Every Spike is Sacred

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Every spike is sacred.
Every spike is great.
If a spike is wasted,
God gets quite irate.

Start with a thought experiment

What is the fewest spikes needed to transmit a DC value?
Assume value is an integer from 1 to a million

Use Rate Code

Just transmit the number of spikes
Could require up to a million spikes
Very robust but wasteful
If a spike is wasted,
God gets quite irate.

Use Temporal Code

Transmit two spikes and measure the time difference
What happens if we lose a spike?
Every spike is sacred

Outline

Part 1: Time-to-first-spike imager
Dynamic range quantifies the ability to image bright and dark areas simultaneously.

Part 2: Neural recording implant
All animal pictures removed

Part 3: Bio-inspired speech processing
Use engineering performance metrics, always willing to sacrifice biological realism.
**Dynamic range definition**

Defined as the ratio of brightest nonsaturated signal to darkest detectable signal.

**Dynamic Range Limitation**

\[ V = \frac{I \times t}{C} \]

Dynamic range extended to ~140dB.

**Rate Coding Scheme**

\[ V = \frac{I \times t}{C} \]

Dynamic range extended to ~140dB.

**Rate Coding Schemes**

Advantages:
- Each pixel chooses its own integration time to optimize noise and dynamic range
- No analog readout noise
- No ADC required
- Firing rate imagers are not new (Mahowald 1990, Yang 1994, Boahen 1995, Ralph’s octopus etc)

Disadvantages:
- Takes too long to form an image (~seconds)
- Wasteful in terms of bandwidth (and therefore power)

**Using Time-To-First-Spike Coding**

\[ V = t \times (I/C) \]

Dynamic range extended to ~140dB.

Only one spike per pixel per frame

Let the heathen spill theirs
On the dusty ground
God shall make them pay for
Each spike that can’t be found
Adjusting the Threshold

\[ V = t \frac{I}{C} \]

Dynamic range extended to ~140dB within time T.

Time-to-First-Spike Coding

Advantages:
- Each pixel chooses its own integration time to optimize noise and dynamic range
- No analog readout noise
- No A/D required
- Low power and small bandwidth
- Parallels in biology (Simon Thorpe)

Prototype Chip

- Technology: 0.18\(\mu\)m TSMC CMOS
- Supply Voltage: 1.8/3.3 Volt
- Transistors per pixel: 24
- Array size: 128 x 128
- Pixel size: 12\(\mu\)m x 12\(\mu\)m
- Photosensitive area: 3\(\mu\)m x 3\(\mu\)m
- Power dissipation: 8.7 mW at 30fps
- Dark current: 1.04 nA/cm\(^2\)
- SNR: 46.4 dB, measured
- FPN: 2.3%, estimated
- Dynamic Range: 110 dB (one pixel, measured at 30fps)
- Dynamic Range: 100 dB (array, measured), limited by the optics

Part 2: Neural Recording Implant

State of the Art, in Utah!

Utah Electrode Array
- Recording chip by Reid Harrison
- 100 electrodes, 100 amplifiers
- 10-bit ADC on one selectable channel, spike detectors on 99 other channels.

Constraints on Bandwidth

- 8 bits/sample x 20 Ksamples/sec = 160 Kbits/sec/channel
- Bandwidth constraints allow transmission of only a few channels but want to scale up to 100’s of channels
- Current solutions can only send one channel full resolution and crudely spike detect on the other channels (no spike sorting possible).
- Need compression method but power constraints rule out a DSP solution.

Time for another thought experiment
Another Thought Experiment

What is the fewest spikes needed to transmit \( x(t) \)?
Assume \( x(t) \) is:
1) Bandlimited to 10KHz,
2) Zero mean
3) Reconstructed with 8-bit precision.

Rate Coding

Transmit a rate coded signal (such that a LPF can recover \( x(t) \))
Could require quite a few spikes
If a spike is wasted, God gets quite irate.

