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Information Transmission in Hippocampal CA1 Neuron Models in the Presence of Poisson Shot Noise: the Case of Periodic Sub-threshold Spike Trains

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Abstract— **This article presents an analysis of the information transmission of periodic sub-threshold spike trains in a hippocampal CA1 neuron model in the presence of a homogeneous Poisson shot noise. In the computer simulation, periodic sub-threshold spike trains were presented repeatedly to the mid-point of the main apical branch, while the homogeneous Poisson shot noise was applied to the mid-point of a basal dendrite in the CA1 neuron model consisting of the soma with one sodium, one calcium, and five potassium channels. From spike firing times recorded at the soma, the inter spike intervals were generated and then the probability, $p(T)$, of the inter-spike interval histogram corresponding to the spike interval, T, of the periodic input spike trains was estimated to obtain an index of information transmission. In the present article, it is shown that at a specific amplitude of the homogeneous Poisson shot noise, $p(T)$ was found to be maximized, as well as the possibility to encode the periodic sub-threshold spike trains became greater. It was implied that setting the amplitude of the homogeneous Poisson shot noise to the specific values which maximize the information transmission might contribute to efficiently encoding the periodic sub-threshold spike trains by utilizing the stochastic resonance.**

Index Terms— **Action Potential, Stochastic Resonance, Hodgkin-Huxley model, Homogeneous Poisson Process, Shot Noise, Synaptic Noise, Numerical Method, Monte Carlo Simulation**

I. INTRODUCTION

Stochastic resonance (SR) is a phenomenon of coupling deterministic and random dynamics in non-linear systems. This phenomena can be interpreted as an increase of detecting a low-level input signal in the output of the system, which is caused by an increase of the noise level in the input signal. In neurosciences, SR has been observed in sensory nervous systems [1], [2], [3] and central nervous system [4],[5], [6]. In each investigation, it was reported that the detection of a sub-threshold input signal was improved when a certain level of noise was added. However, it is still unclear if SR would improve information processing in the nervous systems.

In the present paper, the information transmission of periodic sub-threshold spike trains in a hippocampal CA1 neuron model is investigated in the presence of a homogeneous Poisson shot noise. In the computer simulation, periodic sub-threshold spike trains were presented repeatedly to the mid-point of the main apical branch, while the homogeneous Poisson shot noise was applied to the mid-point of a basal dendrite. in the CA1 neuron model. In this paper, the probability, $p(T)$, of the inter-spike interval histogram (ISIH) corresponding to the spike interval, T, of the periodic input spike trains was utilized as an index of information transmission, like those in [7], [8].

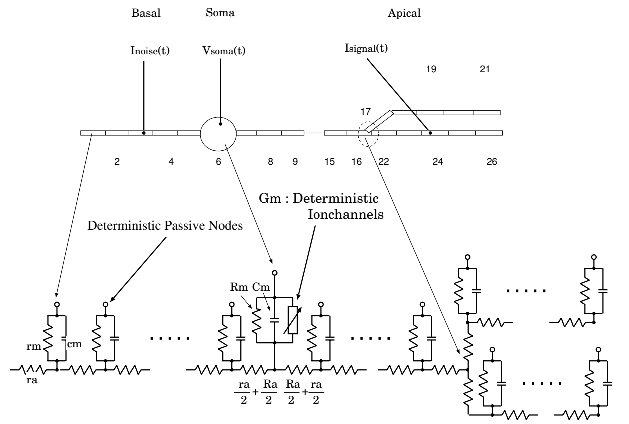

Fig. 1. Hippocampal CA1 neuron was represented as a 5 cylinder multi-compartment model possessing 26 compartments: 5 compartments in the basal, one compartment in the soma, and 20 compartments in the apical branches. The length in each segment was set at $250\mu m$ in the basal, $10\mu m$ in the soma,and $400\mu m$ in apical respectively, while the diameter was set at $4\mu m$(basal), $15\mu m$(soma), $3.5\mu m$(1° apical), $3.13\mu m$(*Auxiliary*2° apical), and $1\mu m$(Main 2° apical). The equivalent electric circuit was shown in which the dendrites were composed of the passive resistances and capacitance, and in which the soma has the active ion channels. The sub-threshold "spiking signal" current, $I_{signal}(t)$, and "synaptic noise" current, $I_{noise}(t)$, were assumed to be applied to the main apical section (the 24th compartment), and the basal section (the 3rd compartment), respectively, while the transmembrane potential at the soma, $V_{soma}(t)$ was recorded.

