Energy-Efficient Neuromorphic Receptors for Wide-Range Temporal Patterns of Post-Synaptic Responses

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***Abstract*—In a neuromorphic integrated circuit synaptic dynamics are of great importance to capture accurate neural behaviors. In this paper, we propose a current-based synapse design mediated with multiple receptor types, namely AMPA, NMDA and GABAa, and a weight-dependent learning algorithm. Due to various biological conducting mechanisms, the receptors demonstrate different kinetics in response to stimulus. The designed circuit offers distinctive features of receptors as well as the joint synaptic function. An increased computation ability is verified through synchrony detection in a two-layer recurrent network of synapse clusters. The design implemented in TSMC 65 nm CMOS technology consumes 1.92, 3.36, 1.11 and 35.22 pJ per spike event of energy for AMPA, NMDA, GABAa receptors and the advanced learning circuit, respectively.**

***Index Terms*—neuromorphic design, synapse, receptor, synchrony detection, synaptic plasticity.**

I. Introduction

Neuromorphic systems, a concept proposed by Carver Mead [1], are artificial systems used to capture biological properties of neurons in nervous system. Silicon implementation is one of popular methods to achieve modelization of neural system from biological experiments as it shares many analogous features with biological nervous system [1]. Phenomenological models, a compromise between high fidelity and computational feasibility, describe crucial properties from theoretical results and applies them in analyses and simulations. These models allow deeper understanding of working principles underlying neuron networks.

Synapses, i.e. the connecting structures between neurons, experience synaptic state modifications based on incoming information and current activities in neural networks. Neurons then convert resulting signals into spikes and pass them to next layer of synapses. It should be noticed that the synaptic state modification induced by a mechanism, commonly called $synaptic\ plasticity$, is an abstraction of synaptic learning. When stimulated by incoming presynaptic spikes, synapses release vesicles, where neurotransmitters are stored, as a way of signal transmission. The binding of released transmitters and receptors at the dendrites of postsynaptic neurons activates receptor channels and thus induces electrical activities in postsynaptic neurons. Synaptic plasticity is influenced by the quantity of transmitters emitted to receptors, and the efficiency of the receptor's response [2]. There are different types of receptors: NMDA, AMPA, GABAa, each exhibiting different temporal dynamics in their response to neurotransmitters [3]. For example, the speed of NMDA receptor response is considerably slower in comparison with AMPA, since a more rigorous condition should be satisfied to open the receptor channel. Additionally, the unbinding of glutamate and receptors for NMDA is relatively slow [4]. A generic synapse structure does not capture diverse temporal dynamics of different types of receptors in biological synapses, which are essential for realization of biophysically accurate neural behaviours in spiking neural networks (SNN) [5].

In recent neural network studies [6], synapse circuit implementation varies from simple constant current sources, which are activated by presynaptic spikes, to more complex realizations of synaptic current dynamics. However, the receptor diversities have usually been ignored. Most research includes single type of synapse in whole neural system [7]-[8], or in some cases, they are partially mentioned but not described comprehensively [6]-[9]. In [10], a conductance-based synapse configuration which discusses various receptor types was proposed. Even though robustness is highlighted, the switched-capacitor based architecture occupies considerable silicon area, and thus limits integration density. In [11], ion-based model is employed to emulate receptor-supported synapse structure. Detailed ion dynamics are captured at a cost of high energy consumptions caused by extra active blocks.

In this paper, we propose a current-based phenomenological synapse model, consisting of efficient weight-dependent synaptic learning algorithms and multi-compartment synapses, namely AMPA, NMDA and GABAa receptors. The designed circuit obtains key functions of distinctive receptor dynamics with a compact and power-efficient structure. A better computation ability is demonstrated through cross-correlation detection verification with a two-layer recurrent network of synapse clusters. The analog multi-compartment synapse structure is able to detect and amplify the temporal synchrony embedded in the synaptic noise. The maximum amplification level is 2 times larger than that of single-receptor configuration. The circuit implemented in TSMC 65 nm CMOS technology consumes 1.92, 3.36, 1.11 and 35.22pJ per spike event of energy for AMPA, NMDA, GABAa receptors and the advanced

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learning circuit, respectively.

