Selection and Optimization of Temporal Spike Encoding Methods for Spiking Neural Networks

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***Abstract*—Spiking neural networks (SNNs) receive trains of spiking events as inputs. In order to design efficient SNN systems, real-valued signals must be optimally encoded into spike trains so that the task-relevant information is retained. This paper provides a systematic quantitative and qualitative analysis and guidelines for optimal temporal encoding. It proposes a methodology of a three-step encoding workflow: method selection by signal characteristics, parameter optimization by error metrics between original and reconstructed signals, and validation by comparison of the original signal and the encoded spike train. Four encoding methods are analyzed: one stimulus estimation [Ben's Spiker algorithm (BSA)] and three temporal contrast [threshold-based, step-forward (SW), and moving-window (MW)] encodings. A short theoretical analysis is provided, and the extended quantitative analysis is carried out applying four types of test signals: step-wise signal, smooth (sinusoid) signal with added noise, trended smooth signal, and event-like smooth signal. Various time-domain and frequency spectrum properties are explored, and a comparison is provided. BSA, the only method providing unipolar spikes, was shown to be ineffective for step-wise signals, but it can follow smoothly changing signals if filter coefficients are scaled appropriately. Producing bipolar (positive and negative) spike trains, SW encoding was most effective for all types of signals as it proved to be robust and easy to optimize. Signal-to-noise ratio (SNR) can be recommended as the error metric for parameter optimization. Currently, only a visual check is available for final validation.**

***Index Terms*—Signal processing, spike encoding, spiking neural networks (SNNs), stimulus estimation, temporal contrast.**

I. Introduction

In a spiking neural network (SNN), information travels between the processing units in the form of binary spiking events. SNN systems are thus inspired by the information processing solutions of the biological brain. Real world measurements provide analog (continuous or discrete) real-value temporal signals; therefore, it is necessary to implement an encoding method to convert the analog values to spike events to provide input to such systems. This analog-to-spike encoding can compress the data size of the signal considerably [1] since the spike train is a binary value series. In turn, this binary signal provides fast processing, especially using purpose-built hardware, e.g., SpiNNaker [2]. Ultimately, a correct spike encoding could lead to better information preservation along with input data reduction and compression [1], [3]–[6].

It is extremely important to generate the spike train input to the SNN such that the task-relevant information content of the signal is preserved. The issues here are what information is lost and what is preserved and thus how effective was the encoding. One approach is not to evaluate the effectiveness of the encoding separately but for the whole SNN application, e.g., the chosen encoding is deemed effective if the output of the whole SNN system yields good results, such as good classification accuracy [1]. Another approach is to try and optimize the encoding step by itself. However, the comparison of original and encoded signals is nontrivial: how to compare a binary event series with a continuous signal or calculate some error metric of the differences? At best, one can apply the corresponding decoding algorithm and compare the reconstructed signal with the original.

Each encoding method has a different way of extracting information from the input signal. Selecting the specific encoding method depends on signal characteristics, such as the presence of relevant information in the time or frequency domain, the presence of noise in the data, can the data be shifted or scaled. It is also necessary to understand how the encoding changes the signal characteristics, e.g., does it cut into the frequency spectrum, and can it suppress noise. Furthermore, the type of SNN to be utilized also has to be considered, i.e., what type of input it can accept. After choosing the encoding algorithm, the optimization of the encoding parameters also has to be done to ensure that meaningful spike trains are generated and consequentially, and this meaningfulness needs to be validated. This paper provides a quantitative and qualitative analysis into different temporal spike encoding methods and aims at providing guidelines to the process of selecting and optimizing the spike encoding method. The analysis covers both time and frequency domains as well.

A. Overview of Temporal Spike Encoding Methods

Spike encoding can be based on firing rate [instantaneous average firing rate (AFR)] [7], population rank coding (relative firing time of a population of neurons) [8], or temporal coding (exact timing of individual spikes) [9]. Firing rate encoding resembles biological systems in that cortical electric activity

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typically has an oscillatory nature. In population rank coding, neurons each have corresponding receptive fields, and they fire in the order of to what extent an input value belongs to their respective receptive field. Temporal encoding methods utilize the exact timing of each spike which marks a change in the signal value. It is thought that biological neurons apply spike timing as information encoding [3]–[6], [10]. At the same time, temporal encoding is well suited for streaming data encoding and fast processing such as magneto/electroencephalography and electrocardiogram. In this paper, only temporal spike encoding methods are further considered.

As a brief overview, existing temporal encoding methods belong to two groups that take two distinct approaches: temporal contrast [3]–[6], [11] and stimulus estimation [12]. Temporal contrast algorithms track the temporal changes in the signal, and the exact timing of spikes represents these changes, similar to the artificial retina [3], [11]. In principle, the next consecutive signal value is compared to an interval and if the value is outside of the interval, a positive or negative spike is generated accordingly. Temporal contrast encoding was first developed as a hardware implementation to allow for the fast visual information processing and was inspired by the human retina [3]. Temporal contrast methods implemented in the NeuCube SNN framework [13] are threshold-based representation (TBR), step-forward (SF) encoding, and moving-window (MW) encoding. These three methods are analyzed in this paper. Another such encoding method that resembles momentum-like algorithms has been presented recently in [14]; however, the corresponding decoding algorithm has not been demonstrated yet. Temporal contrast algorithms produce a bipolar spike sequence (positive and negative spikes, plus zero).

Stimulus estimation encoding is inspired by the response function of the biological neuron and employs a linear filter to find a unipolar (only positive one and zero) spike train that represents the signal [15]. An analog signal can be constructed from a spike train by convolution with a finite-impulse response (FIR) filter, an idea called spike interval information coding. The analog-to-spike encoding is, therefore, an inverse problem, finding the spike train that when reconstructed to analog values gives a close approximation of the original signal. This inverse process is a "deconvolution" by the same filter; a prominent early implementation of which is the Hough Spiker algorithm (HSA) [15]. To overcome some of the disadvantages of HSA, a modified HSA (mHSA) algorithm had been implemented in the CAM-Brain Machine as presented in [12]. A further improved solution of the inverse problem was implemented as Ben's Spiker algorithm (BSA) [12]. BSA calculates two error terms that would result from emitting or not emitting a spike at a time point and makes the decision to spike comparing these errors to a threshold. Of these algorithms, this paper considers only BSA, since it was already shown to perform better than HSA and mHSA [12] and BSA encoding had been implemented in SNNs and successfully applied to EEG data [16], [17]. Stimulus estimation encoding produces a unipolar spike sequence (positive spikes and zero).

Temporal contrast and stimulus estimation encoding differ not only in their mechanisms but also in the polarity of the spike sequence produced (bipolar and unipolar, respectively). Unipolar SNN architectures support only unipolar spike sequences, i.e., the presence or the absence of a firing event at a time point which is transmitted through an excitatory (positive) or inhibitory (negative) connection. Bipolar SNN architectures can support bipolar spike sequences, i.e., positive spikes, negative spikes, and no firing [13]. For example, this can be implemented as changing the state (membrane potential) of the input neuron(s) according to the spike sign. Another approach is that the positive spikes are fed to one input neuron while the negative spikes are fed to another and these neurons are then connected to the rest of the network through positive or negative connections.

B. Related Works on Temporal Spike Encoding Optimization

General studies on SNNs start with the assumption that the encoded spike train is already available as the input to the system. Little has been published on the specific effects of encoding methods on the spike train information content and the reconstructed signal, or in fact on the rationale behind the selection of a particular encoding algorithm. In many cases of application-related studies, the efforts to optimize the encoding are tied to the performance of the whole SNN. For example, the parameters for the chosen encoding method were included in the grid search performed on all other SNN parameters and were evaluated based on the total system performance, e.g., classification accuracy [18]. In this way, the extracted information content was determined by the machine learning process itself without the influence of expert knowledge on the data generation process.

