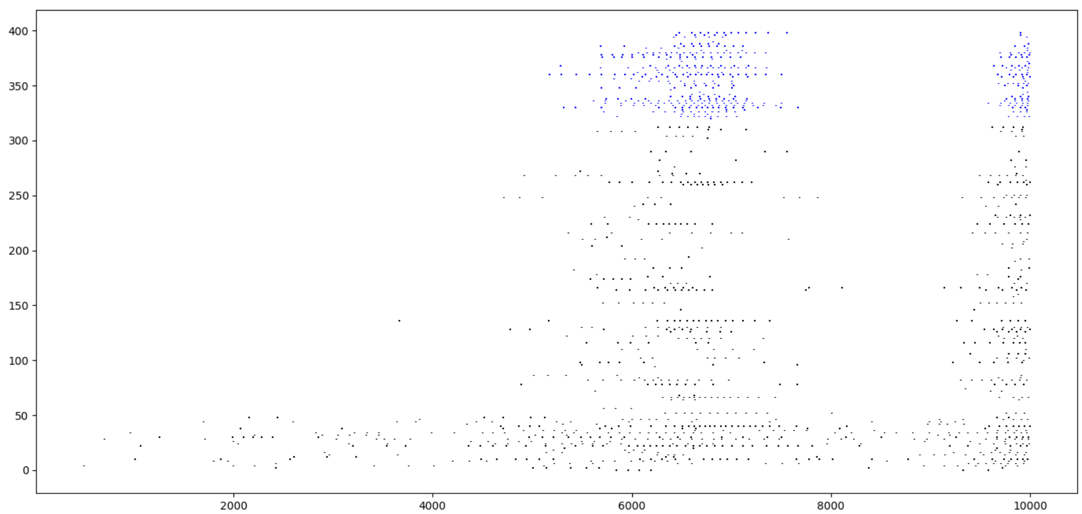

Figure 13: Raster plot for $N = 200$, $T = 1000ms$ neurons with synaptic configuration. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons. $|w_e| = |w_i| = 1500$

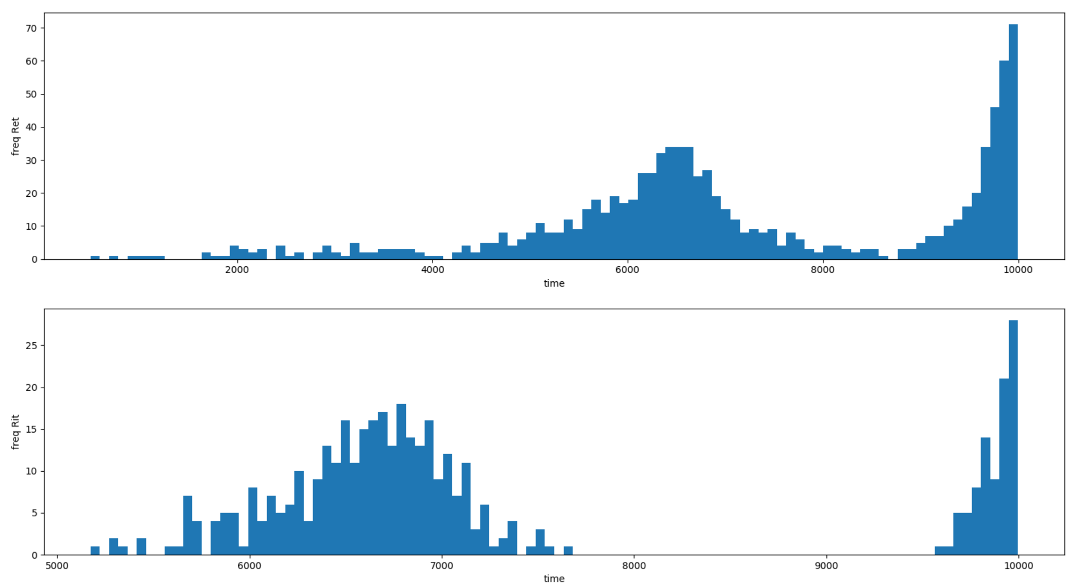

Figure 14: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, the oscillating pattern. $|w_e| = |w_i| = 1500$