II. Synaptic Receptors

The effect of transmitter and receptor pairs on the postsynaptic neurons can be either excitatory or inhibitory, corresponding to positive and negative current flows to postsynaptic neurons, i.e. excitatory postsynaptic current (EPSC) and inhibitory postsynaptic current (IPSC). Different types of receptors display different temporal dynamics due to their distinctive conducting mechanisms. In this paper, we limit the scope to two main glutamate receptors, AMPA and NMDA, and one GABAergic receptor, GABAa.

A. Biological Receptors

AMPA Receptor: The AMPA receptor is one of the most common receptors in the nervous system. Mostly, the AMPA receptor is permeable to sodium (Na^+) via ion channels. Upon binding of transmitters on AMPA receptors, positively charged Na^+ enters the AMPA ion channels and depolarize the cell, thus inducing action potentials. AMPA receptor has a high conduction speed due to a straightforward mechanism of channel opening and closing, and are thus responsible for fast signal transmission [12].

NMDA Receptor: The ion channels NMDA receptor is voltage-dependent, which is distinctive compared with other glutamatergic receptors. This dependency initially arises from the non-selectivity of its ion channels. When ligand-binding occurs, the non-selective ion channels are open to extracellular magnesium (Mg^{2+}) and zinc (Zn^{2+}), which will bind to specific sites on the receptor and block the channels for any other ions. To eliminate this blockage, a certain level of depolarization of the cell is necessary, usually through the influx of Ca^{2+} [13]. Once cleared, the ion channels introduce both Ca^{2+} and Na^+ into the target cell. At the same time, in response to the increased level of depolarization, more AMPA receptors are inserted into the membrane, creating higher possibility that ion influx occurs. Thus, the conductance of NMDA receptor has a boost effect on the postsynaptic current. To activate NMDA receptors, the presynaptic activities introduce free transmitters to the dendrites, while the postsynaptic depolarization opens the receptor ion channels. This kind of dual function of pre- and postsynapses implies the role of NMDA receptor in synchrony detection and biological emulation. On the temporal aspect, the NMDA receptors are typically three to six times slower than AMPA [3], which originates from a more complicated binding mechanism and small unchanneling speed.

GABAa Receptor: The GABAa receptor is a primary inhibitory channel carrier in the nervous system. The GABAa receptor is permeable to chloride (Cl^-). When activated, the GABAa receptor conducts Cl^- through the ion channels, causing the hyperpolarization of the cell and a lower possibility of neural firing. This inhibition function of the GABAa receptor is reported to be a prerequisite for balancing excitation and inhibition, thus stabilizing neural network [14]. The GABAa receptors have a similar temporal dynamics as AMPA, i.e. both the rise and the fall time of EPSCs are comparable. A brief summary of the dynamic features of three receptors are listed in Table I.

TABLE I
Biological dynamics for three receptors [3] [14]

	Rise & Fall Times	Conduction Remarks
AMPA (+)	0.4-0.8, 5 ms	1-step, fast EPSC
NMDA (+)	20, 100 ms	2-step, voltage dependency, slow EPSC
GABAa (-)	3.9, 20 ms	1-step, fast IPSC

Learning Rule: Spike timing dependent plasticity (STDP), a temporally symmetrical form of Hebbian's theory, is a learning process that can adapt the synaptic weight according to temporal correlations between pre- and postspikes of a target synapse. These correlations should be within milliseconds time range in accord with biological temporal features: if the prespike precedes the postspike, a potentiation of the synaptic weight occurs; in contrast, if a reversed sequence happens, depression is induced. Two factors of concern in this learning window are time constants (τ) and amplitudes (A). The time constant indicates the temporal range where the correlation happens while the amplitude controls the adaptation level. The STDP rule is expressed as below:

$$\Delta w^+ = A^+ \cdot e^{-\Delta t/\tau_+} \qquad \Delta t > 0 \qquad (1)$$

$$\Delta w^- = -A^- \cdot e^{\Delta t/\tau_-} \qquad \Delta t < 0 \qquad (2)$$

where Δt is the temporal difference between a single pair of post- and pre-spikes. A_+ and A_- are the maximum amplitude while τ_+ and τ_- are time constants of the potentiation and the depression phase, respectively.