II. METHODS

The hippocampal CA1 neuron was represented by a multi-compartment model [10] having 5 cylinders: 5 compartments in the basal, one compartment in the soma, and 20 compartments in the apical branches, as shown in Fig.1. The dendric model parameters were set as follows: the basal diameter $4\mu m$, the basal length per one segment 40 μm, the soma diameter $15\mu m$, the soma length per 50 μm, the 1° apical diameter $3.5\mu m$, the 1° apical length per one segment $40\mu m$,

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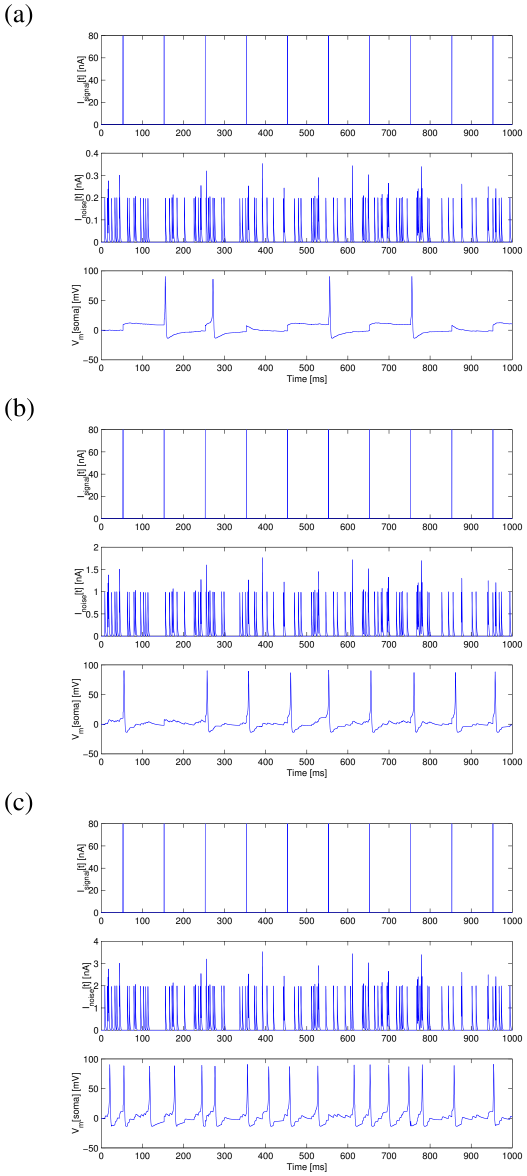

Fig. 2. Top: Input spike trains, $I_{signal}(t)$ with a frequency of 10 Hz and a pulse width of 40 μs, Middle: Shot noise, $I_{noise}(t)$, a homogeneous Poisson shot noise with an intensity of 100 $1/s$, Bottom: Transmembrane potentials at the soma $V_{soma}(t)$ relative to the resting potential $E_{rest} = -66[mV]$. The amplitude of $h(t)$, a_{noise}, was set at 0.2 nA in (a), 1.0 nA in (b), and 2.0 nA in (c).

