Time-Frequency Acoustic Processing and Recognition: Analysis and Analog VLSI Implementation

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- Introduction
- Template Correlation
- An Acoustic Transient Processor in VLSI:
  - Frontend Filterbank Systems
  - Template Correlation
  - Experimental Results
- A Trinary-Trinary Correlator
- Conclusion

Research Goals:

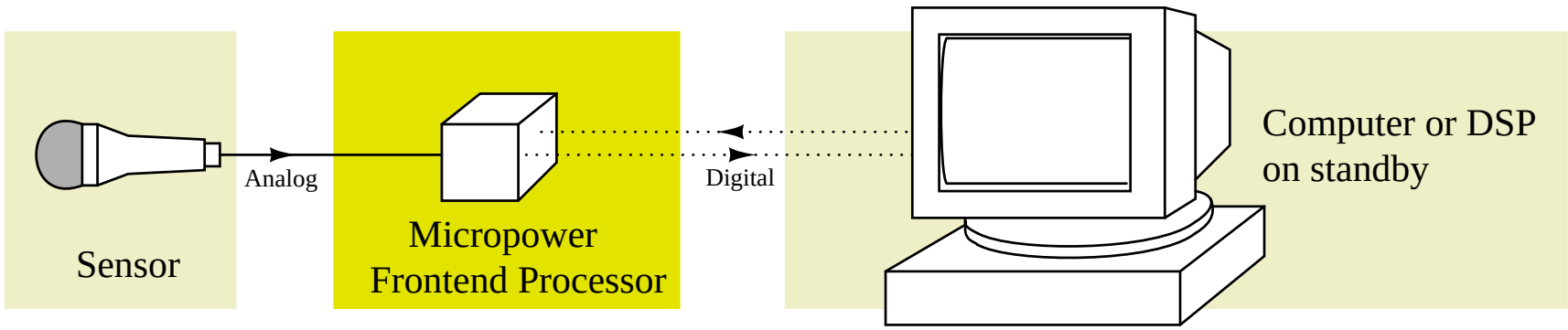
Investigate signal processing systems for which primary constraints are **power consumption** and **physical area**.

- Develop these systems into efficient analog and digital hardware
- Maintain high accuracy with respect to microprocessor and DSP solutions
- Use circuits with ultra-low (μW) power consumption
- Exploit parallel architectures to achieve robustness in the presence of noise and mismatch

Performance depends critically on the choice of **algorithm** and **hardware**.

Applications:

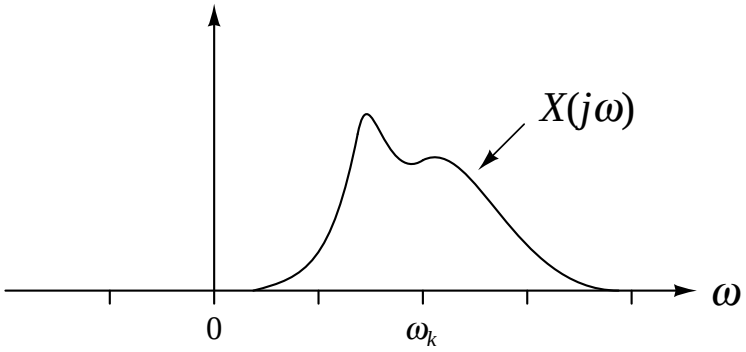
- Handheld or mobile (battery-operated) environments
- Can be used to monitor environment and wake up systems in “standby” mode
- “Smart” A/D conversion

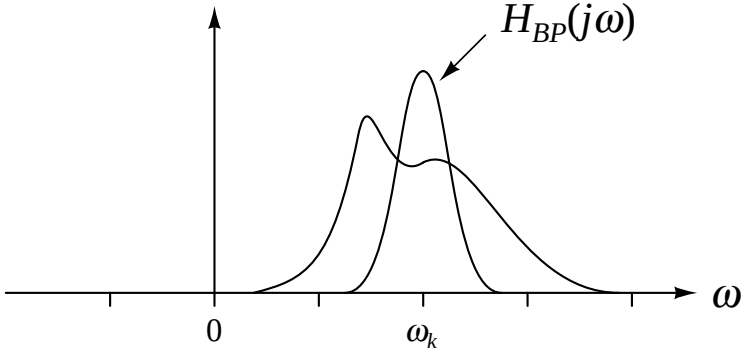


Microelectronic Systems Laboratory Research: Systems and Algorithms

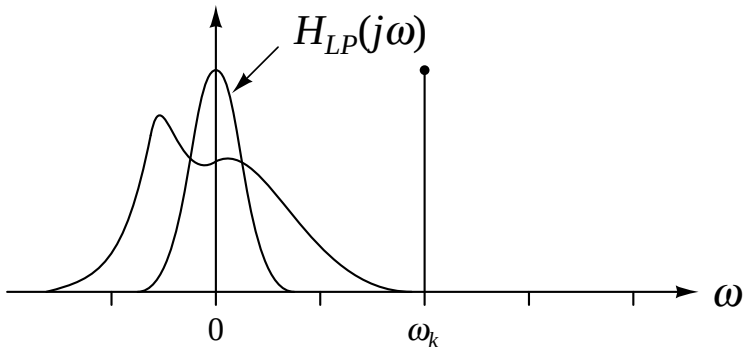
- Continuous wavelet transform (CWT) processor
- Log-domain filters for audio-frequency applications
- Micropower mixed-mode template correlation acoustic pattern classifier
- Model-free adaptive correction of optical aberrations