B. Circuit Implementation

The top-level structure diagram is shown in Fig.1. The synaptic weight, generated by STDP learning block is transmitted through receptors, resulting in wide-range of temporal dynamics of EPSCs or IPSCs. Those overlapping responses are then integrated in the integrated and fire (I&F) neuron [14], further generating firing spikes. The voltage-dependent NMDA receptor receives the feedback membrane voltages from the I&F neuron. The three receptors integrated with an

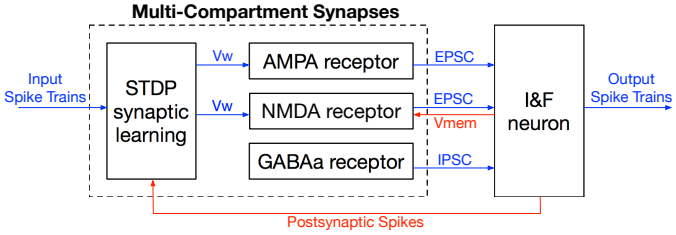


Fig. 1. Top-level diagram of multi-receptor mediated synapse architecture. The blue arrowed lines represent signal transmissions while red ones represent feedback signals. The dashed block denotes the multi-compartment synapse.

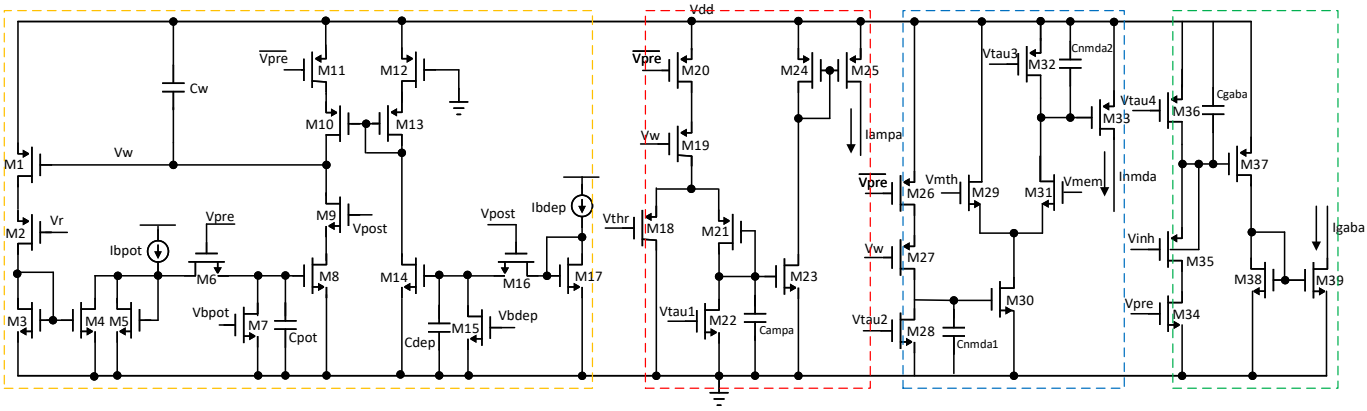


Fig. 2. The cluster structure including an advanced STDP learning circuit with three receptors. Different color dashed blocks denote different functional unit: yellow - advanced STDP learning, red - AMPA receptor, blue - NMDA receptor, green - GABAa receptor. The synaptic weight value is transmitted through node Vw between component circuits.

advanced STDP learning circuit [8] form a multi-compartment cluster structure. The transistor level implementation is shown in Fig.2.

A differential-pair integrator [6] structure is applied to emulate the fast rising and decaying dynamics of AMPA receptor. The receptor generates biologically analogous synaptic currents, which are modeled as a time-dependent alpha function with finite duration in rising phase [15]. The dual function of an extra scaling V_{thr} and a leaky rate adjustment V_{tau1} offers flexibility to amplitude and time constant control of AMPA EPSCs. Additionally, linear filtering properties makes it possible to sum multiple currents from identical synapses, yielding significant area savings. Moreover, the circuit has a low power consumption because the main circuit mostly conducts only in presence of the presynaptic spikes, which lasts for no more than 2 ms.