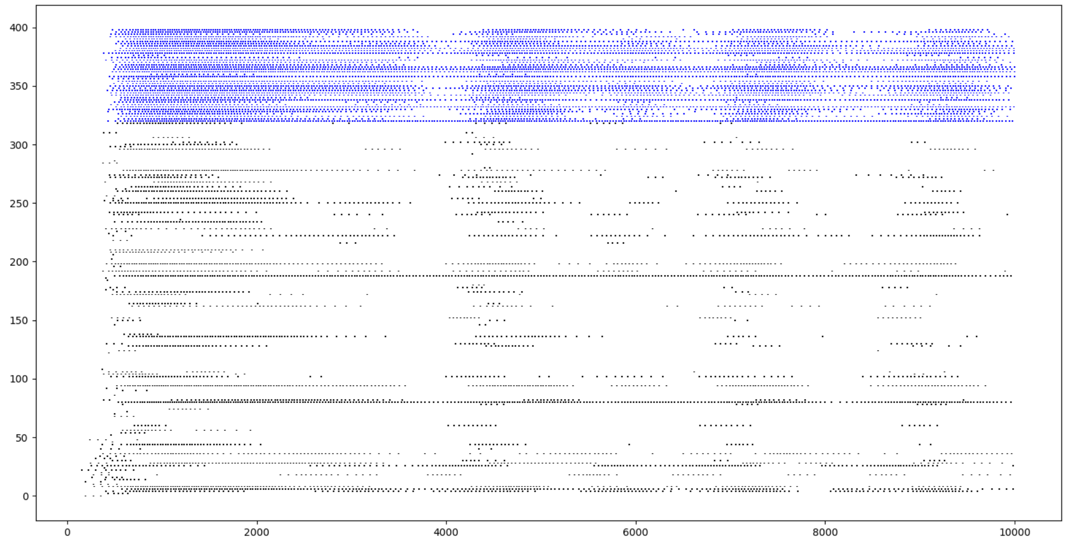

Figure 15: Raster plot for $N = 200$, $T = 1000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons. $|w_e| = |w_i| = 4000$

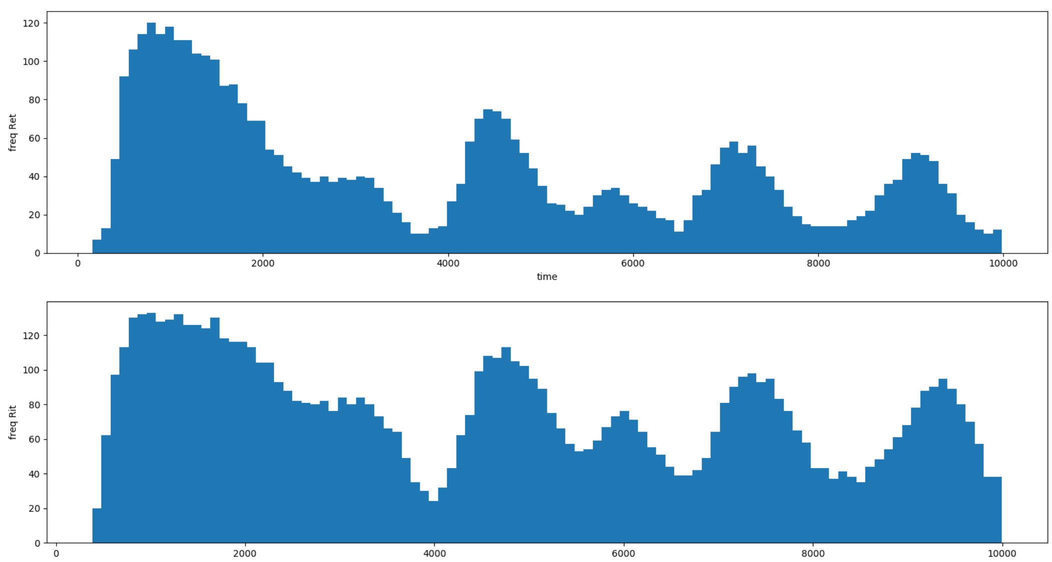

Figure 16: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, the oscillating pattern. $|w_e| = |w_i| = 4000$

c) As evident, For smaller networks, $|w_i| = |w_e|$ can not give the network behavior observed earlier. The net *excitation* and *inhibition* in the network should be *decreased* and *increased*, respectively in order to observe the network behavior observed in problem 2.

d) To achieve similar dynamical behavior in terms of the overall number of spikes, implementing the following modification of the synaptic configuration, $w_e = -\gamma w_i$, we observe that for $\gamma < 1$ the network shows dynamic behaviour similar to what was seen in large networks.