Bandpass Filterbank vs. Complex Demodulation





$X(j\omega)\, H_{BP}(j\omega)$

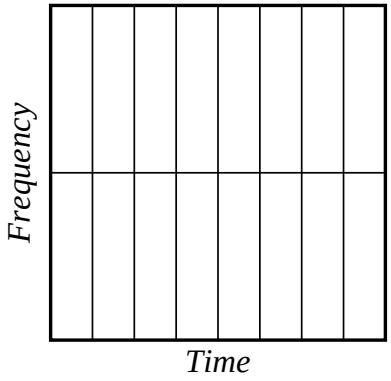


$(X(j\omega) * \delta(j\omega - j\omega_k))\, H_{LP}(j\omega)$

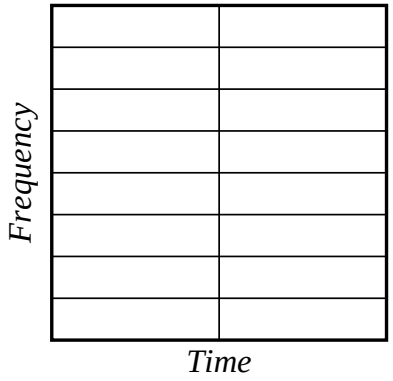
Tilings of the Time-Frequency Plane

Area of uncertainty in time and frequency: $\Delta f \Delta t \geq \frac{1}{2}$

Gives good time resolution but poor frequency resolution



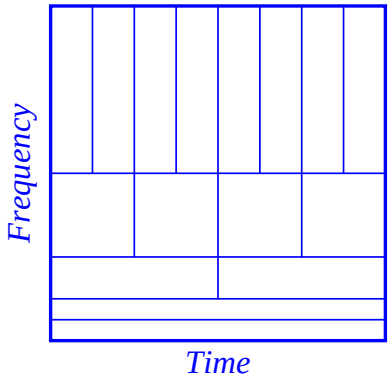
(a) FFT, short window



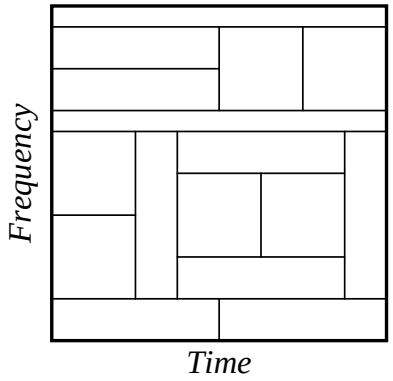
(b) FFT, long window

Gives good frequency resolution but poor time resolution

Most efficient time/frequency tradeoff for arbitrary inputs



(c) Wavelet Basis



(d) Wavelet Packets

The most efficient description of a specific signal; difficult to compute on the fly

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Acoustic Event Classification Using Correlation

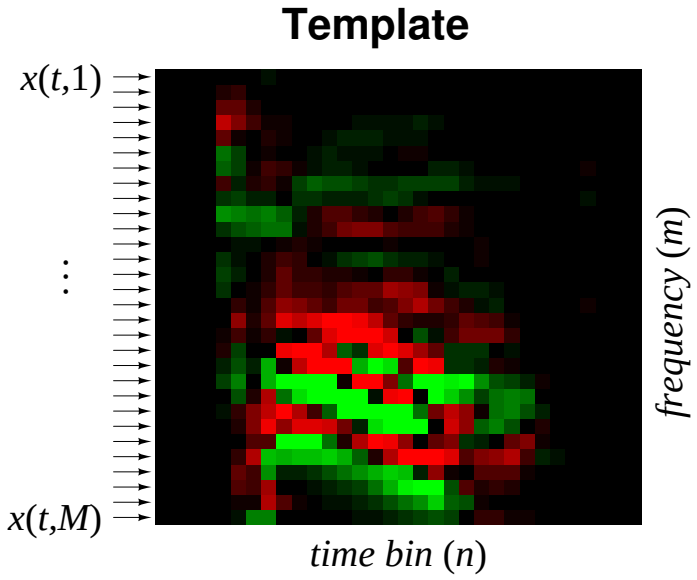
Goal: Try to classify an acoustic event by matching the time-frequency decomposed input against a set of templates. Each template has $M \times N$ values and represents a "typical" example of one class.

Signal (x) characteristics (output of frontend filtering system):

- M frequency channels (log-spacing)
- Continuous-time (or Discrete-time)
- Continuous-valued
- Normalized energy envelope

Template (p_z) characteristics:

- One template per class (z)
- M frequency channels (log-spacing)
- N time-bins (1 ms per bin for transients)

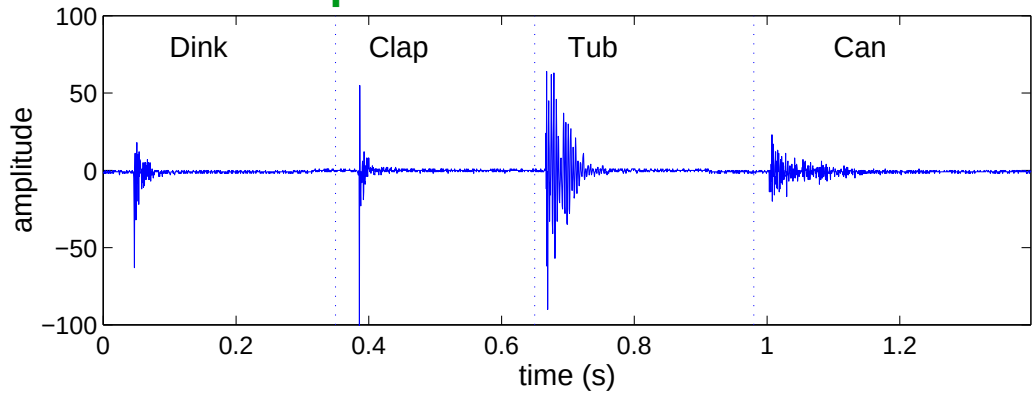


Basic Correlation equation:

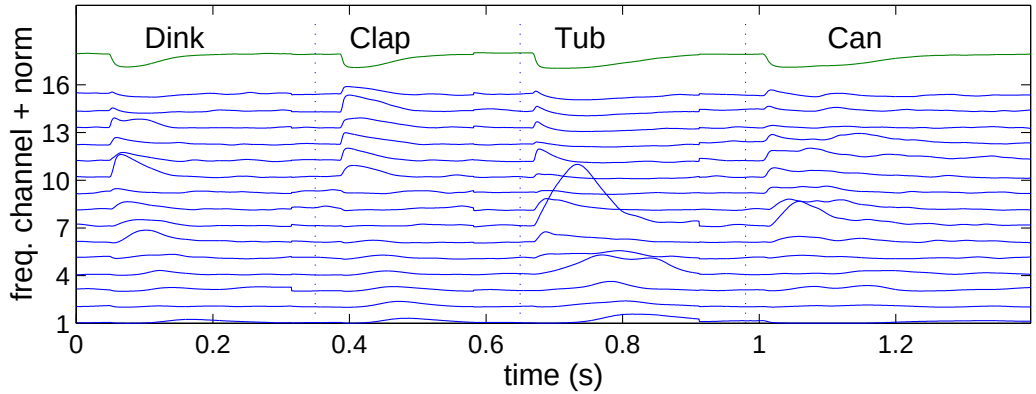
$$c_z[\,t\,] = \sum_{m=1}^{M} \sum_{n=1}^{N} x[t-n, m]\, p_z[n, m]$$

Acoustic Event Recognition: Example

Inputs: acoustic data

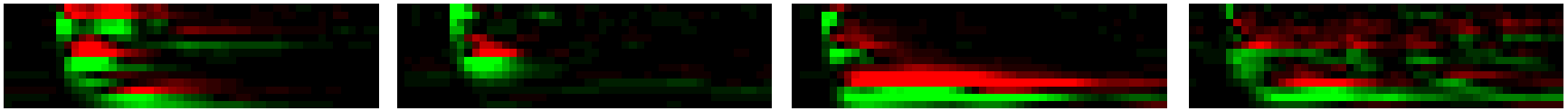


Frontend processing



Classification via template correlation

Dink Clap Tub Can



Acoustic Signal Classification

Three main components:

1. **Filterbank**: Time-frequency decomposition converts the input signal into an efficient representation for subsequent processing.
2. **Template Correlator**: Simple correlation is sufficient to recognize complicated acoustic events.
3. **Digital Post-processing**: Uses correlator outputs as **features** for tasks such as speech recognition.

This talk will focus on current research (parts 1 and 2) and conclude with comments about (3).

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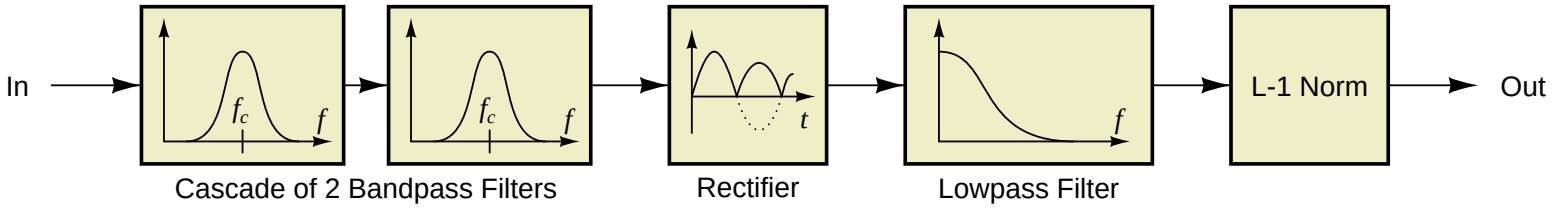
Filterbank Frontend Systems

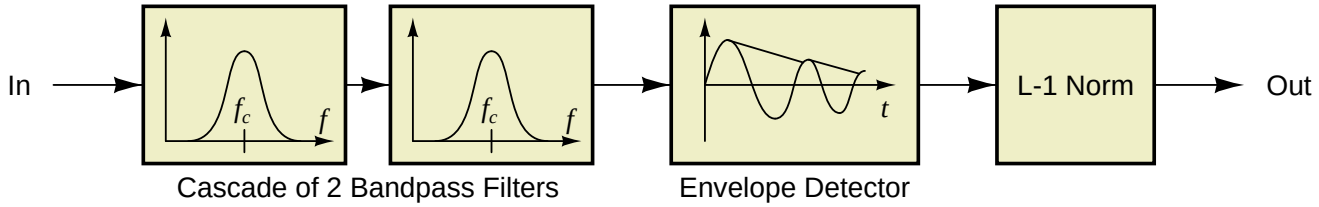
- Cochlear-model filters:
  - Mead and Lyon (1989)
  - Weimin Liu et al. “HEEAR” (1994)
  - . . . and many others
- Unnikrishnan, Hopfield, and Tank (1991)
- Shihab Shamma (1994)
- Pineda, Edwards, and Cauwenberghs (1995)

Our frontend architecture: two versions

(original)



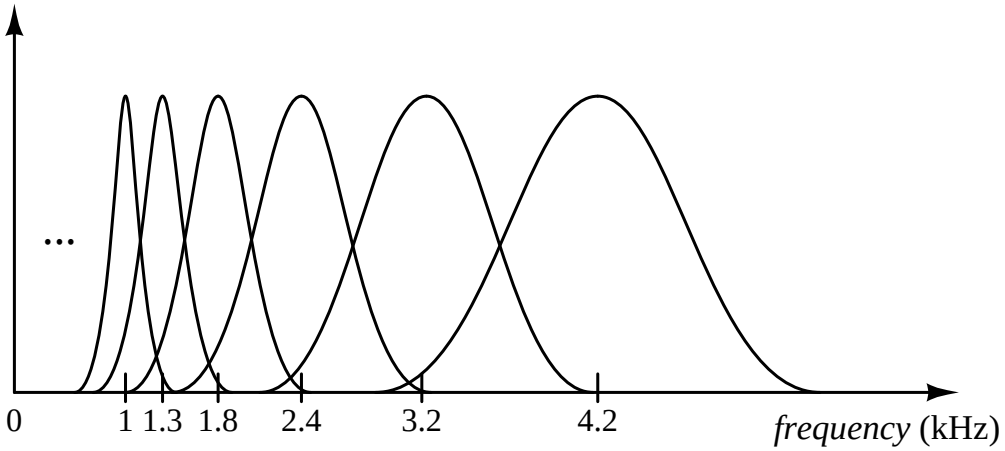
(modified)