Unlike the single exponential dynamics used for AMPA receptor, the charging phase of NMDA receptor can not be ignored due to its relatively large portion in the whole temporal range. Thus, a double exponential function should be displayed in NMDA receptor design as well as its distinctive weight dependence. The presynaptic spike enables a instantaneous current influx into C_{nmda1} in the rising phase, the amplitude of which is mediated by V_w. The bias V_{tau2} determines the discharge speed of C_{nmda1}. During this controllable period of time, the transistor M4 is always active, inducing the charge of C_{nmda2}. After that, capacitor C_{syn} begins to discharge through M32 biased by V_{tau3}, adjusting the falling time constant. In this way, controllable double exponential dynamics are generated. To incoporate the distinctive voltage dependence of NMDA receptors, a differential pair is added to the circuit, forming a comparison between the membrane voltage V_{mem} and the threshold V_{mth}. When the postsynaptic neuron is depolarized, V_{mem} surpasses V_{mth}, introducing valid current flux into C_{syn}. On the contrary, if V_{mth} surpasses V_{mem}, no or only small fraction of current is induced to generate EPSCs.

The GABAa receptor has analogous dynamics as AMPA except for the polarity. However, since the inhibitory synapses do not exhibit learning properties, i.e. the inhibitory level is independent on the synaptic weight, it is not necessary to have two control voltages over the inhibitory level (V_{thr} and V_w). A log-domain integrator is chosen as the implementation of the GABAa receptor for its simplicity as well as a linear dynamics.

The advanced STDP learning circuit [8] incorporates presynaptic and postsynaptic spike trains, and conducts weight adaptation according to the STDP learning rule. The potentiation and depression phases exhibit almost symmetrical structures, inducing charge influx and efflux from the weight capacitor C_w depending on the relative timing of pre- and post-spike pairs. Note that the circuit in this paper follows a complementary design, i.e. larger V_w represents smaller weight value. The time constants and amplitudes of the learning window are tuned through V_{bpot}, V_{bdep} and I_{bpot}, I_{bdep}, respectively. A weight dependence feature is added to the potentiation domain via M1-M3 to match with experimental observations obtained in [16]. When synaptic weight increases (corresponding to a decrease in V_w), a larger current is subtracted from I_{bpot} through M5, resulting in lower current influx to C_{pot}.

III. Experimental Results

A. Synaptic Receptors

Single Receptor: The EPSC amplitude is determined by the width of prespike signal and the synaptic weight value. In our experiments, pulse width of spike trains is set to 100 μs. The time constants of receptors are regulated by transistor control voltages V_{tau1}-V_{tau4} to cover wide temporal range. For AMPA receptors, the possible time constant ranges from several to tens of milliseconds. Similarly, the time constants for NMDA receptor in both rising and falling phases are adjustable via two separate transistors M28 and M32.

The weight dependence of NMDA receptor is demonstrated through a comparison of $Vmem$ and a reference voltage $Vmth$. A sequence of presynaptic spikes are introduced to synapse. The $Vmem$ is a step signal from 0 to 500mV (larger than $Vmth$) onset time at 40ms (In reality, the membrane voltages are in spike forms, here the setting is made to examine