Few are the studies that considered optimizing the encoding step separately. In the seminal paper that introduced BSA [12], the applied FIR filter was a "cleaned-up," normalized, quantized version of a filter that was found through genetic search algorithms in [19]. The threshold was then optimized for the signal-to-noise ratio (SNR) between the original signal and the noise (i.e., the encoding error between original and reconstructed signals). In [20], BSA was applied to normalized EEG signals; filter design parameters were sought by trial and error, while the applied threshold was found through minimizing the normalized absolute error between original and reconstructed signals. As validation, the signals were compared visually.

Another framework for spiking data encoding related to stimulus estimation was formulated in [21] which aims at maximizing information content while minimizing spike density, i.e., AFR to achieve better data compression. The idea is that if existing knowledge is available about how the data was generated in the examined system, this should be taken into account (via "knowledge injection") when the optimal encoding method is sought. For stimulus response encoding, the applied convolution function is created based on a model of the signal generation [21]. For example, in fMRI data encoding, a hemodynamic response function can be used to biologically model how neural activity generates fMRI signals [1]. This response function can be modeled as a gamma function that can be employed for stimulus estimation

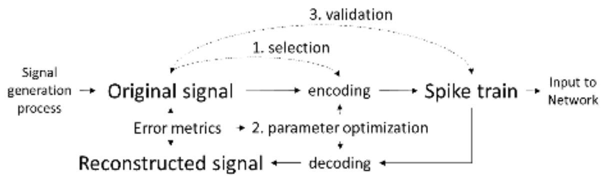

Fig. 1. Proposed encoding workflow.

encoding and the filter itself is learned from the data through genetic algorithms (GAGamma). Parameters are optimized simultaneously while imposing practical limits on them and on spike density as well; the optimization was evaluated based on the root-mean-square error (RMSE) between the signals [21]. As the literature above show, the SNN community has not settled on any encoding method selection and optimization methodology with regards to temporal data.

The rest of this paper is organized as follows. Section II introduces the proposed encoding methodology, and Section III introduces the encoding methods (note the algorithms in the Appendix) that are employed in this investigation. Section IV details the investigative methods, and Section V presents the results and offers discussions. Finally, Section VI offers concluding remarks.

II. Proposed Encoding Methodology and Aim of Study

This paper sets out to provide an analytical background for encoding method selection and optimization in and of itself, utilizing a signal reconstruction approach as generated by the corresponding decoding algorithm. Comparing the original and reconstructed signals can employ different error metrics, based on which the encoding parameter(s) can be tuned. A comparison in time or frequency domain can verify to what extent the encoding method preserved the information in the original signal. This is important for classification tasks where we may have prior knowledge about the nature of useful information in the signal, e.g., task-specific response signals or a frequency band of interest. For prediction tasks, decoding the spike train to real-value signals is crucial in interpreting the output of the SNN.

Based on these remarks, a three-step encoding workflow is proposed (Fig. 1). First, the encoding method is selected based on signal characteristics. Second, the encoding parameters are optimized based on error metrics between reconstructed and original signals (verification in the time domain). Third, the encoding is validated by comparing the spike train to the original signal in the time/frequency domain.

The aim of this paper is to provide guidelines for these three steps, i.e., selection, optimization, and validation of encoding methods. This warrants an investigation utilizing well-defined and characteristic test signals as inputs to the encoding algorithms in question. Specific properties and the possible optimization of the encoding methods are explored on test signals, and the implications are discussed. An overview is provided to aid in the selection of method according to the signal characteristics.

III. Encoding and Decoding Algorithms Investigated in This Research

The following encoding and corresponding decoding algorithms are studied here for the selection and optimization of a suitable spike encoding method and its optimized parameters for a given task: TBR, SF, MW, and BSA. The algorithms are described in the following, and pseudocodes are also presented in the Appendix.

A. Threshold-Based Representation

The simplest implementation of temporal contrast encoding, TBR [3], [22], is based on tracking temporal changes in the signal as demonstrated in the artificial retina [3], [11]. The absolute value change between consecutive signal values is compared to a threshold; if large enough, a positive/negative spike is emitted (based on the sign of change). To calculate this threshold, the whole sample length is taken into account. The first derivative is calculated; then, the standard deviation of this derivative is multiplied by a factor to obtain the encoding threshold (see Algorithm 1 in the Appendix). The only parameter of this encoding is this factor which is independent of the signal amplitude but is determined by the signal characteristics. Decoding of the signal is straightforward: the reconstructed signal is given by a summation of positive and negative spikes multiplied by the encoding threshold (see Algorithm 5 in the Appendix). The initial reconstruction value should match the initial signal value.

B. Step-Forward Encoding

The SF encoding [13] utilizes an interval around a moving baseline with a set threshold (see Algorithm 2 in the Appendix). The initial baseline equals the initial signal value. If the next signal value is above/below baseline $\pm$ threshold value, a positive/negative spike is registered and the baseline is moved to the upper/lower limit of the threshold interval. The set threshold is signal amplitude dependent and is the only parameter of this encoding. The decoding process is essentially the reconstruction of this moving baseline, similar to TBR (see Algorithm 5 in the Appendix).

C. Moving Window

The MW encoding [13] uses a moving baseline with a set threshold value, where the baseline always equals the mean of the preceding signal values in a time window (see Algorithm 3 in the Appendix). Thus, the moving baseline is essentially the application of a moving average filter. If the signal value is above/below baseline $\pm$ threshold value, a positive/negative spike is registered. MW thus has two parameters: the threshold and the window size. Decoding is essentially the same as for TBR or SF (see Algorithm 5 in the Appendix). At this point, an additional moving average filter could be applied to make the reconstructed signal smoother, in which case the encoding–decoding corresponds to a two-pass (twice applied) moving average filter.

D. Ben's Spiker Algorithm

An analog signal can be constructed from a spike train by convolution with an FIR filter. BSA is an algorithm for producing the spike train from which the original signal can be reconstructed well [12] (see Algorithm 4 in the Appendix). BSA works only for positive-valued signals. First, an FIR filter is created. Then, two error terms are calculated at each time point: one that results from subtracting the filter coefficients from the subsequent signal values, and one that results from not changing the signal (no subtraction). If the subtraction error is smaller than the unchanged signal error term minus a threshold, a positive spike is generated and the filter coefficients are subtracted from the signal. Decoding is straightforward since it was kept in mind during the encoding: a convolution of the spike train with the filter coefficients gives the reconstructed signal (see Algorithm 6 in the Appendix). BSA encoding results in a unipolar (only positive) spike train.

The original BSA encoding requires input with [0, 1] limits. However, BSA can be applied to any positive-valued signal if the filter coefficients are scaled up such that they appropriately match the signal boundaries. Therefore, a simple signal shift above zero is sufficient. The recommended scaling of coefficients is discussed in Section V. (part E/2).

IV. Methods of Investigation

A. Test Signals Used for Quantitative Analysis

A number of signal types were considered as test signals, such as purely step-wise signals, smooth (sinusoidal) signals, signals with trends, and event-like signals. These signal types can model a wide variety of important behaviors such as sudden or smooth changes, slopes and plateaus, trend effects, different amplitude events, and important frequency spectra. The rationale behind using sinusoidal signals is that from a modeling standpoint, measured EEG signals are comprised a mixture of sinusoidal waves plus multisource Gaussian noise [23]. The signal parameters were randomly generated, and to analyze noise effects, random white noise was added.