Bandpass Filterbank Frontend Processor

System characteristics:

- Parallel bank of 2nd- or higher order bandpass filters with constant Q
- Logarithmically-spaced center frequencies across the bank



- Rectification and smoothing of output to get energy envelope of signal
- Automatic gain control through *L-1* normalization across outputs (or other method)

A BiCMOS Current-Mode Filterbank Frontend

System implementation:

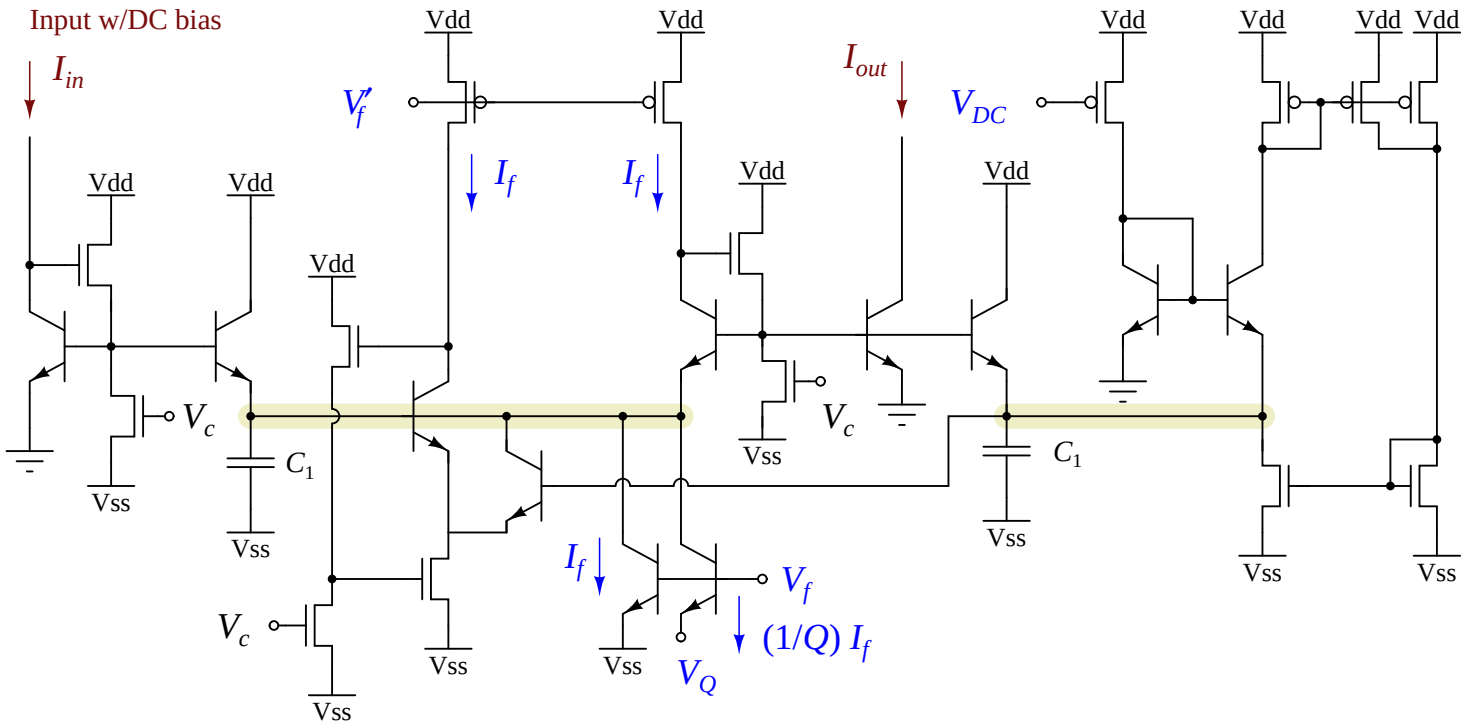
- *Log-domain filters*[*] based on *translinear circuits*
- BiCMOS design for greatest dynamic range and linearity

Why a Current-Mode VLSI Implementation?

- Large dynamic range compared to voltage-mode circuits
- Dense circuit layouts
- Filter parameters (f_c, Q) are tunable over multiple decades
- μW-range power consumption: good linearity at low power
- Most convenient format to interface to current-mode backend processors

[*]B. Gilbert (1975), D. Frey (1996), Y. Tsividis (1997), R. T. Edwards and G. Cauwenberghs (1998), and others