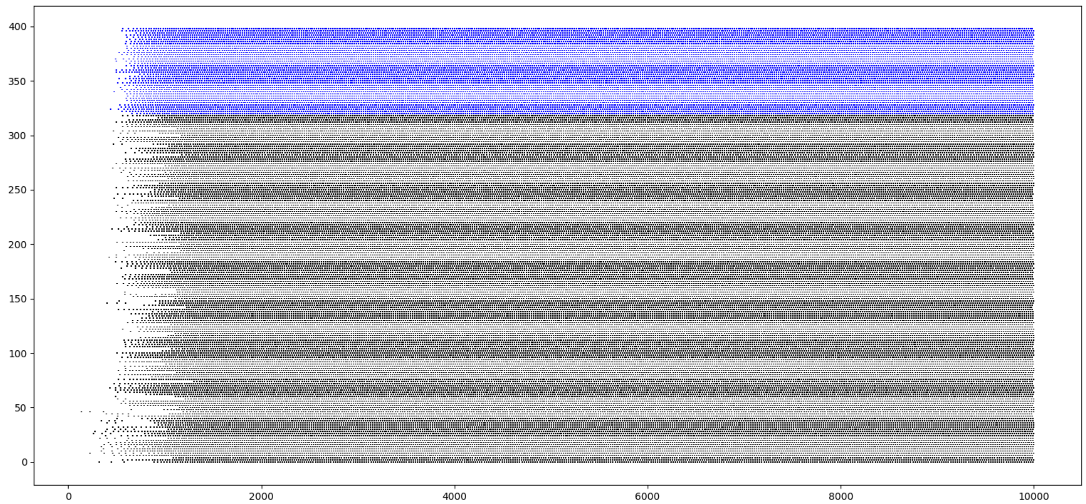

Figure 17: Raster plot for $N = 200$, $T = 1000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons. $\gamma = 1.3$

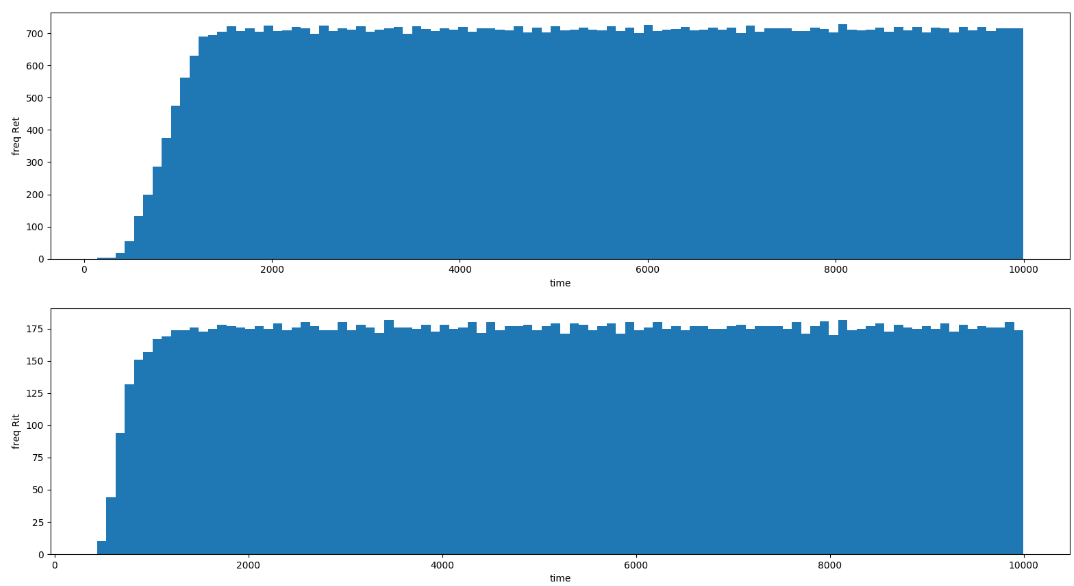

Figure 18: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, the oscillating pattern. $\gamma = 1.3$