The following test signals were constructed with the length of 1000 samples to test the properties of encoding methods:

1) step-wise signal with increasing step size without noise [Fig. 2(a)];
2) smooth signal with sine components continuously ranging from 2 to 20 Hz with random power, combined with random phase lags plus white noise [Fig. 2(b)];
3) trended signal, the same smooth signal as before multiplied by an exponential saturation trend plus white noise [Fig. 2(c)];
4) event-like signal, resembling EEG signals during perturbation-evoked potential events [24] plus white noise [Fig. 2(d)].

B. Properties to Investigate

In order for the analysis to allow a comparison between the encoding methods, the following behaviors/properties were investigated for each encoding method (where applicable):

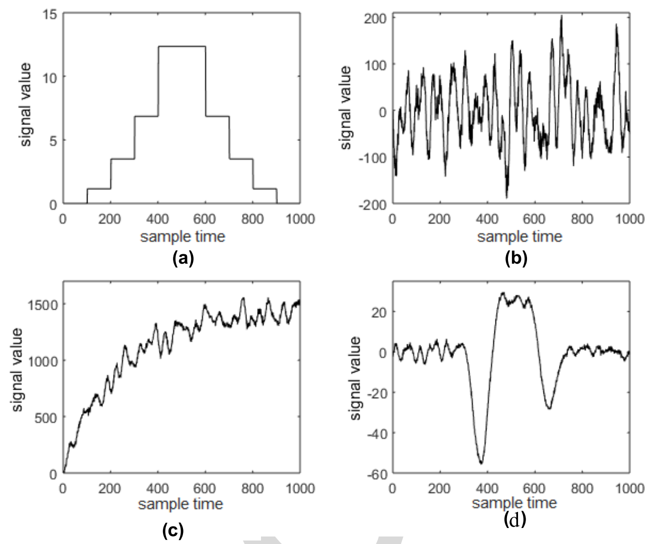

Fig. 2. Test signals used for analysis. (a) Step-wise signal. (b) Smooth signal. (c) Trended smooth signal. (d) Event-like signal.

1) ability to follow various test signals, and offset and scaling error in time domain (qualitatively and quantitatively);
2) false encoding at start and/or end of signal;
3) frequency characteristics such as noise suppression, artifacts, white noise, and spink noise introduced during signal reconstruction;
4) parameter dependencies;
5) optimization curves, robustness, and methods.

It is important to note that both time and frequency domain effects were included in the analysis because in many applications although the signal is in the time domain, the important information is in the frequency spectrum, even if it is not the spectrum that is to be encoded per se.

C. Error and Indicator Metrics

The optimization criterion considered here is the accurate recovery of the signal; minimizing the difference between original and reconstructed signals serves as the objective function. There are multiple candidate error metrics since there is no consensus on which one to use. In this paper, the following optimization criteria were used:

1) SNR;
2) RMSE;
3) coefficient of regression (R-squared).

SNR is defined here as the signal-to-noise ratio where the difference between the original (s) and reconstructed (r) signal is considered as "noise" [12]. SNR is to be maximized and is calculated as

$$\mathrm{SNR} = 20 \cdot \log \frac{\mathrm{Power}(s)}{\mathrm{Power(s\text{-}r)}} [\mathrm{dB}]. \tag{1}$$

A negative SNR means that the error introduced through the encoding is more substantial than the information content itself; SNR of 0 dB means equality between the two.

RMSE is to be minimized and is defined classically as

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{N}(r_t - s_t)^2}{N}} \tag{2}$$

where s is the original and r is the reconstructed signal and gives a summation of the modeling errors.

The R-squared, although classically used for measuring regression fit, in a broader sense is a measure of modeling fit in general and it is employed here in this capacity. The R-squared gives a relation between the variance unexplained by the modeling ($\mathrm{SS_{res}}$) and the variance of the original input ($\mathrm{SS_{tot}}$) data

$$R^2 = 1\frac{\mathrm{SS_{res}}}{\mathrm{SS_{tot}}} \tag{3}$$

$$\mathrm{SS_{res}} = \sum\nolimits_{t=1}^{N}(r_t - s_t)^2 \tag{4}$$

$$\mathrm{SS_{tot}} = \sum\nolimits_{t=1}^{N}(s_t - \bar{s_t})^2. \tag{5}$$

R-squared is to be maximized. Note that in this case, R-squared can assume negative values as well; a negative R-squared means that the fit is worse than substituting the mean of the signal (in which case R-squared equals 0).

As an indicator metric, AFR shows how saturated the spike train is and is calculated as the quotient of all spikes (sp) in a given spike train and the number of total time points

$$\mathrm{AFR} = \frac{\sum_{t}^{N}|sp_t|}{N}. \tag{6}$$

V. Quantitative, Qualitative, and Comparative Analysis of Different Encoding Methods and Optimization of Their Parameters

A. Numerical Performance of Encoding Methods

To present numerical performance for future reference, best error metric values that could be achieved by the optimization of each encoding method are presented in Table I for the test signals. In the following sections, results from the individual encoding methods are analyzed.

B. Threshold-Based Representation Encoding

TBR registers large enough signal changes only; thus, it is expected that small, gradual changes are not represented. In addition, tracking only signal change causes that sudden, step-wise changes will be poorly represented (Table I) since the step size of the reconstruction is uniform as it equals the threshold. Dynamics of smoothly changing signals are followed (Table I); however, the uniform steps introduce a scaling error which is prominent in the case of trended signals [Fig. 3(a)]. For small and large amplitude events, the selected encoding threshold determines the captured event type [Fig. 3(b)]; there is clearly a tradeoff between representing small and large events. Since the whole sample length is considered for threshold value calculation, this encoding can be disadvantageous for long samples where there may be amplitude differences between events of different parts of the sample. As an advantage, there are no falsely registered values at the start or end of neither the spike train nor the reconstructed signal.

TABLE I

Numerical Performance Evaluation of the Studied Encoding Methods With Optimized Parameters for the Test Signals

signal	metric	TBR	SF	MW	BSA
step-wise	SNR	7.77	21.79	**22.57**	11.09
	RMSE	2.67	0.53	0.49	1.82
	R-sq.	0.64	0.99	0.99	0.83
smooth	SNR	2.74	**13.47**	0.03	10.23
	RMSE	49.89	14.55	68.40	61.42
	R-sq.	0.47	0.96	0.01	0.20
trended smooth	SNR	9.64	**38.22**	27.40	12.40
	RMSE	368.61	14.94	50.00	281.19
	R-sq.	-0.14	1.00	0.98	0.40
event-like	SNR	5.88	**26.24**	9.43	10.44
	RMSE	8.66	0.83	5.75	17.31
	R-sq.	0.74	1.00	0.89	-0.03

TBR reduces white noise to a certain extent by applying the threshold to small perturbations in the signal. At the same time, it is sensitive to the presence of strong white noise in the signal, since the spurious signal changes due to white noise cover the more gradual changes. As observed, the presence of white noise causes TBR to introduce strong $1/f$ noise ("pink noise") during reconstruction; strong low-frequency artifact components appear. For longer signals, this may cause the reconstructed signal to drift away. Parameter optimization is not straightforward for TBR because typically, multiple minima and wider plateaus can be observed due to different amplitude events, even in the case of a continuous, not event-specific signal (Fig. 4). Selecting a certain threshold results in an encoding that better represents events having amplitudes that correspond with the threshold. As observed, all three metrics give similar optimization curves (remember that SNR and R-squared are to be maximized) (Fig. 4).