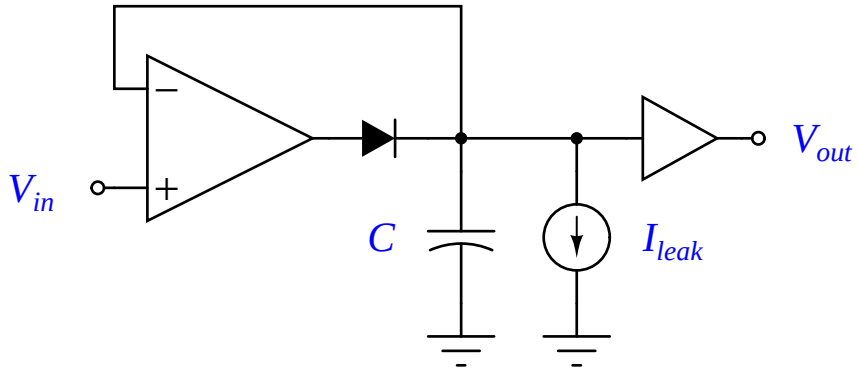
The Log-domain Bandpass Filter



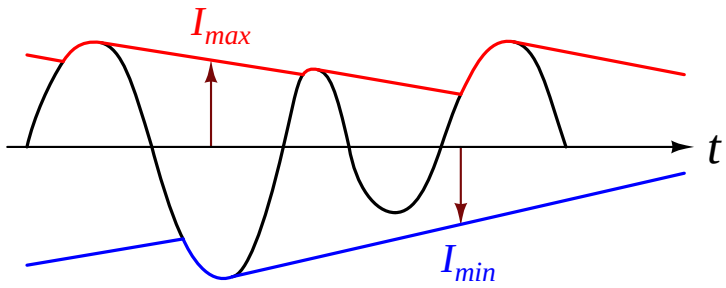
$$I_{out} = I_{in}\left(\frac{\tau s}{1+(1/Q)\tau s+\tau^2 s^2}\right)+I_{DC} \qquad \text{where} \qquad \tau=\left(\frac{V_t C_1}{I_f}\right) \qquad \text{and} \qquad Q=e^{V_Q/V_t}$$