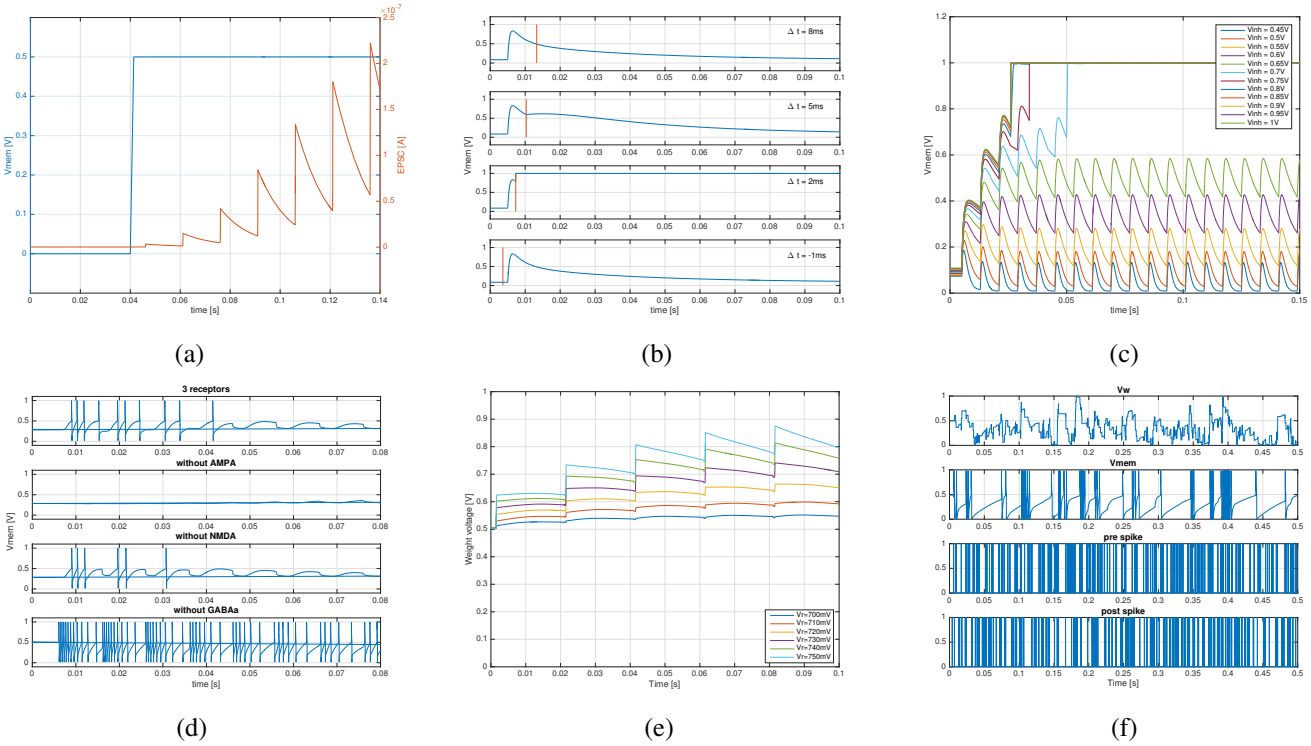


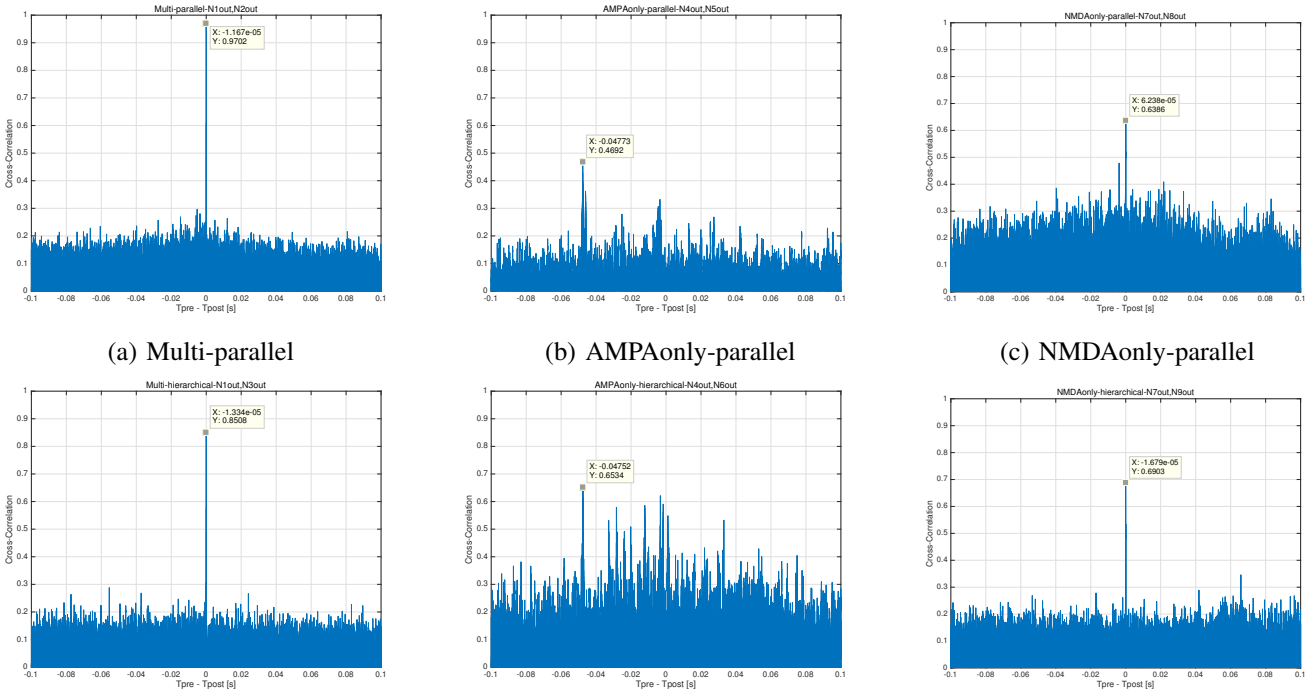
Fig. 3. (a) Weight dependence of NMDA receptors. (b) NMDA receptor mediated potentiation function on membrane voltage. AMPA currents are induced at a onset time of 5ms while the time for NMDA receptors varies (labeled with red vertical lines). Δt represents the interval between NMDA and AMPA activations, ranging from -1 to 8ms. (c) The role of GABAa receptor in synaptic integration. Due to a complementary design, larger inhibitory weight voltage means a smaller function of GABAa receptors. (d) The membrane voltage dynamics with different receptor configurations. From top to bottom, the strips represent: three receptors, without AMPA, without NMDA and without GABAa, respectively. (e) Weight dependence of the advanced STDP circuit. In this example, the presynaptic and postsynaptic signals are of 50 Hz frequency with 1 ms delay. V_r determines the weight dependence level. (f) Sample synaptic weight evolvement and the membrane voltage distribution in the advanced STDP circuit. From top to bottom, the strips represent: synaptic weight, membrane voltage, presynaptic spikes and postsynaptic spikes.