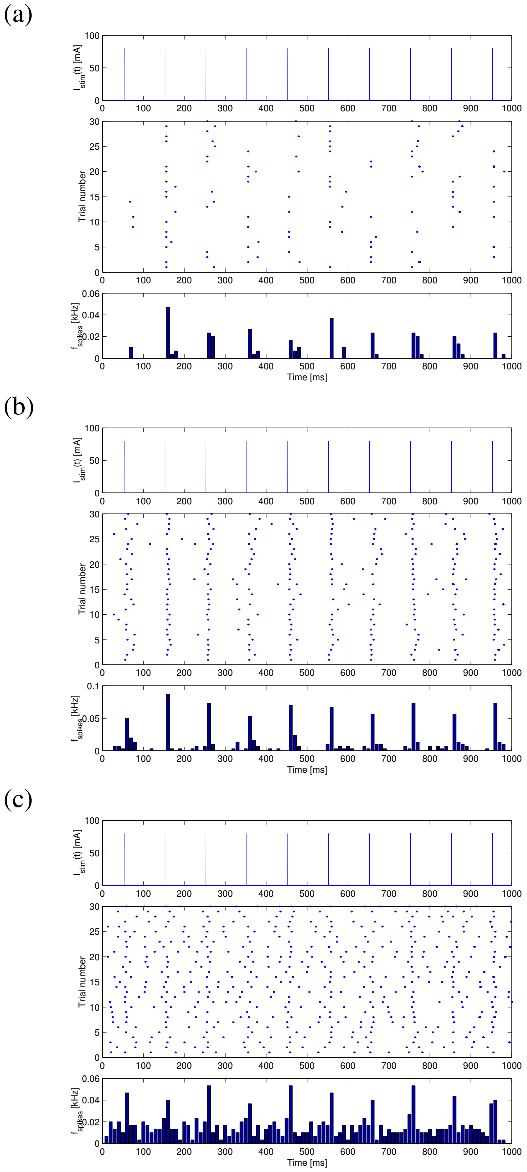

Fig. 3. Top: Input spike trains, $I_{signal}(t)$ with a frequency of 10 Hz and a pulse width of 40 μs, Middle: Raster plots of 30 trials Bottom: Post-stimulus time histogram (PSTH) The amplitude of $h(t)$, a_{noise}, was set at 0.2 nA in (a), 1.0 nA in (b), and 2.0 nA in (c) in the case of $I_{signal}(t)$ with a frequency of 10 Hz.

the auxiliary 2° apical diameter $3.13\mu m$, the auxiliary 2° apical length per one segment 80 μm, the main 2° apical diameter $1\mu m$, and the main 2° apical length per one segment 80 μm. The membrane specific resistance and capacitance in the dendrites were set at 14,000 Ωcm^2 and 2 $\mu F/cm^2$, while those in the soma were set at 28,000 Ωcm^2 and 1 $\mu F/cm^2$. All model parameters were adopted from those in [4]. The soma contained one sodium, one calcium, and five potassium channels in which conductances, and transition rates were adopted from those in [9]. The transmembrane potentials were numerically calculated by solving a diffusive partial differential equation with the Crank-Nicholson method at a sampling step of 20 μs (see Appendix).

In computer simulations, the sub-threshold "spiking signal" current, $I_{signal}(t)$, and "synaptic noise" current, $I_{noise}(t)$, of 30 s in time length were assumed to be applied to the main apical section, and the basal section, respectively, as shown in the top of Fig. 1, while the transmembrane potential at the soma, $V_{soma}(t)$, was recorded. The "spiking signal" was assumed to be a periodic input spike train with an amplitude of 80 nA, a pulsatile duration of 40 μs, and a spike interval of T (set at 5, 10, 15, and 20 ms). The "synaptic noise" current was generated by a homogeneous Poisson process filtered by

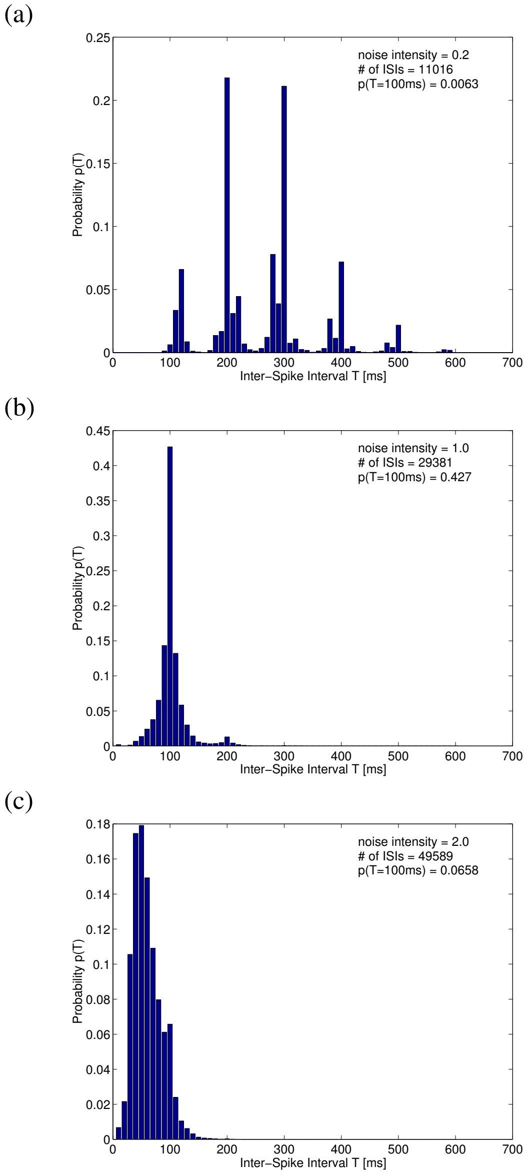

Fig. 4. Inter-spike interval histogram (ISIH) in which the amplitude of $h(t)$, a_{noise}, was set at 0.2 nA in (a), 1.0 nA in (b), and 2.0 nA in (c). $p(T = 100ms)$ was estimated to be 0.0063 in (a), 0.427 in (b), and 0.0658 in (c) in the case of $I_{signal}(t)$ with a frequency of 10 Hz (T=100ms).