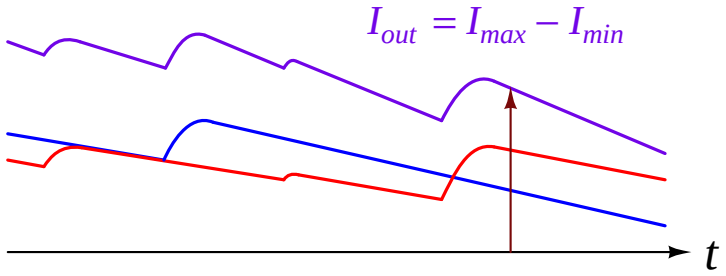
The Envelope (Peak) Detector

Simple Op-Amp Peak Detector

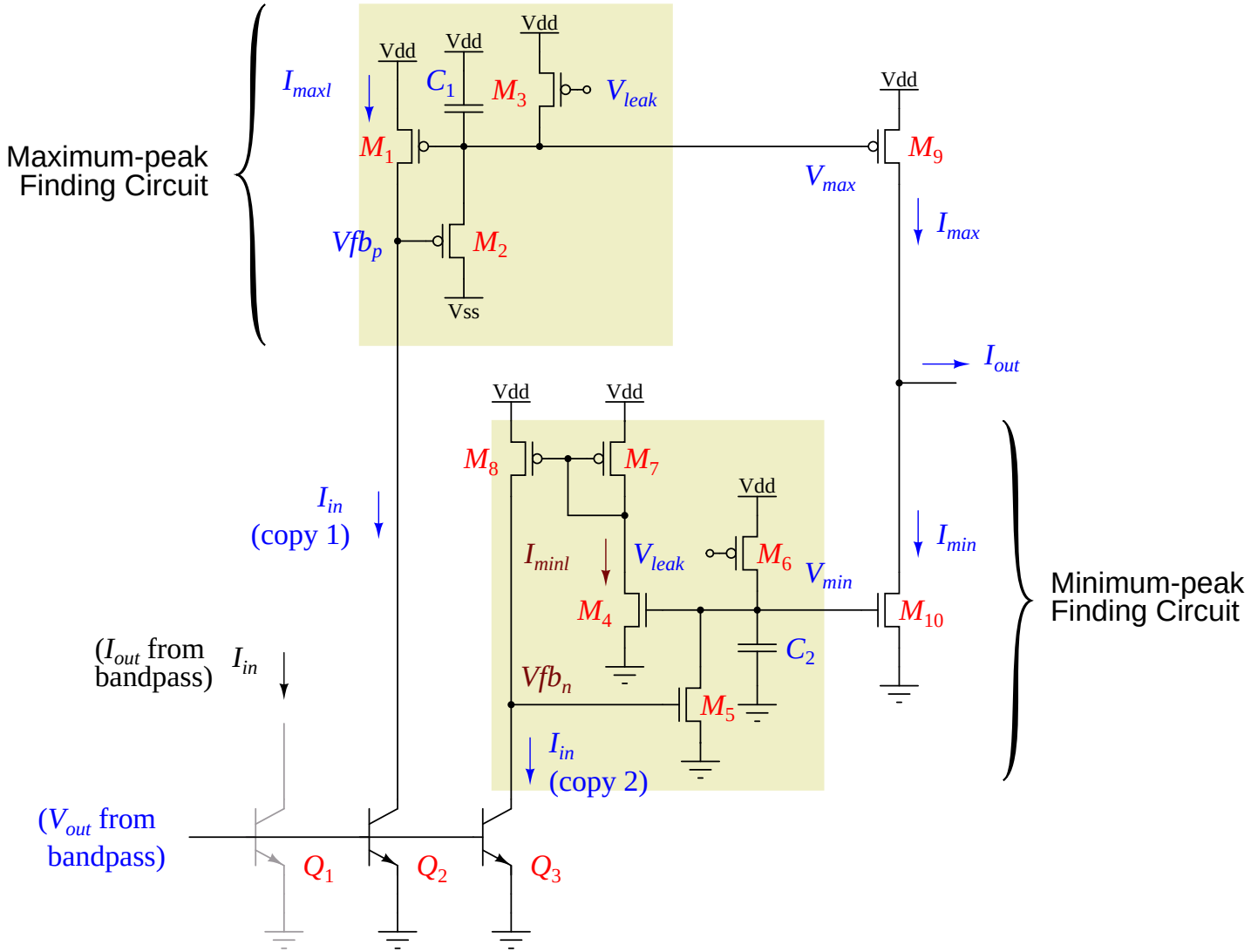


Behavior of a Peak-to-Peak Detector

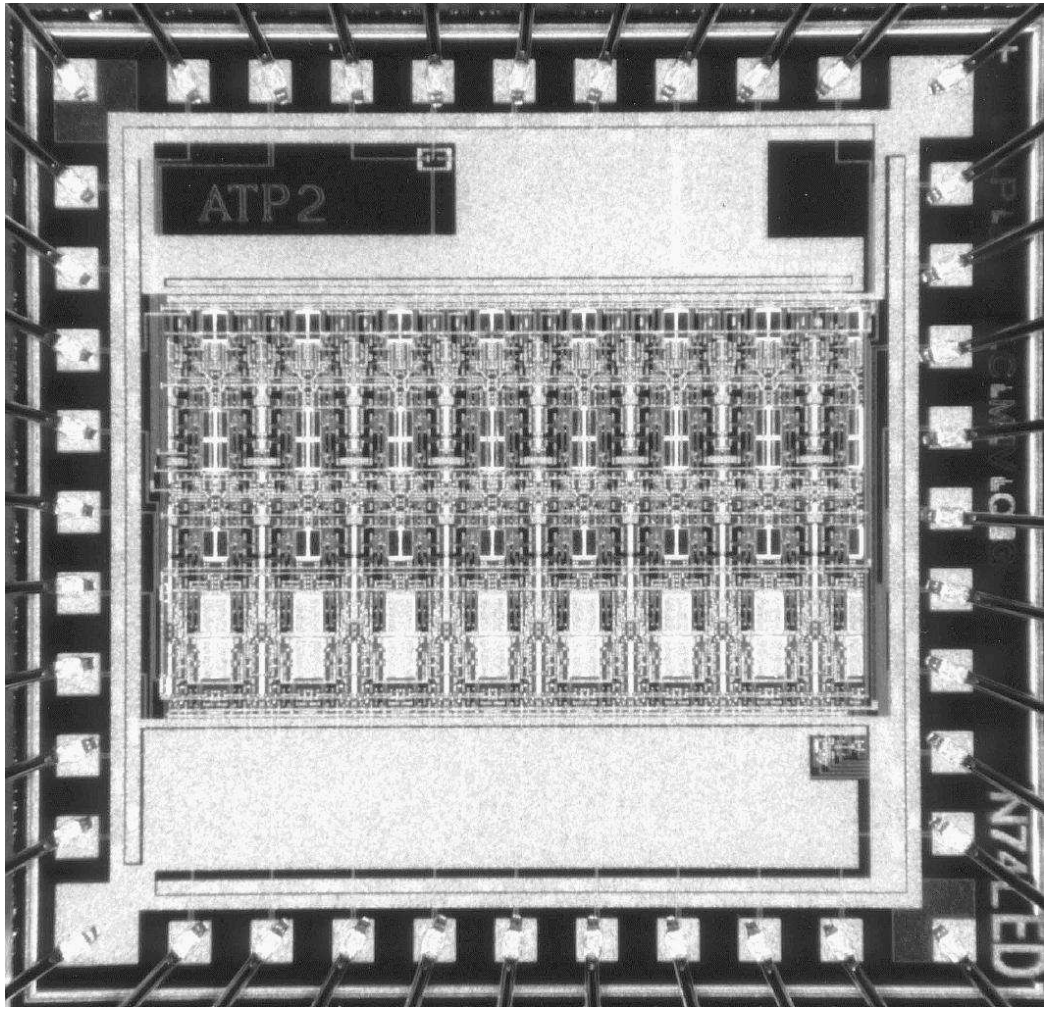




The Envelope Detector

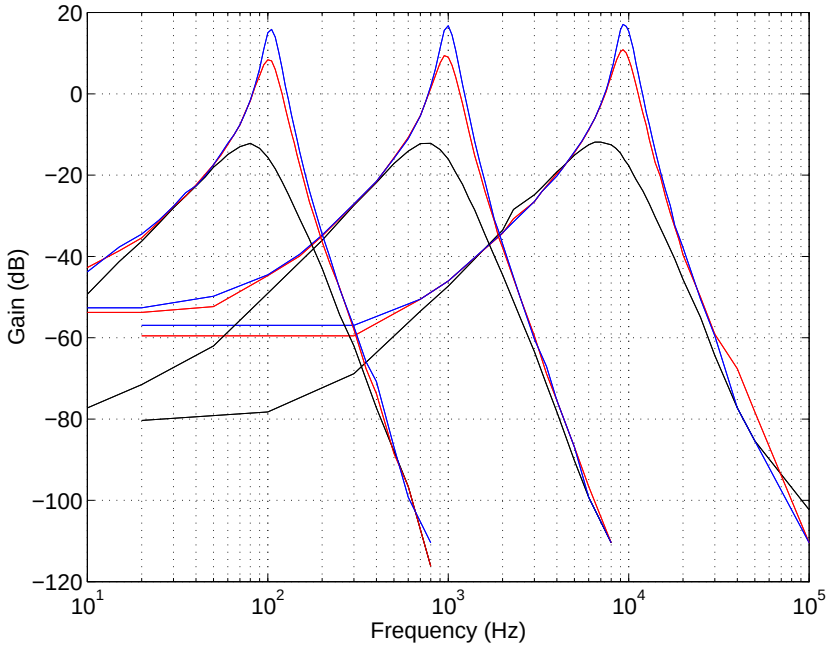


Log-Domain Frontend Filterbank—Photomicrograph

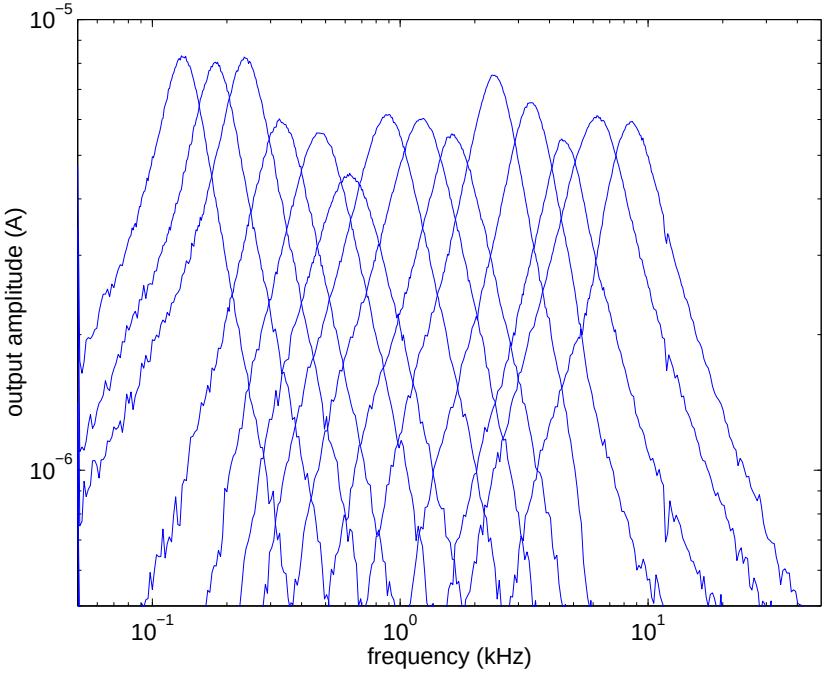


The fifteen-channel bandpass filterbank fabricated in 1.2 µm technology inside a 2.2 mm $\times$ 2.2 mm padframe.

Measured results of the Log-domain filters



Measured frequency response of one filter (4th-order bandpass) measured at three different center frequencies and three different Q-values.