the specific function of NMDA receptor). It can be observed in Fig.3(a) that a growing current output appears from the onset of $Vmem$. A linear increase of EPSC amplitudes can be found at each stimuli. When stimulus are densely distributed, single NMDA EPSC fails to return to resting line before the next stimuli comes due to large decaying time constants, resulting in a summation behavior of previous activities.

In Fig.3(b), AMPA currents are introduced at the onset time of 5 ms, and NMDA currents are injected at different times. Two cases needs to be discussed individually. In the first case where AMPA stimuli precedes NMDA, the excitatory function of NMDA receptors can be demonstrated by the increase of V_{mem} (Δt= 2, 5, 8 ms). As NMDA stimuli approaches AMPA stimuli, larger V_{mem} is detected by NMDA synapse, which gives a greater voltage amplification. However, if delivered in reversed sequence (Δt= -1 ms), no modification is observed. This can be principally explained by the cooperation mechanism of those two receptors, i.e. AMPA receptors usually act as preliminary depolarization of post neurons by inducing small amount of ions (Na^+) into cells. When depolarization threshold is surpassed, NMDA receptors are activated, which allows substantial incursion of ions (both Na^+ and Ca^{2+}) and bigger electrical stimuli are produced. Thus, it is implied that NMDA receptors are not self-initiated. However once activated, the NMDA receptor acts as a major contribution to electrical signal transmission in neuron system.

In Fig.3(c), the contribution of inhibitory synapses to synapse integration is identified. Various levels of inhibition are applied to the system while the setting of excitatory synapses are maintained. When inhibition behavior is larger than certain level ($Vinh \leq 0.65V$), neuron system operates normally. Conversely, if the inhibition level decreases, excitation prevails, driving membrane state to the upper boundary, and consequently information may be lost during this process. This result suggests that inhibitory synapses are of great importance in balancing membrane activities, especially in the case of NMDA receptors where long-term summation of multiple receptors may exist.

Joint Function: Input spikes at a rate of 100Hz, with prespikes precede postspikes for 1 ms, are introduced to synaptic learning circuit, inducing consecutive depression to synaptic weight. In presence of three receptors, ten membrane spikes are generated as shown in Fig.3(d). A gradually sparser distribution of the spikes is observed along with the decline of synaptic weight. When synaptic weight reaches lower bound, the network fails to produce any spike trains. In absence



(a) Multi-parallel (b) AMPAonly-parallel (c) NMDAonly-parallel

(d) Multi-hierarchical (e) AMPAonly-hierarchical (f) NMDAonly-hierarchical

Fig. 4. Normalized cross-correlogram results from the two-layer recurrent testing network. (a)(b)(c) and (d)(e)(f) are the parallel and hierarchical cross-correlation plots of multi-receptor, AMPA-receptor and NMDA-receptor configurations, respectively. The annotation above each figure tells "receptor configuration-correlation source type" For example, "Multi-parallel" means the parallel correlation of multi-receptor settings.

of AMPA receptor, no postspike trains are observed. This result is analogous to biological experiments observed in hippocampal region [4]. Synapse with only NMDA receptors, also called *silent synapse*, will only transmit information when the postsynaptic neuron is depolarized, caused by synchrony pairing of other synapses with AMPA receptors. Otherwise, a minimal current will be produced by this silent synapse. When NMDA receptor is inhibited, the temporal intervals to generate equal number of spikes are larger, while the amount of spike clusters is lower due to a lack of long-term dynamics. NMDA receptor acts as a supplement to synaptic excitation. In the last case where GABAa receptor is inhibited, a burst of postspikes are produced even though the spike dynamics should decline with a decreasing synaptic weight. The network fails to transmit learning information carried by synapses. Hence, GABAa receptor is essential to create stable signal transmission in SNNs.