In summary, TBR encoding had been developed to quickly process streaming, online data; the computation is simple and fast. In contrast, the threshold parameter determines the amplitude of the events that are represented correctly by the spike sequence. Therefore, it is encouraged that for each application, the possible events that can appear in the signal are considered and the threshold is chosen such that the relevant events are captured. This knowledge should guide the parameter optimization since multiple peaks can usually be observed, e.g., selecting a higher threshold if higher peaks are of interest in the given application.

C. Step-Forward Encoding

For SF encoding, even though the reconstructed signal is step-wise, it follows most types of continuous signals exceptionally well (Table I) both in time and frequency domains since multiple steps are allowed to account for a single change in the original signal. Step-wise, smooth [Fig. 5(a)], and trended signals [Fig. 5(b)] are all followed well (Table I).

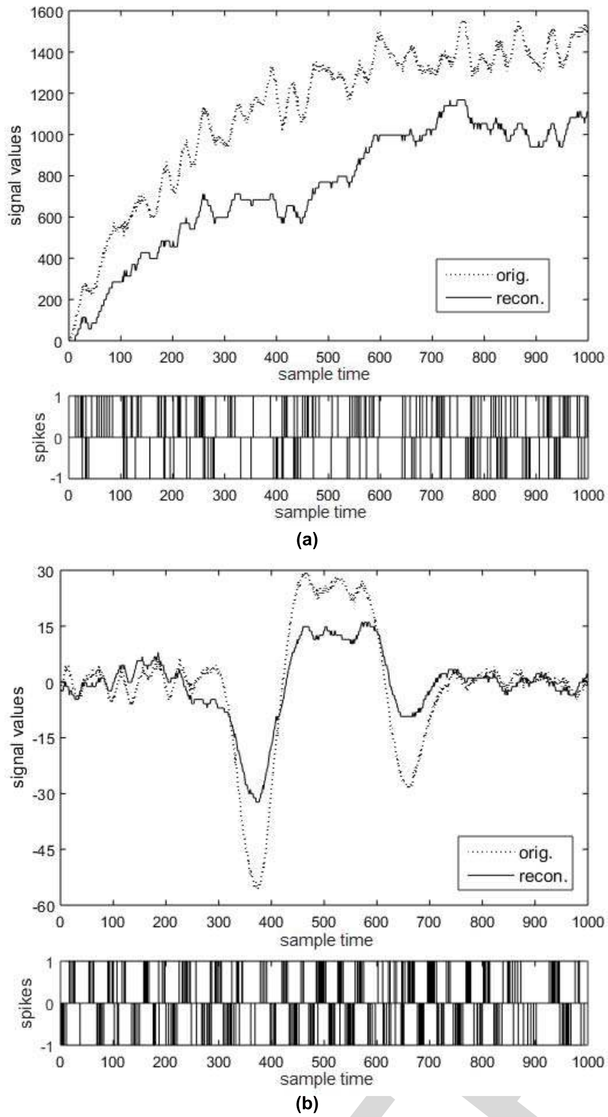

Fig. 3. (a) Scaling error of a trended signal with TBR encoding. (b) TBR-generated spikes show that TBR cannot represent different amplitude events well simultaneously.

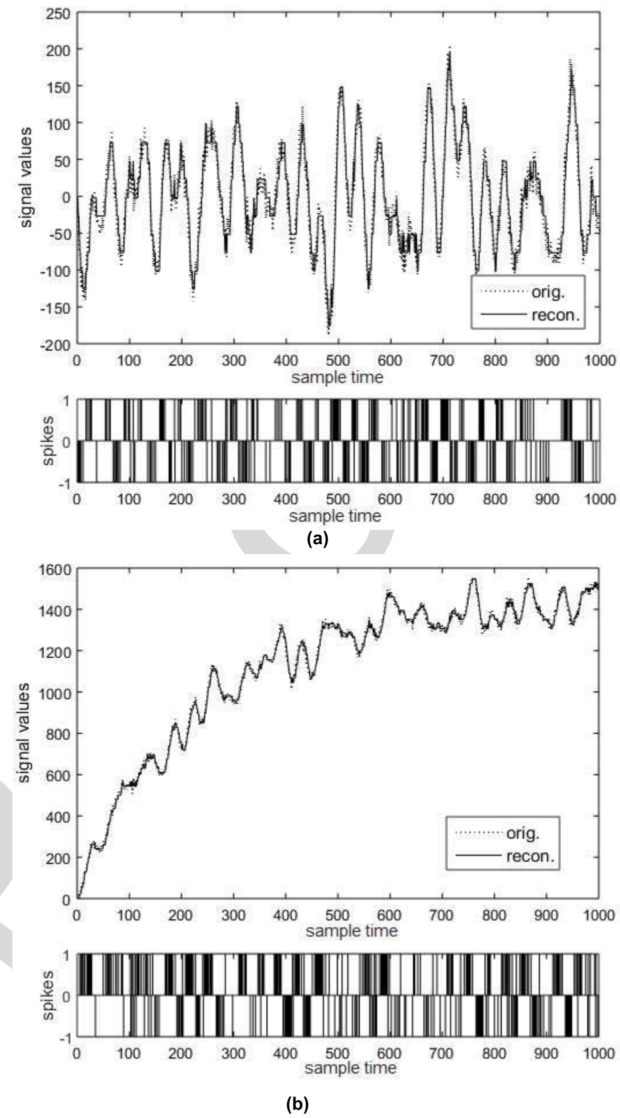

Fig. 5. (a) Smooth signal is followed well by using SF encoding. (b) Spike sequence generated by SF represents a trended signal well.

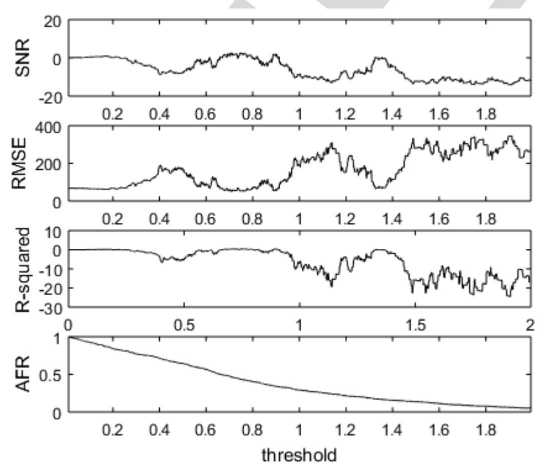

Fig. 4. Threshold optimization curves for TBR (smooth signal).

The threshold can be chosen such that small and large amplitude events are both well represented. Similar to TBR, SF encoding represents only signal changes and thus offset error is expected to be present in the reconstructed signal unless the initial values are matched. Noise in the signal is minimally reduced by the threshold.

SF encoding reconstructs the frequency spectrum as is; in addition, it introduces no artifact frequency components and only minimal noise that is related to quantization. For noisy input signals, the noise is minimally reduced but mostly encoded; however, this does not lead to $1/f$ noise as was the case with TBR, which is favorable.