Measured output of the envelope detector of all filter outputs, showing mismatch between channels.

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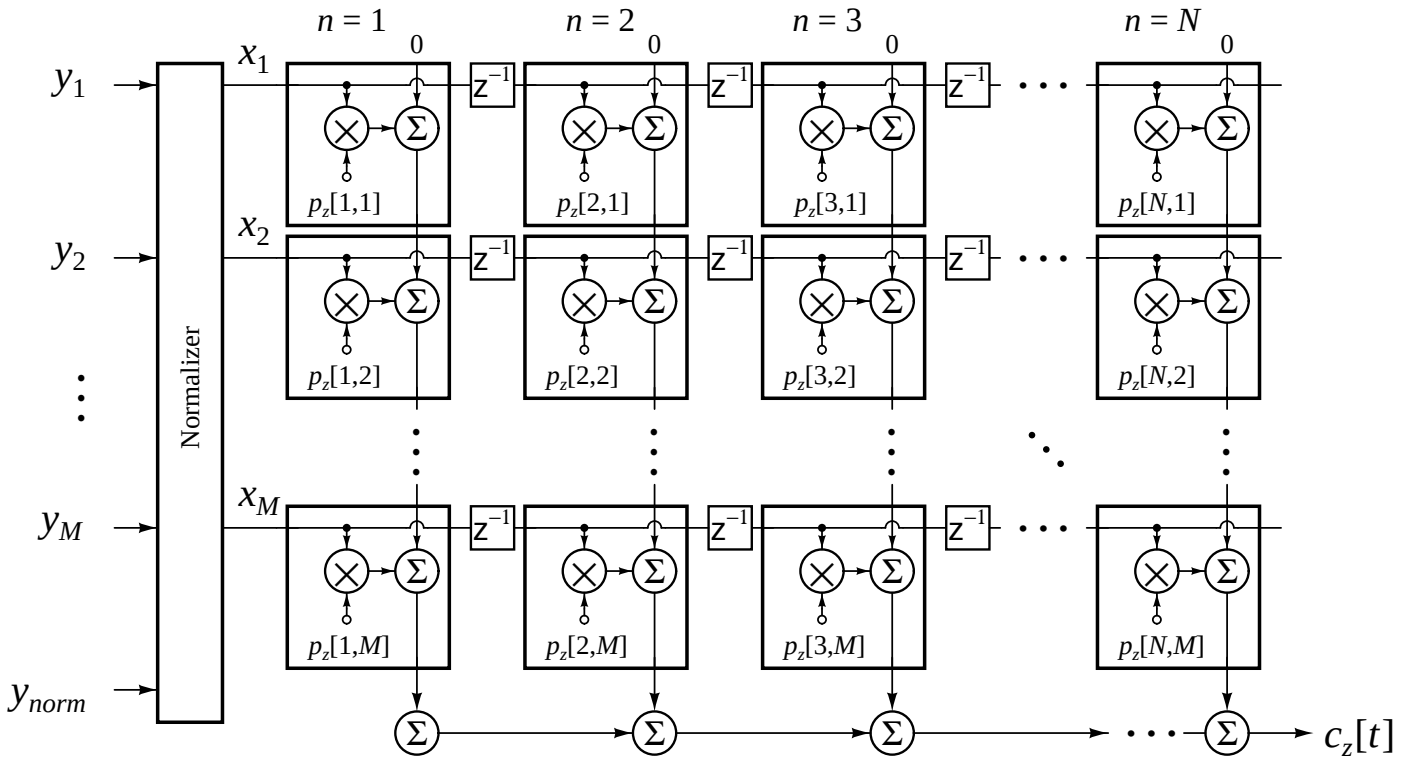
The Acoustic Transient Processor Correlation Algorithm

$$c_z[t] = \sum_{m=1}^{M} \sum_{n=1}^{N} x[t-n, m]\, p_z[n, m]$$



Original Software Trials of the Transient Classifier

Confusion Matrix for Cross-Validation Test

Baseline Algorithm Results

Event	Bar	Book	Can	Dink	Door	Finger	Hand	Mallet	Shelf	Tub
Bar	28	0	0	0	0	0	0	0	0	0
Book	0	19	0	0	0	0	0	0	0	1
Can	0	0	27	0	2	0	0	0	0	0
Dink	1	0	0	25	0	0	1	1	0	0
Door	0	0	0	0	9	0	0	1	0	0
Finger	0	0	0	0	0	17	1	0	0	0
Hand	0	0	0	0	0	0	21	0	0	0
Mallet	0	0	0	0	0	0	0	12	0	0
Shelf	0	0	0	0	0	0	0	0	28	0
Tub	0	0	0	0	0	0	0	0	0	28