B. Advanced STDP Learning Circuit

Fig.3(e) demonstrates the functionality of the weight dependence block in the advanced STDP circuit. The input signal pairs induce a stable increment of the synaptic weight value. As the weight adjustment level decreases (V_r increases), this increment becomes less effective designating a unimodal weight distribution [5]. An example weight evolvement and the corresponding membrane voltage distribution with Poisson distributed presynaptic and postsynaptic input signals of 200 Hz are displayed in Fig.3(f).

C. Synchrony Detection

A two-layer recurrent network consisting of the cluster structures is utilized to explore the parallel and hierarchical synchrony detection and amplification function of the multi-compartment synapses. The system detects the spike-timing synchrony between spike trains embedded in a noisy environment and amplify this correlation from layers.

A correlated Poisson distributed spike trains are offered to synapse inputs. More correlated spike trains are more likely to coincide in the defined learning window of STDP learning, which will cause more valid weight update events. The cross-correlogram is used to demonstrate the temporal synchrony level between two output spike patterns within the same or between different layers of neurons.

The histograms in Fig.4(a)(d) evaluate the cross-correlations between parallel and hierarchical clusters. In both cases, a large level of correlation is observed at close to zero time point. This indicates a strong synchrony between both parallel and hierarchical spike trains after synaptic learning process with multi-receptor settings. In Fig.4(b)(d), the synchrony level is decreased almost by half. Similarly, the background noise is observed as well as several sub-peaks occurring near the origin in the hierarchical relations, which implies a relatively poorer stability performance. Along with the amplitude decay, a peak shift occurs. The delay between the inputs to the clusters is passed through layers while that of the multi-receptor synapses is mitigated. Finally, Fig.4(c)(f) characterize the synchrony

TABLE II
PERFORMANCE COMPARISON BETWEEN CURRENT WORKS

	[10]	[11]	[17]	This work
Model Type	conductance-based	current-based	current-based	current-based
Receptors Included	AMPA, NMDA, GABA	AMPA, NMDA, GABA	AMPA, NMDA, GABA	AMPA, NMDA, GABAa
Technology	180 nm	1.5 μm	0.35 μm	65 nm
Supply Voltage	1.8V	5V	-	1V
Power Consumption	45 μW for 1 neuron and 1 receptor	10-100 nW per receptor	-	111-336 pW per receptor
Remarks	switched-capacitor structure, large area	ion-based, biologically realistic	phenomenological, dendritic dynamics	phenomenological, achieving key features

detection function of NMDA-receptor network. Both parallel and hierarchical pairs have similar correlation plots as multi-receptor network but with reduced amplitudes (approximately 60-70% as that of multi-receptor).

The circuit shows efficient learning ability that the consecutive neural clusters generate almost synchronized output spike patterns in the presence of delay in inputs signals, i.e. it takes shorter time for system with multiple-receptor to achieve synchrony. Analysis indicate that this ability originates from the NMDA receptor as NMDA receptor displays similar correlations except for a decrement in the amplitude of correlation level. AMPA and NMDA receptors have a collaborate relation in inducing efficient synchrony detection and amplification for synapse structures. A comparison between current works is present in Table II.

IV. CONCLUSION

In this paper, we propose a current-based neuromorphic synapse architecture for SNN, which incorporates the structures of the weight-dependent learning rule and multiple receptors, namely AMPA, NMDA and GABAa, and thus provides distinctive temporal dynamics of each type of receptors in one synapse design. Improved synchrony detection and amplification ability is demonstrated through cross-correlation study. The synaptic design implemented in TSMC 65 nm CMOS technology consumes 1.92, 3.36, 1.11 and 35.22 pJ per synaptic event for AMPA, NMDA, GABAa receptors and the advanced STDP learning circuit, respectively.

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