Figure 19: Raster plot for $N = 200$, $T = 1000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons. $\gamma = 0.77$

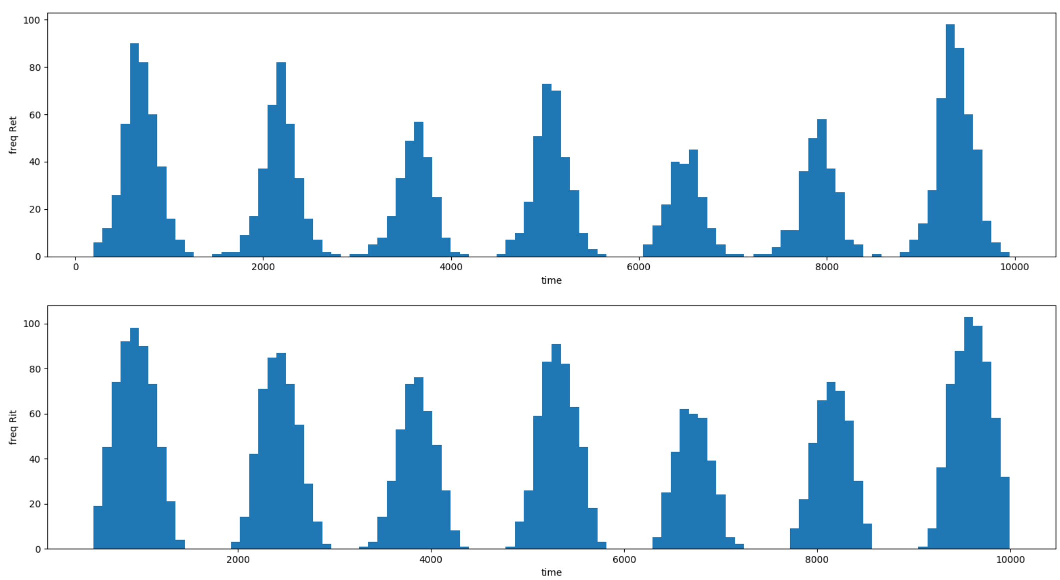

Figure 20: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, the oscillating pattern. $\gamma = 0.77$

Problem 4: Adjusting the weights dynamically

a) For small network ($N = 200$), the response of the network for initial weights $w_e = +3500$, $w_i = -3500$, and all the excitatory synapses are plastic and obey STDP, and the inhibitory synapses are non-plastic:

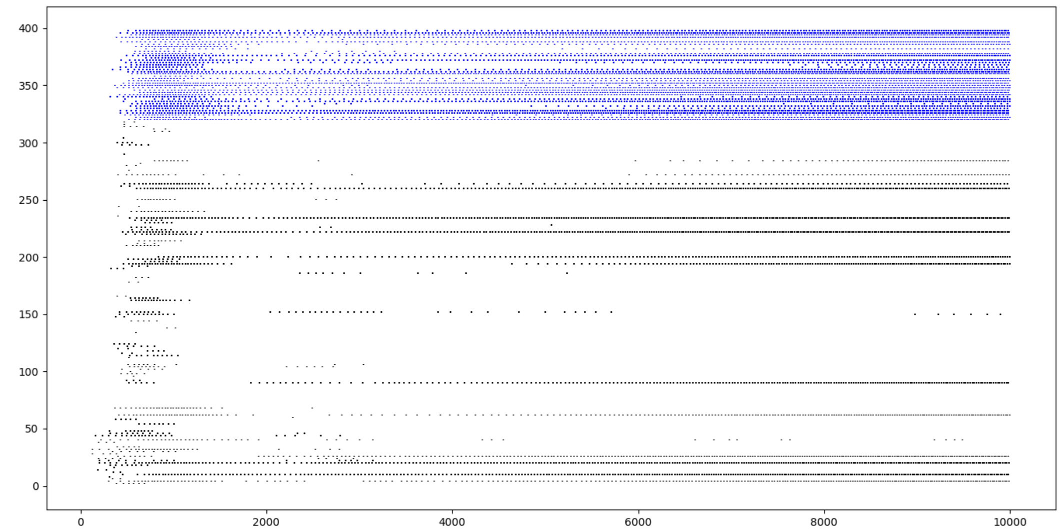

Figure 21: Raster plot for $N = 200$, $T = 1000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons.