Due to the moving baseline, the reconstructed signal does not drift away even for longer signals. Overshoot does not occur with SF since the moving baseline is adjusted only by the threshold value; thus, the change is equal or less than the signal change. The optimization curves match for all three metrics and show a wide, high fit plateau (Fig. 6). The wide plateau means that the threshold can be increased, and thus spike density can be lowered without a significant loss of encoding accuracy, which can be favorable in certain

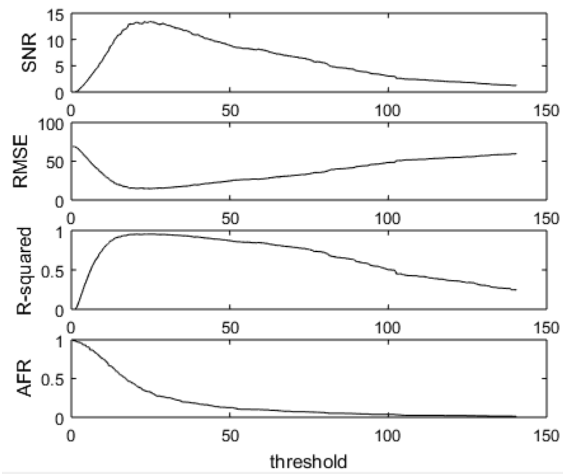

Fig. 6. Threshold optimization curves for SF with a high good fit plateau (smooth signal with noise).

applications or cases. Furthermore, a lower AFR further enhances data compression and helps to prevent the saturation of SNN. Lowering the AFR also improves noise suppression but magnifies the quantization noise, especially in the lower frequency ranges.

In summary, SF encoding performed well for all types of test signals (Table I), both in time and frequency domains with straightforward and robust optimization. SF encoding can thus be recommended for any applications, especially when there is little information on the nature of the original signal.

D. Moving-Window Encoding

1) Theoretical Considerations of MW Encoding: The MW encoding was suggested to be robust against noise [13]. The signal values are compared to a moving average, which acts as a moving average filter. Moving average is an optimal smoothing filter in the time domain against white noise, while a poor low-pass filter in the frequency domain [25]. The frequency response function of moving average filters of windows size M is the sinc function

$$H(f) = \frac{\sin(\pi f M)}{M \sin(\pi f)}. \tag{7}$$

The window size influences the cutoff frequency, the slope of the frequency response, and the noise reduction. The cutoff frequency at -3 dB is approximately given by

$$f_{\mathrm{co}} = 0.8859 \cdot \sqrt{(M^2 - 1)} \left[\frac{\pi \cdot \mathrm{rad}}{\mathrm{sample}}\right]. \tag{8}$$

The noise suppression is proportional (equal in amplitude) to the square root of the window size. This means a tradeoff between noise reduction and the spectrum width retained during the encoding. Another implication is that the MW encoding in principle could be used to filter out a strong, artifact frequency component, e.g., power line noise in EEG signals. However, as it was pointed out, the band-stop characteristics of this filter are disadvantageous as the attenuation is rather shallow. Thus, it is recommended to apply a separate digital band-stop filter to remove line noise before encoding the signal altogether. An important point is that the signal beginning is not encoded well until the window size is reached. This can be managed with a slight modification of the algorithm: for the first M points, the baseline can be set to the mean of these M points.

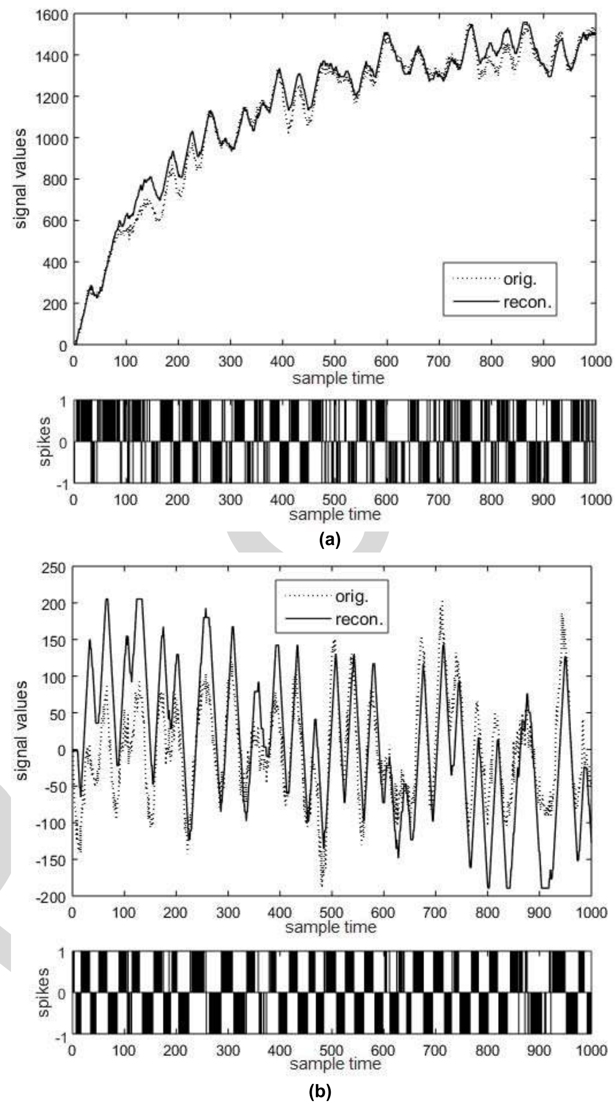

Fig. 7. (a) MW encoding follows a trended, smooth signal well. (b) Noise and sharp peaks are reduced using MW encoding.

2) Quantitative Results of MW Encoding: Similar to SF, MW follows sharp steps well (Table I). Trended [Fig. 7(a)], smooth [Fig. 7(b)], and event-like signals are represented well (Table I), but overshoot-type errors often appear. Interestingly, error metrics indicate a poor match for the smooth signal despite that visually, the signal dynamics appear to be well captured.

As stated before, MW encoding reduces white noise. However, the $1/f$ (pink) noise also appears during signal reconstruction, the amount of which appears to be proportional to the suppressed components in the spectrum above cutoff frequency. For longer signals, this may cause the reconstructed signal to drift away.

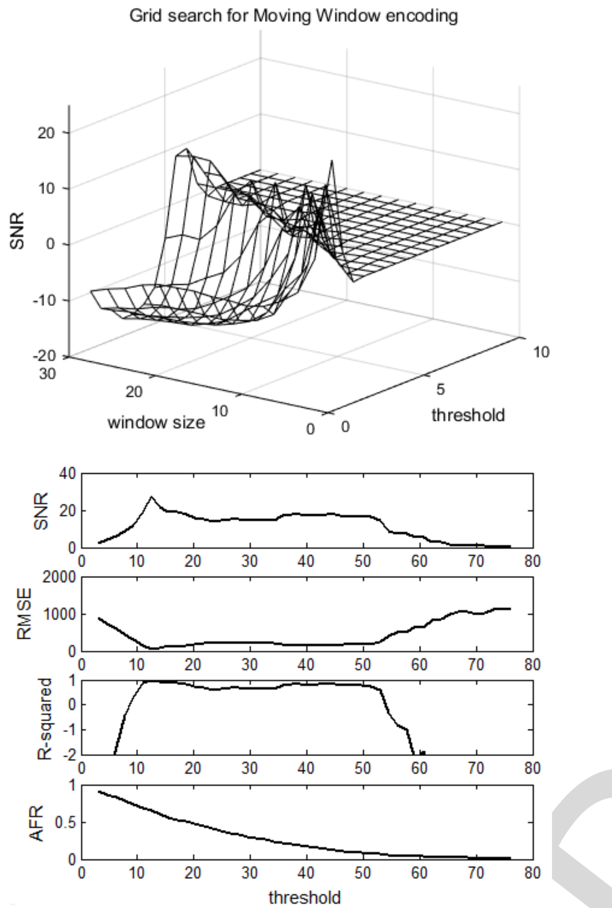

Fig. 8. Grid search for MW parameters and optimization curves (noisy trended smooth signal).

