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Online Meta-neuron based Learning Algorithm for a spiking neural classifier

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ABSTRACT

This paper presents a new spiking neural network architecture with a meta-neuron which envelopes all the pre- and postsynaptic neurons in the network. The concept of the meta-neuron is inspired by the role of astrocytes in modulating synaptic plasticity in biological neural networks. The meta-neuron utilizes the global information stored in the network (synaptic weights) and the local information present in the input spike pattern to determine a weight sensitivity modulation factor for a given synapse. Based on the weight sensitivity modulation factor and the postsynaptic potential of a neuron, the meta-neuron based learning rule updates the synaptic weights in the network to produce precise shifts in the spike times of the postsynaptic neurons. Using this learning rule, an Online Meta-neuron based Learning Algorithm (OMLA) is presented for an evolving spiking neural classifier. The learning algorithm employs heuristic learning strategies for learning each input spike pattern. It can choose to add a neuron, update the network parameters or delete a spike pattern depending on the spike times of the output neurons. OMLA employs a meta-neuron with memory that stores only those spike patterns which are used to add a neuron to the network. These spike patterns (spike patterns in meta-neuron memory) are used as representative of past information stored in the network during subsequent neuron additions. The performance of OMLA has been compared with both the existing online learning and batch learning algorithms for spiking neural networks using the UCI machine learning benchmark data sets. The statistical comparison clearly indicates that the OMLA performs better than other existing online learning algorithms for spiking neural networks. Since, OMLA uses both, the global as well as the local information in the network, it is also able to perform better than other batch learning algorithms.

1. Introduction

The neural circuitry in the brain is continuously updated to adapt the response of the neurons to future events. This property of the brain is termed as plasticity. It is the primary reason behind the ability of the brain to exhibit a wide range of functionalities and also for its eternal learning capabilities. These qualities have motivated the developments in the field of Spiking Neural Networks (SNNs) that try to emulate, both the behavioral and structural properties of the brain (biological neural networks).

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SNNs are quite different from the earlier generations of artificial neural networks and as a result it is difficult to directly extend the existing neural network learning algorithms to SNNs. But, the ability of SNNs to mimic the feedforward sigmoidal neural networks [21] and their superior computational power in comparison to sigmoidal neurons [22] based networks have motivated researchers to develop new learning algorithms for SNNs. The mathematical models of spiking neural networks are closer to their biological counterparts, which encouraged researchers to look more deeply towards the learning phenomena observed in the brain.

Spike Timing Dependent Plasticity (STDP) [7,23] is one of the most studied learning phenomenon observed in biological neural systems. It uses the temporal differences between the pre- and postsynaptic spike times for adapting the weights. This implies that STDP considers only the information that is locally available to a neuron for adapting the weights of the incoming synapses. In the absence of any counterbalancing mechanism, a local learning rule like STDP would act as a positive feedback loop for potentiated synapses, thereby leading to their further potentiation. This can lead to the creation of regions in the brain, which contain highly active dendrites at the expense of the regions having inactive dendrites [16]. Hence, there is a need to develop a learning algorithm which can overcome this problem.

It is well-known that the synapses in our brain are capable of simultaneously exhibiting multiple forms of plasticity [6]. For example, it has been reported in the neuroscience area that astrocytes are star-shaped cells found in the brain that form an envelope around the synapses connecting the neurons in the brain. They can also make contacts with up to 100,000 synapses at a given time [5,17], thereby allowing them to intercept and process the information transmitted across these synapses [1,24]. This allows the astrocyte cells to utilize the global information in the network for modulating the sensitivities of multiple synapses simultaneously [29].

Inspired by the roles of astrocytes, in this paper, we develop a spiking neural network architecture with a newly defined concept of a meta-neuron. The meta-neuron envelops the pre- and the postsynaptic neurons. Also, there exists bidirectional communication between the meta-neuron and the enveloped synapses. Based on the global information contained in the network (synaptic weights) and the local information present in a synapse (presynaptic spikes), the meta-neuron modulates the sensitivities of all the synapses in the network. Each synapse changes its weight based on the weight sensitivity modulation factor generated by the meta-neuron and the required change in the postsynaptic potential such that the postsynaptic neuron spikes at the desired time. This is referred to as the meta-neuron based learning rule. It is a generic learning rule that updates the weights of the postsynaptic neurons in one-shot to produce precise shifts in their spike times.

Since the meta-neuron based learning rule can determine the appropriate adjustments in the synaptic weights of a postsynaptic neuron in one-shot, we propose an Online Meta-neuron based Learning Algorithm (OMLA) for pattern classification problems that evolves the spiking neural network architecture and simultaneously adapts its synaptic weights. The learning algorithm employs three heuristic strategies to evolve the network and update the network parameters; they are the ‘neuron addition strategy’, the ‘delete spike pattern strategy’ and the ‘parameter update strategy’. The appropriate learning strategy for a given spike pattern is selected based on the first spike generated by the output layer neurons. In case of neuron addition strategy, a new neuron is added to the network when the knowledge stored in the network is not sufficient to approximate the information present in the current input spike pattern. The weights of the newly added neuron are initialized to the normalized contributions of the corresponding input neurons for the current input spike pattern. Based on the initialized weights, the threshold of the new neuron is set as its postsynaptic potential at the target firing time. The spike patterns used by the learning algorithm to evolve the network (add a neuron) are also stored in meta-neuron memory. The learning algorithm uses these spike patterns as pseudo-inputs to efficiently capture the past knowledge while adding a neuron for a subsequent spike pattern. For the delete spike pattern strategy, the learning algorithm discards a spike pattern from the learning process when it is similar to the previously learned spike patterns. In the parameter update strategy, the synaptic weights are adapted using the meta-neuron based learning rule.

To illustrate the effect of the ‘delete spike pattern strategy’ and the meta-neuron memory on the performance of OMLA, a study is conducted using the Ionosphere problem from the UCI machine learning repository [20]. As highlighted in a previous work [32], the study showed that deleting similar spike patterns improves the generalization performance of the learning algorithm. The study also showed that the performance of the learning algorithm is significantly better when meta-neuron memory is used for approximating the past knowledge. The Ionosphere problem is also used to analyze the impact of its algorithm parameters on the performance of the learning algorithm. Based on this study, guidelines have been suggested for setting the algorithm parameters to appropriate values.

A detailed comparison on multiple benchmark problems has also been done between the performance of OMLA and other existing online learning algorithms for SNNs, namely, online spiking neural network [35] and the online version of Self-Regulating Evolving Spiking Neural (SRESN) classifier [8]. The performance of OMLA has been statistically compared with the performance of other online learning algorithms using one-way ANOVA [13] test followed by a pairwise comparison using the Bonferroni test [11,12]. The results of performance comparison indicate that OMLA performs better than the other online learning algorithms in a 95% confidence interval. For completeness, the performance of the OMLA is also compared with three well-known batch learning algorithms for SNNs, viz. SpikeProp [4] Synaptic Weight Association training (SWAT) [34] and the batch version of SRESN classifier. The performance of OMLA is better in comparison with batch learning algorithms as well as it utilizes both the local as well as global information in the network.

Rest of the paper is organized as follows. Section 2 provides a brief overview of the existing learning algorithms in the spiking neural network literature. Section 3 describes the newly introduced spiking neural network with a meta-neuron. Section 4 presents the online meta-neuron based learning algorithm. Section 5 describes the working of the learning al-