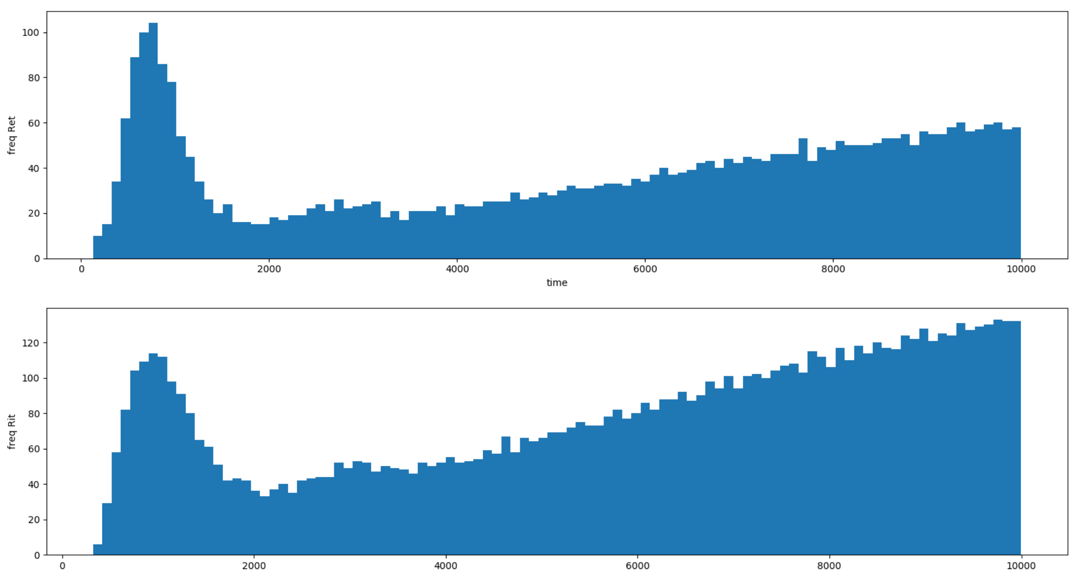

Figure 22: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, here there isn't an oscillatory pattern similar to that of Problem 2.

b) The average excitatory synaptic strength in the network is seen to increase with time since the nature of causal spikes between any pre-post neuron connection is much more as compared to anti-causal spikes owing to the design.

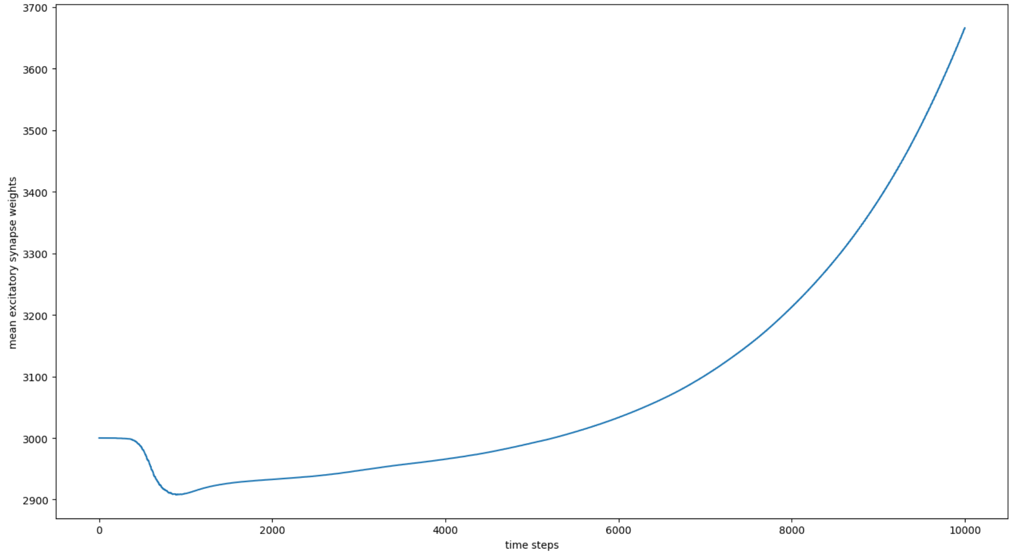

Figure 23: The variation in the average excitatory synaptic strength in the network as a function of time.