Temporal Code

Send \( x(t) \) into an integrate fire neuron
And achieve perfect reconstruction on receiver

Temporal Code

Send \( x(t) \) into an integrate and fire neuron
And achieve perfect reconstruction on receiver

Signal Reconstruction

Any bandlimited signal can be expressed as a low-pass filtered version of an appropriately weighted sum of delayed impulse functions.
(Derived from Duffin et al. 1952, Feichtinger et al. 1994, Lazar et al.)

\[ x(t) = h(t) * \sum \delta(t - \tau_j) \]
Where \( \delta \) is computed by solving a linear system

Simulation Results (Matlab)

X(t) is a Gaussian random noise signal bandlimited to 1.5kHz
Maximum ISI = 0.14ms < T
SNR = 103dB
SNR is limited by the finite number of spikes and finite computational precision.
IF Advantages

- Pulses are noise robust and efficiently transmitted at low bandwidth
- Front-end is simple and low power
- No conventional ADC required
- Reduces power, bandwidth and size

One drawback is that the back-end requires a reconstruction algorithm

Florida Wireless Implantable Recording Electrodes (FWIRE)

Overall FWIRE Schematic

- Polyimide substrate
- Hybrid process
- 50 um W microwires
- Micropatterned Au interconnects
- Omnetics connector
In vivo implantation

- Cranioplastic cement, bonding substrate to screw #1
- Screw #1
- Screw #2

In vivo Recording Results

Can we use spike trains to represent this kind of signal?

Sub-Nyquist Compression

- Original Signal
- Recovered Signal w/ 17.8 K pulses/s
- Recovered Signal w/ 9.2 K pulses/s
- Recovered Signal w/ 6.1 K pulses/s

160 Kbits/sec → 10 Kspikes/sec = 16x compression (not enough)

Pulse Based Feature Extraction

- Realize that the output needs spike sorting
- Can achieve further compression with feature extraction
- Using exactly the same biphasic circuit, extract pulse-based features

Pulse-based feature extraction

Feature Extractor Output
Pulse-Based Spike Sorting

Form template signatures for each neuron

Convolve signatures with Gaussian

$\sigma$ small - coincidence detector

$\sigma$ larger - spike count

Find min MSE and if < noise classify as that neuron

Spike2’s Templates

Sorting Error as a Function of Bandwidth

10Kbits/sec $\rightarrow$ 600 spikes/sec = 16x compression (256x total)

Part 3: Bio-Inspired Speech Processing

Will show a better view of the cochlea

How to process the spikes?

Should be easy

Doesn’t the firing rate at each point on cochlea determines the energy at the corresponding frequency in the input signal (place coding)?

Place code has some troubles

FIGURE 1.16 Isointensity contours for a single fiber in the auditory nerve of an anesthetized squirrel monkey. The number next to each curve indicates the sound level (dB SPL) used to obtain that curve. Note that the frequency producing maximal firing varies as a function of level. Data from Rose et al. (1971).
Can Use Phase Locking

Can extract frequency information from spike timing
Not only should spikes not be wasted, but there is information available in their precise timing

Phase Locking

Inter-Spike Interval Histogram

The integrate and fire neuron can compute the degree of phase lock

Degree of Phase Locking

The Overall Algorithm (1)

The Overall Algorithm (2)
Revised Algorithm

• Rank order coding is simple and can learn with very few training patterns
• Unfortunately it’s performance was poorer than conventional methods (MFCC/HMM)
• Then used Liquid State Machine (LSM), a pattern classifier for spikes

Liquid State Machines

Provides a mechanism for processing spike trains.

Uses a recurrent collection of spiking neurons to form a large dimensional basis set.

A linear readout can be trained to classify the inputs.

Experiment with Vowels

5 vowel classes from the TIMIT database

Two types of noise
White noise
Pink noise

Training => Two vowels for each class, one male and one female

Testing => 25 vowels randomly chosen for each class, multi-speaker

Baseline classifier => 39 dimension MFCC with standard HMM

Final Results (% correct)

<table>
<thead>
<tr>
<th>SNR</th>
<th>25dB</th>
<th>10dB</th>
<th>5dB</th>
</tr>
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<tr>
<td>MFCC-HMM</td>
<td>94.0</td>
<td>88.0</td>
<td>78.5</td>
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<tr>
<td>Phaselock</td>
<td>93.0</td>
<td>92.5</td>
<td>91.0</td>
</tr>
</tbody>
</table>

Results only for pink noise, white noise is similar
Promising results, particularly for low SNR cases

Needs to be extended to:
more phoneme classes
more noise types
word recognition
Can we augment the feature vector?

Conclusions

1. Save bandwidth (and power) by using fewer spikes
2. Use the spikes more efficiently by taking advantage of their timing (if you can)
3. Try to understand what implications all this has to biology

OR

Every spike is sacred

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Questions?