MW encoding has two parameters: window size and threshold. The window size affects the encoded spectrum width and noise suppression and thus should be chosen first. Then, the threshold can be optimized according to any of the error metrics (Fig. 8). SNR is favorable here since negative values clearly indicate prohibited areas. However, at a low threshold (close to continuous firing), the peak SNR can lead to a false threshold selection.

In sum, MW encoding was conceived to provide the robustness against noise by what is essentially a moving average filter. However, this noise suppression can only increase with the window size which in turn lowers the cutoff frequency. This may not be permissible in some applications, e.g., for EEG data that is not sufficiently oversampled. In such cases, it is recommended to use a separate digital filter as a preprocessing step instead and applying a spike encoding other than MW.

E. Ben's Spiker Algorithm Encoding

1) Theoretical Considerations of BSA Encoding: In the original BSA implementation, the error threshold is an exact value and is subtracted [12]. However, this can effectively be replaced by a multiplication with a factor smaller than one. This method was implemented for this investigation. Such a threshold value is scale invariant; thus, the encoding becomes more robust. For BSA, scaling of the filter coefficients provides a reconstruction boundary: the maximum value that can be reached (by constant firing) is the sum of coefficients, while the minimum value equals 0 (if all coefficients are nonnegative) or a small negative value.

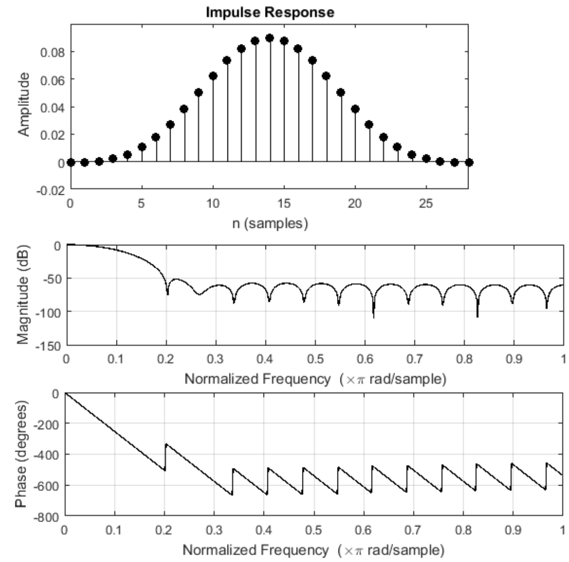

Fig. 9. Exemplar filter coefficients and frequency response.

Filter design is based on at least two parameters, e.g., a low-pass filter with cutoff frequency (f_{co}) and filter size (Fig. 9). Design of the filter is crucial since the signal components that can be represented are determined by the applied filter [12]. If a low-pass filter was used with cutoff frequency $f_{\text{co}} = 0.05$, the SNR of the reconstructed signal will sharply fall to 0 dB above this frequency. This means that the cutoff frequency is to be chosen based on the task-relevant frequency spectrum. The number of coefficients gives the width of the filter and determines the sharpness of the frequency response function. With regards to scaling, it should be sufficient in principle that the coefficients are scaled such that the reconstruction boundary equals the signal boundary. However, this limits the dynamic characteristics which the reconstructed signal can take. During the implementation steps of this investigation, several values were experimented with. It was found that if the sum of coefficients (the upper boundary of the reconstructed signal) is scaled up to twice the original signal upper boundary, the spike train is less saturated and the encoding is more flexible.

2) Quantitative Results for BSA Encoding: For BSA, the deconvolution algorithm works only for positive-valued signals [12]; thus, the signals need to be shifted to the positive range. BSA encoding favors a continuously changing signal; these are represented (e.g., smooth signal, Fig. 10) and reconstructed well (Table I), even with trends in the signal. At the same time, BSA has a weakness for plateaus since firing with a constant rate is required to represent a nonzero constant value; without spikes, the reconstructed signal does not hold but quickly returns to 0. This weakness for constant values can lead to critical, conceptual failures for sharp step

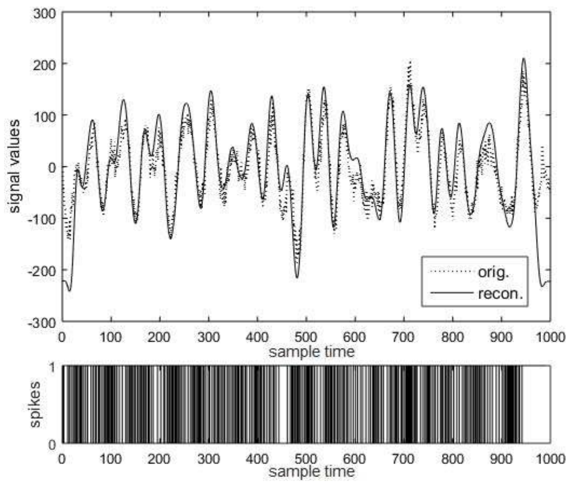

Fig. 10. Reconstruction of a smooth signal with well-scaled BSA filter coefficients with the corresponding spike sequence.

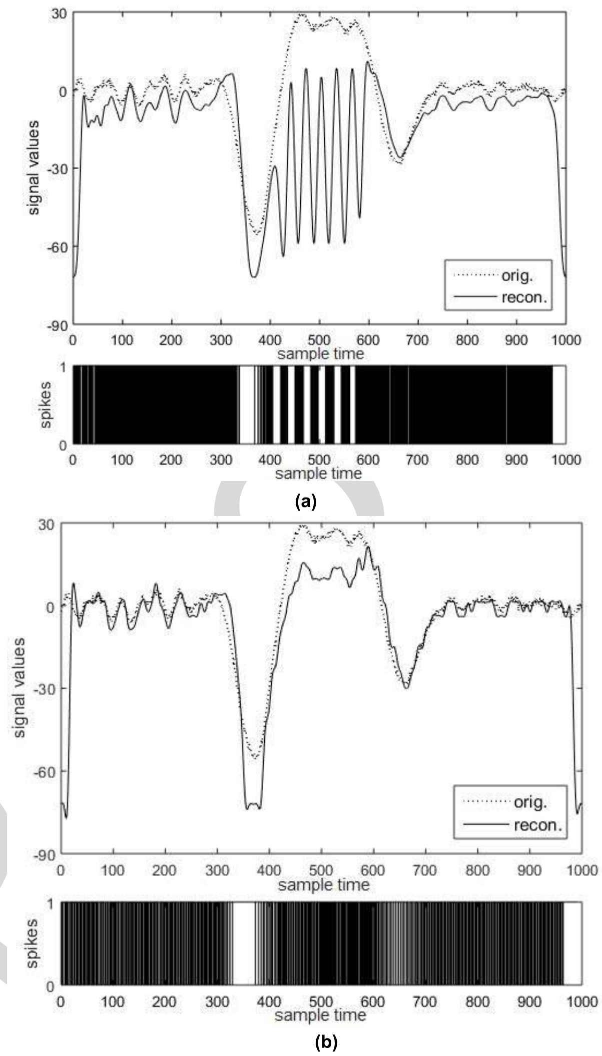

Fig. 11. (a) Error at high plateaus with poorly scaled coefficients of BSA encoding. (b) High plateau error disappears with well-scaled coefficients.

signals and signals with plateaus in general. Higher plateaus (in the upper half of the signal range) can be particularly problematic, especially if the filter coefficients are not scaled up appropriately [Fig. 11(a)]. Here, this effect is demonstrated through scaling the coefficients such that their sum equals the maximum amplitude of the signal ("poorly scaled" case) and to equal twice the maximum ("well-scaled" case). In addition, BSA in general tends to show offset and scaling error in the reconstructed signal, depending on the optimization.