the impulse response function, $h(t)$ (i.e., shot noise):

$$I_{noise}(t) = \int_{-\infty}^{t} h(\tau)dN(t-\tau) \tag{1}$$

in which the intensity of the counting process $N(t)$ was set at 100 $1/s$, and

$$h(t) = a_{noise}e^{-\alpha t} \qquad (t \geq 0) \tag{2}$$

where α=1000 $1/s$, and a_{noise} denotes the amplitude of the impulse response function. a_{noise} was varied between 0.1 and 3.0 to see how the synaptic noise would improve the spike signal transmission.

The spike firing times were detected by determining when the transmembrane potential at soma, $V_{soma}(t)$, took the peak amplitude and was greater than 50% of the peak amplitude of action potentials. The probability, $p(T)$, of the inter-spike interval histogram (ISIH) corresponding to the spike interval, T, of the periodic input spike trains was used as a measure of signal transmission.

All computer simulations were performed on an IBM compatible PC with a Pentium 4 CPU.

III. RESULTS

Figure 2 shows the sub-threshold input spike trains, $I_{signal}(t)$ with a frequency of 10 Hz and a pulse width of 40 μs (top), the shot noise, $I_{noise}(t)$, a homogeneous Poisson process filtered by the impulse response function $h(t)$ (i.e., Poisson shot noise) with an intensity of 100 $1/s$ (middle), and the transmembrane potentials at the soma $V_{soma}(t)$ relative to the resting potential $E_{rest} = -66[mV]$ (bottom). The amplitude of $h(t)$, a_{noise}, was set at 0.2 nA in (a), 1.0 nA in (b), and 2.0 nA in (c) in Figure 2. The input spike trains tended to be encoded reliably into the spike firings (action potential occurrences) observed in the bottom trace, as a_{noise} increased (a-b). However, the noisy spike firings were observed when a_{noise} was set at 2.0 nA in (c).

Figure 3 shows the sub-threshold input spike trains, $I_{signal}(t)$ with a frequency of 10 Hz and a pulse width of 40 μs (top), the raster plots of 30 trials (middle) in which the dots denotes the spike firings, and the post-stimulus time histogram (PSTH) (bottom). The amplitude of $h(t)$, a_{noise}, was set at 0.2 nA in (a), 1.0 nA in (b), and 2.0 nA in (c) in Figure 3. It follows from the raster plots (middle) and the PSTH (bottom) that the input spike trains were encoded with a higher reliability into the spike firings, as a_{noise} increased from 0.2 to 1.0 nA, whereas the noisy spike firings were observed when a_{noise} was set at 2.0 nA.

Figure 4 shows the inter-spike interval histogram (ISIH) in which the amplitude of $h(t)$, a_{noise}, was set at 0.2 nA in (a), 1.0 nA in (b), and 2.0 nA in (c). The probability, $p(T = 100ms)$, of the inter-spike interval histogram (ISIH) corresponding to the spike interval, T, of the periodic input spike trains was estimated to be 0.0063 in (a), 0.427 in (b), and 0.0658 in (c) in the case of $I_{signal}(t)$ with a frequency of 10 Hz (T=100ms).

Figure 5 shows the probability, $p(T)$, of the inter-spike interval histogram (ISIH) corresponding to the spike interval, T, of the periodic input spike trains as a function of a_{noise} in which T was set at 50ms (20Hz), 67ms (15Hz), 100ms (10Hz), and 200ms(5Hz). It was implied that the information transmission was maximized due to the stochastc resonance.