Problem 5: A network that adapts dynamically

a) According to 3d, we need to modify the weight in such a manner that we see a rhythmic pattern in the raster plots. This will happen because initially some excitatory neurons will be triggered by external poisson stimulus this will leas to spiking in the fan out neurons which may have inhibitory neurons as well. Soon, these inhibitory neurons will start inhibiting the excitatory neurons (because inhibitory neurons are connected only to excitatory neurons) and this will kill the spiking in the system. Soon again excitatory neurons will start spiking (due to external poisson stimulus) and cycle will repeat. To encorporate this we need to make inhibitory neuronal connections stronger w.r.t excitatory neuronal connection, we do this by introducing a const factor $\gamma < 1$ which will reduce the effective A_{up} by γ i.e $A_{up}\gamma$ and will increase the effective A_{down} by γ i.e $\frac{A_{down}}{\gamma}$

Upstream excitatory synaptic weight update rule:

$$w_{new} = w_{old} + w_{old} A_{up} \gamma e^{\frac{-(t_i^k - t_j^{last})}{\tau_L}}$$

Downstream inhibitory synaptic weight update rule:

$$w_{new} = w_{old} + w_{old} \frac{A_{down}}{\gamma} e^{\frac{-(t_i^k + \tau_d - t_j^{last})}{\tau_L}}$$

b)

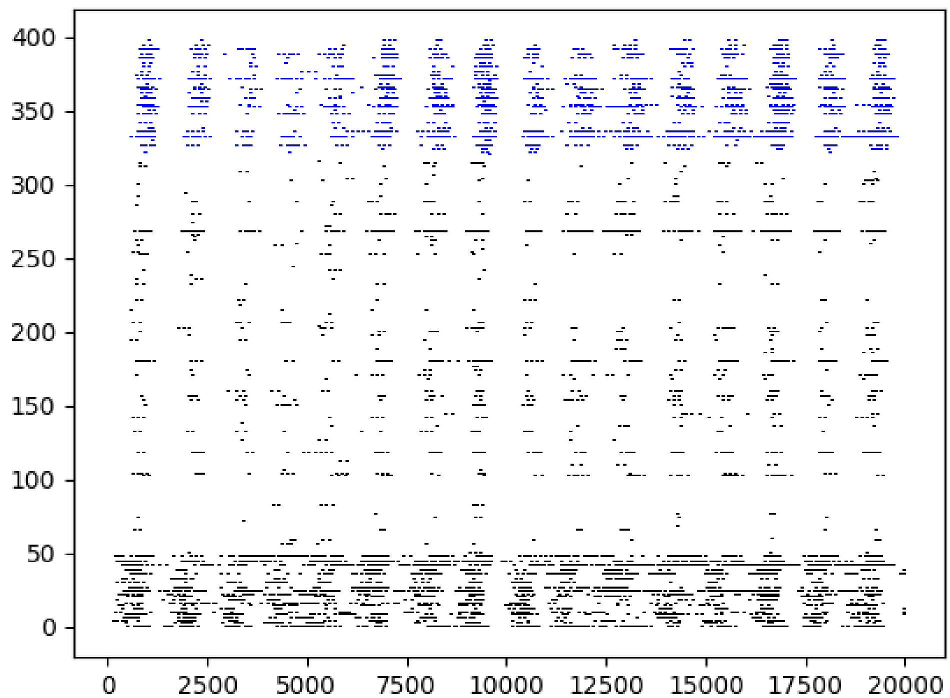

Figure 24: Raster plot for $N = 200$, $T = 2000ms$ neurons. Note, the blue coloured response is of the inhibitory neurons and black represents response of excitatory neurons. $\gamma = 0.4$