Another implication is that there are false spikes and false reconstructed values at the start of the signal since the value has to catch up from 0. This means that the data should be shifted to have a minimum of 0 to improve the BSA encoding. The end of the signal is also falsely encoded due to the convolution; the number of erroneous points corresponds to the filter size. Depending on the sample length, substantial loss of information may occur here.

In the frequency domain, the spectrum (Fig. 12) is changed similarly as if the FIR filter were applied to the original signal: frequencies above the cutoff point are suppressed (see Fig. 9). In effect, the encoding performs filtering at the same time. However, some artifact components with low frequencies can appear, especially if the filter size is large.

The first step of parameter selection and optimization for BSA is the filter design which is aimed at retaining the task-relevant frequency spectrum. It is suggested that cutoff frequency and filter size are selected jointly since these determine the frequency response together. A grid search or other optimization can be performed to determine the highest encoding fit for possible cutoff size (Fig. 12). SNR is recommended as the error metric of the search since negative values indicate forbidden areas. Other optimization, e.g., genetic or differential evolving algorithms, could also be applied. As an initial guess, cutoff could be selected at twice the highest important frequency with a filter size of 20–24. It can be observed that the solution across the search space is not smooth (Fig. 12) as there are multiple local peaks. The resulting filter coefficients and especially the cutoff frequency must be cross-checked against the signal's relevant frequency spectrum. With increased size, the filtering is sharper; a limitation on the filter size is the false encoding and decoding at the start and end of the signal due to the convolution. For the optimal error threshold parameter corresponding to a set filter, all error metrics give the same results (Fig. 13). For many signals, a (multiplicative) threshold in the range of 0.94–0.98 provides a good solution.

In sum, BSA encoding is the only one of the four encodings analyzed here that produces a unipolar (only positive) spike train and thus may be the only option for some SNN architectures. BSA produces major errors for suddenly changing, step-like signals and also has problems with plateaus, especially in the higher value ranges. The filter design and optimization are also nontrivial. Using a multiplicative error threshold provides a robust solution, but the effects of this algorithmic modification need further analysis. The false encoding start and end are also of concern; padding the signal with constant values might address this issue to a certain extent.

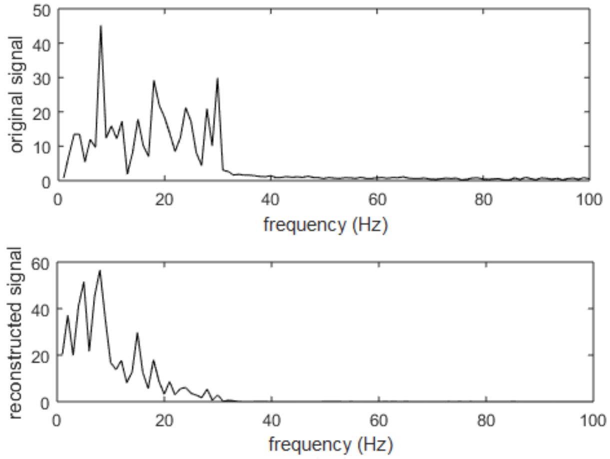

Fig. 12. Frequency spectrum effects of BSA encoding: single-sided amplitude spectrum is filtered in effect and pink noise appears.

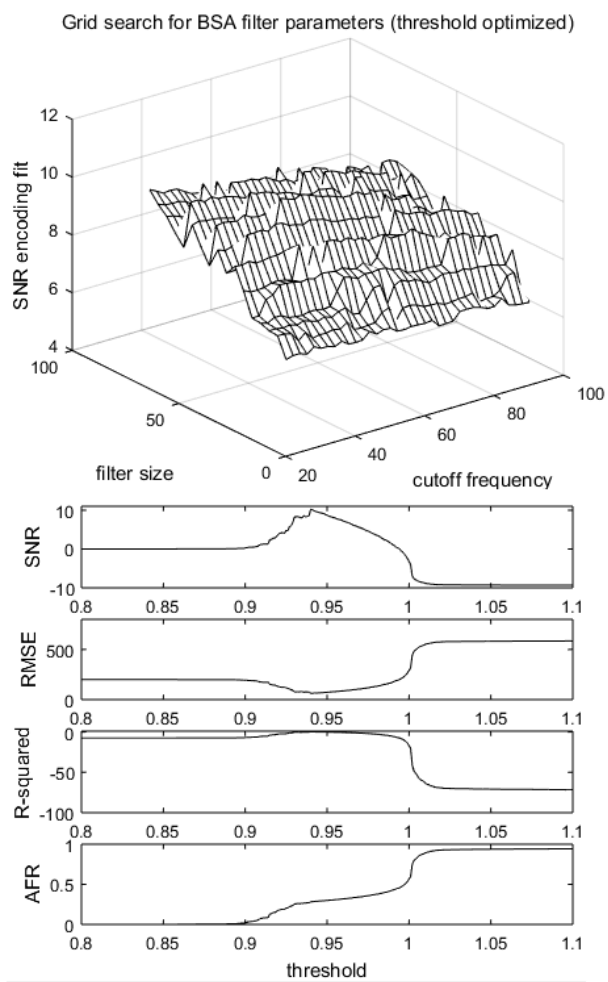

Fig. 13. Grid search for BSA filter parameters, threshold optimization curves for a selected filter (smooth test signal).

F. Comparison of Encoding Methods

A comparison of the key characteristics of analyzed encoding methods is given in Table II to aid with the first step of the encoding process, i.e., selecting the method. The first and foremost selection criterion is whether the SNN architecture accepts only positive or bipolar spike trains as well. Of the analyzed methods, BSA was the only one producing unipolar spikes (Table II). BSA is not suitable to encode step-like signals; continuously changing, constant mean signals are represented most efficiently while a trend in the signal causes some scaling error. Signals with high plateaus are most difficult to encode with BSA. Noise suppression above the cutoff frequency is excellent. However, it must be stressed that the filter design has to be congruent with the task-relevant frequency spectrum and there is a single peak optimum threshold value for a set filter.

TABLE II
SUMMARY AND COMPARISON OF ENCODING METHOD CHARACTERISTICS

Methods	BSA	TBR	SF	MW
spike train polarity	+	+/-	+/-	+/-
false encoding at start/end	yes, both	no	no	yes, at start
cuts into frequency band	yes	no	no	yes
suppresses (white) noise	yes, greatly	yes, little	yes, little	yes, greatly
optimization	non-trivial	non-trivial	easy	non-trivial

Comparing the three temporal contrast methods, SF proved to be very effective for all test signals (Table I) with the further advantage of having a single parameter with a wide, high fit optimization plateau (Table II). In addition, SF does not suffer from systematic errors other than offset in the reconstruction and even suppresses white noise to a small degree. Thus, SF is recommended as a universal encoding method. In the case of a very noisy raw signal, choosing MW encoding could be justified. However, this moving average filtering cuts into the frequency spectrum and the reconstructed signal suffers from pink noise, artifact components, and often scaling error as well (Table II). Thus, a preprocessing step with a digital filter and SF encoding is recommended instead. The numerous disadvantages (Table II) of TBR mean that it should be used only when necessary, e.g., for the simulation, development or deployment of hardware implementations.