IV. DISCUSSION AND CONCLUSION

In the present article, we have investigated the information transmission of neural spike trains in which a periodic sub-threshold spike train was presented as stimuli into a hippocampal CA1 neuron model with the soma consisting of one sodium, one calcium, and five potassium channels in the presence of a homogeneous Poisson shot noise. We have

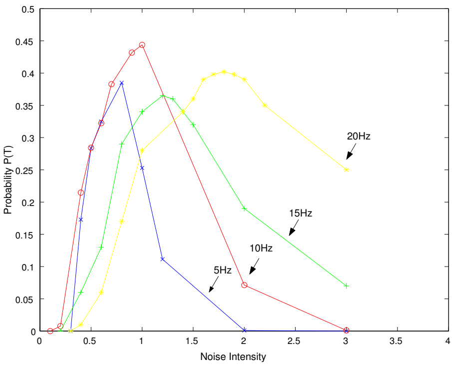

Fig. 5. The probability, $p(T)$, of the inter-spike interval histogram (ISIH) corresponding to the spike interval, T, of the periodic input spike trains as a function of a_{noise} in which T was set at $50ms$ ($20Hz$), $67ms$ ($15Hz$), $100ms$ ($10Hz$), and $200ms$($5Hz$).

shown that at a specific amplitude of the homogeneous Poisson shot noise, the possibility to encode the periodic input spike trains became greater, i.e., the information transmission was found to be maximized (the stochastic resonance).

It is implied that setting the amplitude parameter of the homogeneous Poisson shot noise to some specific values makes it possible to efficiently encode the periodic subthreshold input spike trains to the output spike trains in the hippocampal CA1 neuron model. Therefore, these modeling endeavors may significantly advance our understanding of information transfer in the Hippocampal CA1 neuron model.

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V. APPENDIX

The cable equation can be obtained from the equivalent circuit shown in Fig. 1 as follows:

$$C_m(x)\frac{\partial V_m(x,t)}{\partial t}+\frac{V_m(x,t)}{R_m(x)}+I_{ion}(t) = h^2\frac{\partial}{\partial x}\frac{1}{R_a(x)}\left(\frac{\partial V_m(x,t)}{\partial x}+\frac{\partial V_a(x,t)}{\partial x}\right) \quad (3)$$

where C_m, R_m, and $V_m(t)$ stand for membrane capacitance respectively, resistance and potential, Δt is infinitesimal length, R_a and $V_a(t)$ stand for axial resistance and potential respectively. In order to perform numerical calculations, (3) is discretized in spatially and temporally as follows:

$$C_m^{[k]}\frac{V_m^{[k]}(t+\Delta t)-V_m^{[k]}(t)}{\Delta t}+\frac{V_m^{[k]}(t)}{R_m^{[k]}}+I_{ion}^{[k]}(t) = \frac{1}{R_a^{[k-1,k]}}\left(V_m^{[k-1]}(t)-V_i^{[k]}(t)\right)+\frac{1}{R_a^{[k+1,k]}}\left(V_i^{[k+1]}(t)-V_i^{[k]}(t)\right) + \frac{1}{R_a^{[j,k]}}\left(V_i^{[j}](t)-V_i^{[k]}(t)\right) \quad (4)$$

where k stands for the number of compartments, ($k=1,2,\ldots,26$). Note here that $\frac{V_m^k(t)}{R_m^k}=0$ at $k=6$, and $I_{ion}^k(t)=0$ at $k\neq 6$, and the third term in right-hand side is applied just to $k=16$.

The Crank-Nicholson method was utilized to solve the transmembrane potentials, $V_m^{[k]}(t)$, by using the following expression:

$$\begin{aligned} C_m^{[k]}&\frac{V_m^{[k]}(t+\Delta t)-V_m^{[k]}(t)}{\Delta t} \\ &= \frac{1}{2}\left\{\frac{1}{R_a^{[k-1,k]}}\left(V_m^{[k-1]}(t)-V_i^{[k]}(t)\right)\right. \\ &\quad+\frac{1}{R_a^{[k+1,k]}}\left(V_m^{[k+1]}(t)-V_i^{[k]}(t)\right) \\ &\quad+\frac{1}{R_a^{[j,k]}}\left(V_i^{[j]}(t)-V_i^{[k]}(t)\right)-\frac{V_m^{[k]}(t)}{R_m^{[k]}} \\ &\quad+\frac{1}{R_a^{[k-1,k]}}\left(V_m^{[k-1]}(t+\Delta t)-V_i^{[k]}(t+\Delta t)\right) \\ &\quad+\frac{1}{R_a^{[k+1,k]}}\left(V_m^{[k+1]}(t+\Delta t)-V_i^{[k]}(t+\Delta t)\right) \\ &\left.+\frac{1}{R_a^{[j,k]}}\left(V_i^{[j]}(t+\Delta t)-V_i^{[k]}(t+\Delta t)\right)-\frac{V_m^{[k]}(t+\Delta t)}{R_m^{[k]}}-I_{ion}^{[k]}(t)\right\} \end{aligned} \quad (5)$$