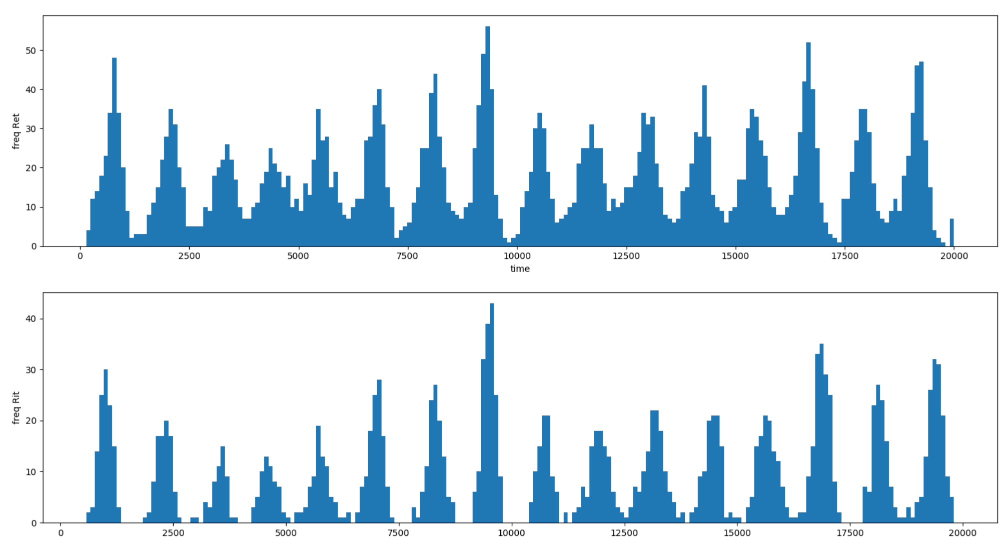

Figure 25: Histogram of frequency of spikes by excitatory and inhibitory neurons in different time bins for $N = 500$ neurons. Note, the oscillating pattern for this smaller network. $\gamma = 0.4$

c)

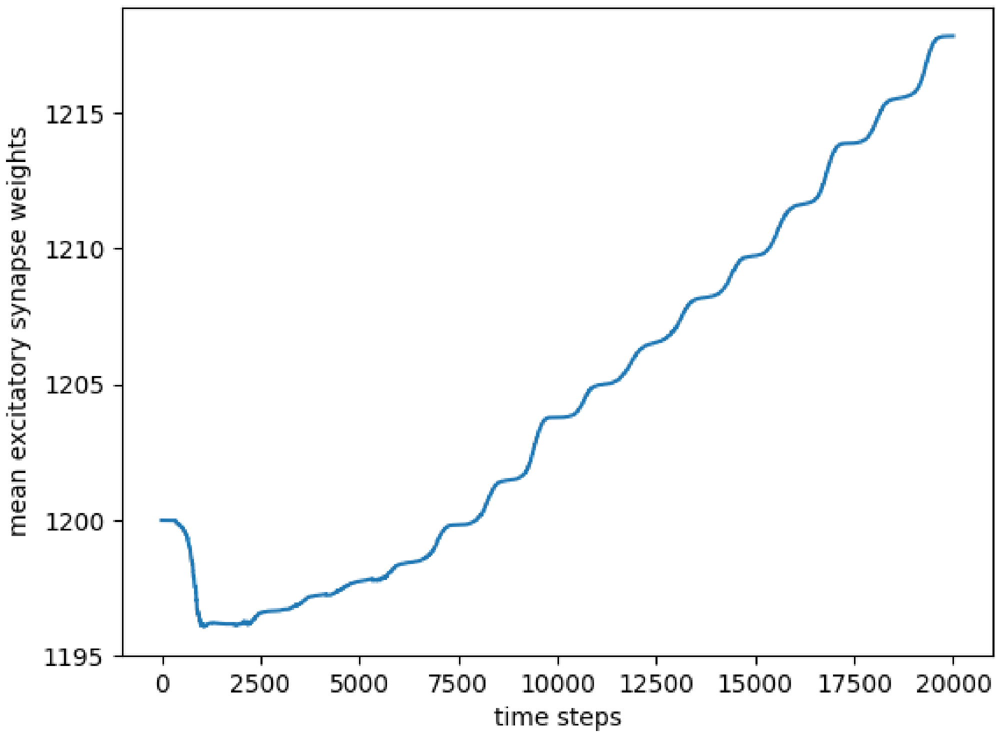

Figure 26: The variation in the average excitatory synaptic strength in the network as a function of time for smaller network with modified weight-update rule.