G. Observations on the Error Metrics

The optimization curves for the test signals showed that all three metrics give the same optimization curve (Figs. 4, 6, 8, and 13). To account for this, consider that R-squared and RMSE are both calculated based on the fitting error variance while SNR calculates the power ratio of original signal and fitting error. Furthermore, it was assumed that the initial signal value is available for the decoding step; thus, it was possible to match the initial original and reconstructed signal values. If this was not the case, that would mean strong implications for the optimization step. The error metrics would yield different curves and thus different optimal parameter values. The R-squared optimization works to represent the signal dynamics as well as possible (even with a constant offset error), while SNR aims to diminish the difference altogether such that the signal values will match. This often leads to false encoding–decoding at the start of the signal. RMSE would still yield the same results as SNR.

The question of which error metric to choose for optimization arises. SNR can be interpreted based on its sign; it has to be positive for meaningful signal reconstruction. Therefore, SNR is recommended because of favorable interpretability. For computational load, RMSE is favorable, but note that the absolute value of RMSE obtained will differ for different inputs as there are no broadly accepted ways to normalize RMSE, making comparisons across signals difficult.

The low-frequency erroneous components in the reconstructed signal may cause a significant drift away from the original signal. Although the final output of the encoding optimization is the resulting spike train, this drift is of interest because such a great difference between the two signals heavily influences the error metrics. It is possible that applying boundaries to the reconstruction could address this issue to some extent.

H. Observations on the Validation Step

As outlined in the three-step encoding workflow, a final validation step is required to check that task-relevant, meaningful information is retained in the spike train. Currently, a visual check is the only available method for this step. The original signal can be visually compared with the reconstructed signal or the spike train itself. Frequency spectra can also be compared, especially for a sinusoid signal in which the frequency components are of particular interest (Fig. 12). Another option for validation would be testing the accuracy of the whole SNN application. However, this would be influenced by the many parameters of the SNN as well.

I. Observations on Biological Plausibility

It could be of interest to consider the biological rationale of different encoding methods. As mentioned previously, BSA as a neuron stimulus estimation method has a strong biological plausibility considering the functioning of individual neurons. As for the temporal contrast encodings, these mostly rely on the biological strategy that only (large enough) changes of the important property are registered to improve robustness and energy efficiency. TBR registers only large changes between consecutive values, much like retinal cells [3]. SF does the same, but the basis of comparison is the previously registered large change that caused a spike and not necessarily the previous signal value; in this way functioning as a short-term memory or adaptation. MW takes a moving average of previous signal values as a baseline to improve robustness, for which the biological rationale is hard to determine.

J. Limitations of This Investigation

To limit the scope of investigation, the analyzed signals were all 1000 samples long. A future study may address effects of the sample size, e.g., short (50–100) or long (5000–10 000) samples. The momentum-like TBR algorithm introduced in [14] was not considered because the corresponding decoding method has not been demonstrated. The GAGamma methodology [21] is based on the knowledge about the signal generation, and this study is aimed at evaluation different encoding methods for a wide variety of signals; GAGamma was not included in our analysis. Another limitation was that only individual samples were included in the encoding parameter optimization. Future work is to be carried out with regards to optimizing multiple sample data and furthermore, data with multiple features.

Algorithm 1 TBR Encoding

```
input: s signal, f factor
startpoint = s(1)
diff = zeros(length(s))
for t = 1:(length(s)-1))
  diff(t) = s (t+1) − s(t)
end for
diff(end) = diff(end-1)
threshold = mean(diff) + f*std(diff)
out = zeros(length (s))
for t = 1:length(s)
  if diff(t) > threshold
    out(t) = 1
  elseif diff(t) < -threshold
    out(t) = −1
  end if
end for
output: out
```

Algorithm 2 SF Encoding

```
input: s signal, threshold
startpoint = s(1)
out = zeros(length (s))
base = s(1)
for t = 2:length(s)
  if s(t) > base + threshold
    out(t) = 1
    base = base + threshold
  elseif s(t) < base - threshold
    out(t) = −1
    base = base - threshold
  end if
end for
output: out, startpoint
```

VI. Conclusion

Any machine learning process can be effective and valid only if the input data contain the relevant information in a meaningful representation. For SNNs, this input format is a unipolar or bipolar spike event sequence (spike trains). Encoding real-valued data (signals) to spike trains, therefore, has to retain the task-relevant information with as little artifacts

Algorithm 3 MW Encoding

```
input: s signal, threshold, window, startpoint
startpoint = s(1)
out = zeros(length (s))
base = mean(s(1:window + 1))
for t = 1:(window + 1)
  if s(t) > base + threshold
    out(t) = 1
  elseif s(t) < base - threshold
    out(t) = −1
  end if
end for
for t = (window+2):length(s)
  base = mean(s(t-window−1:t-1)
  if s(t) > base + threshold
    out(t) = 1
  elseif s(t) < base - threshold
    out(t) = −1
  end if
end for
output: out, startpoint
```

Algorithm 4 BSA Encoding

```
input: s signal, fir, threshold
L = length(s)
F = length(fir)
out = zeros(L)
shift = min(s)
s = s − shift
for t = 1:(L-F)
  err1 = 0
  err2 = 0
  for k = 1:F
    err1 = err1 + abs(s(t+k)-fir(k))
    err2 = err2 + abs(s(t + k − 1))
  end for
  if err1 <= (err2 * threshold)
    out(t) = 1
    for k = 1:F
      s(t+k+1) = s(t+k+1) − fir(k)
    end for
  end if
end for
output: out, shift
```

Algorithm 5 TBR, SF, MW Decoding

```
input: spikes, threshold, startpoint
recon = zeros(length (spikes))
recon(1) = startpoint
for t = 2:length(spikes)
  if spikes(t) == 1
    recon(t) = recon(t-1) + threshold
  elseif spikes(t) == −1
    recon(t) = recon(t-1) - threshold
  else
    recon(t) = recon(t-1)
  end if
end for
output: recon
```

Algorithm 6 BSA Decoding

```
input: spikes, fir, shift
out = conv(spikes, fir) + shift
output: out
```

as possible. A three-step workflow methodology is proposed here: selecting the encoding method appropriate to the original signal, optimizing its parameters, and validating the encoded signal. This paper aimed at providing analysis and guidelines for these steps. The investigation was limited to temporal signals and algorithms: temporal contrast (TBR, SF, and MW) and stimulus encoding (BSA) method. If the SNN architecture allows only unipolar spikes, BSA is the only appropriate method of these. If bipolar spike trains are allowed, temporal contrast methods can also be used. In most cases for bipolar systems, SF should be the encoding method of choice due to its versatility and robustness. TBR has numerous disadvantages and, therefore, is only recommended for hardware simulation, development, or implementation since it suits online, fast applications. MW encoding suits very noisy signals but significantly cuts into the frequency domain; if this is not permissible, a digital filtering preprocessing step and SF encoding are recommended. Parameter optimization is based on calculated error metrics between the original and reconstructed real-value signals. Here, SNR is the recommended metric since negative values indicate prohibited areas and SNR values are invariant of signal amplitude which allows for comparisons. An additional validation step is done through the visual exploration of the original signal, encoded spike train, and reconstructed (decoded) signal in the time and/or frequency domain.

Future work is planned in the following directions:

1) development of error metrics in the frequency domain;
2) multiple variable encoding optimization in parallel, e.g., optimizing the encoding for each of the EEG channels;
3) automated validation of the encoding process;
4) adaptive encoding method selection and parameter optimization for streaming data with concept drifts.

Custom MATLAB software with graphical user interface for the selection and optimization of encoding methods is available on www.kedri.aut.ac.nz/neucube (named "spike encoding tools").

Appendix

Encoding algorithms 1–4 and corresponding decoding algorithms 5 and 6 for all methods are as follows.

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