Statistics:

Total instances presented:	222
Correct:	214
Incorrect:	8
Accuracy:	96.4%

Template Correlation: Computational Requirements

- M = 32 frequency channels
- timestep = 1 ms
- N = 100 bins (timespan of 1/10 second)
- one correlation per timestep

$>$3 million multiply-accumulate operations per second per template

Implementation goals:

- minimize operations per timestep (modify algorithm)
- minimize power per operation (analog design)

Different Correlation Architectures

Method	Both Cont.	Binary Input	Both Binary	Binary $(1,-1)$ Template	Binary $(1,0)$ Template
One-to-One	96.40%	—	—	—	—
Time Difference	85.59%	65.32%	59.46%	82.43%	81.98%
Channel Difference	90.54%	53.60%	95.05%	94.59%	94.14%
Center-Surround	92.79%	53.60%	95.05%	92.34%	92.34%

Conclusion:

Best architectures use channel difference computation and binary template values and either binary or continuous-valued input.

Software Trials of the Transient Classifier

Confusion Matrix for Cross-Validation Test

Channel-differenced input and binary-valued template

Event	Bar	Book	Can	Dink	Door	Finger	Hand	Mallet	Shelf	Tub
Bar	27	0	0	0	1	0	0	0	0	0
Book	0	19	0	0	0	0	0	0	0	1
Can	1	0	22	0	4	0	0	0	1	0
Dink	1	0	0	26	0	0	1	0	0	0
Door	0	0	0	0	10	0	0	0	0	0
Finger	0	0	0	0	0	18	0	0	0	0
Hand	0	0	0	0	0	3	18	0	0	0
Mallet	0	0	0	0	0	0	2	10	0	0
Shelf	0	0	0	0	1	0	0	0	27	0
Tub	0	0	0	0	0	0	0	0	0	28

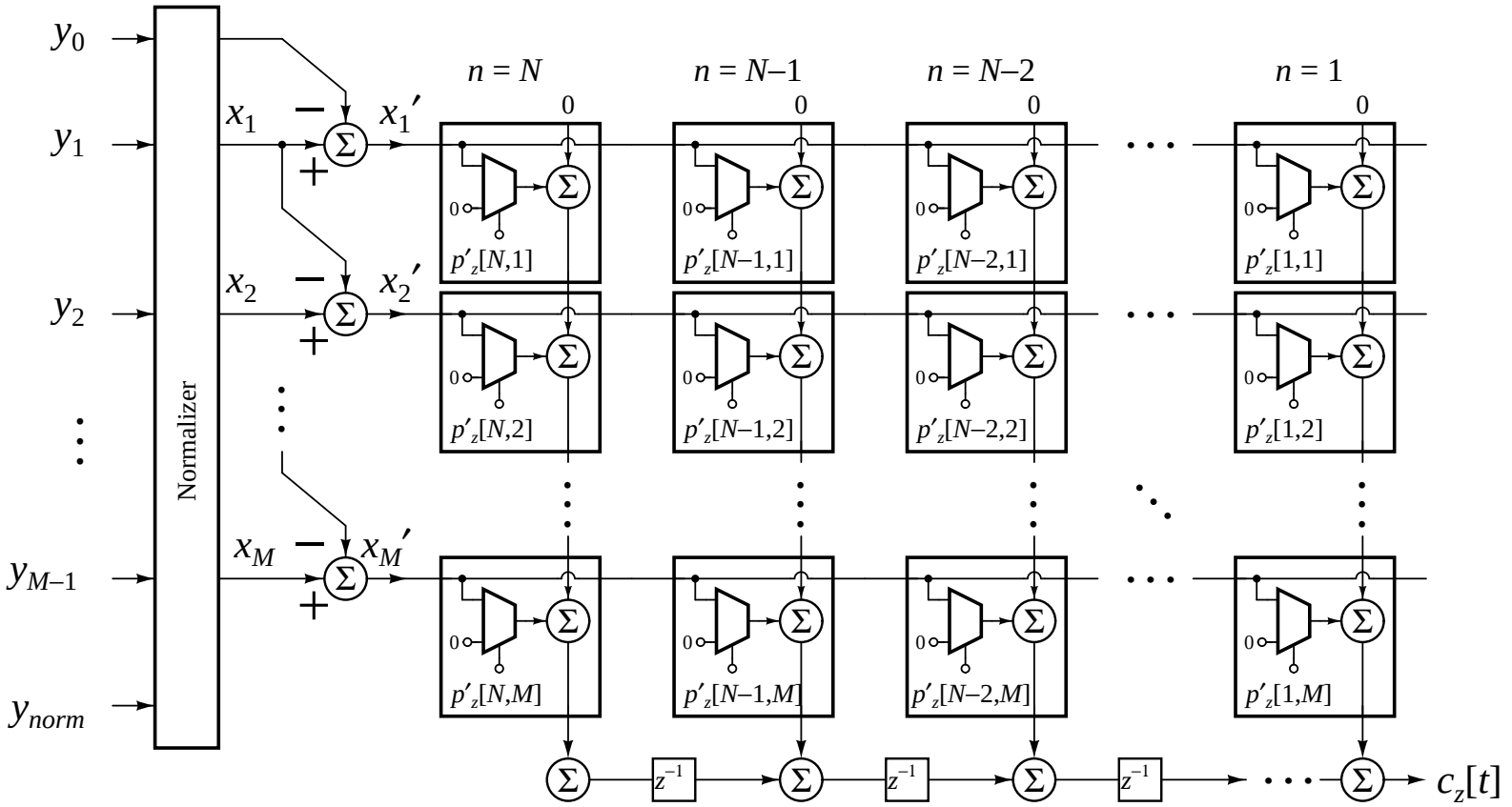
Statistics:

Total instances presented:	221
Correct:	205
Incorrect:	16
Accuracy:	92.7%

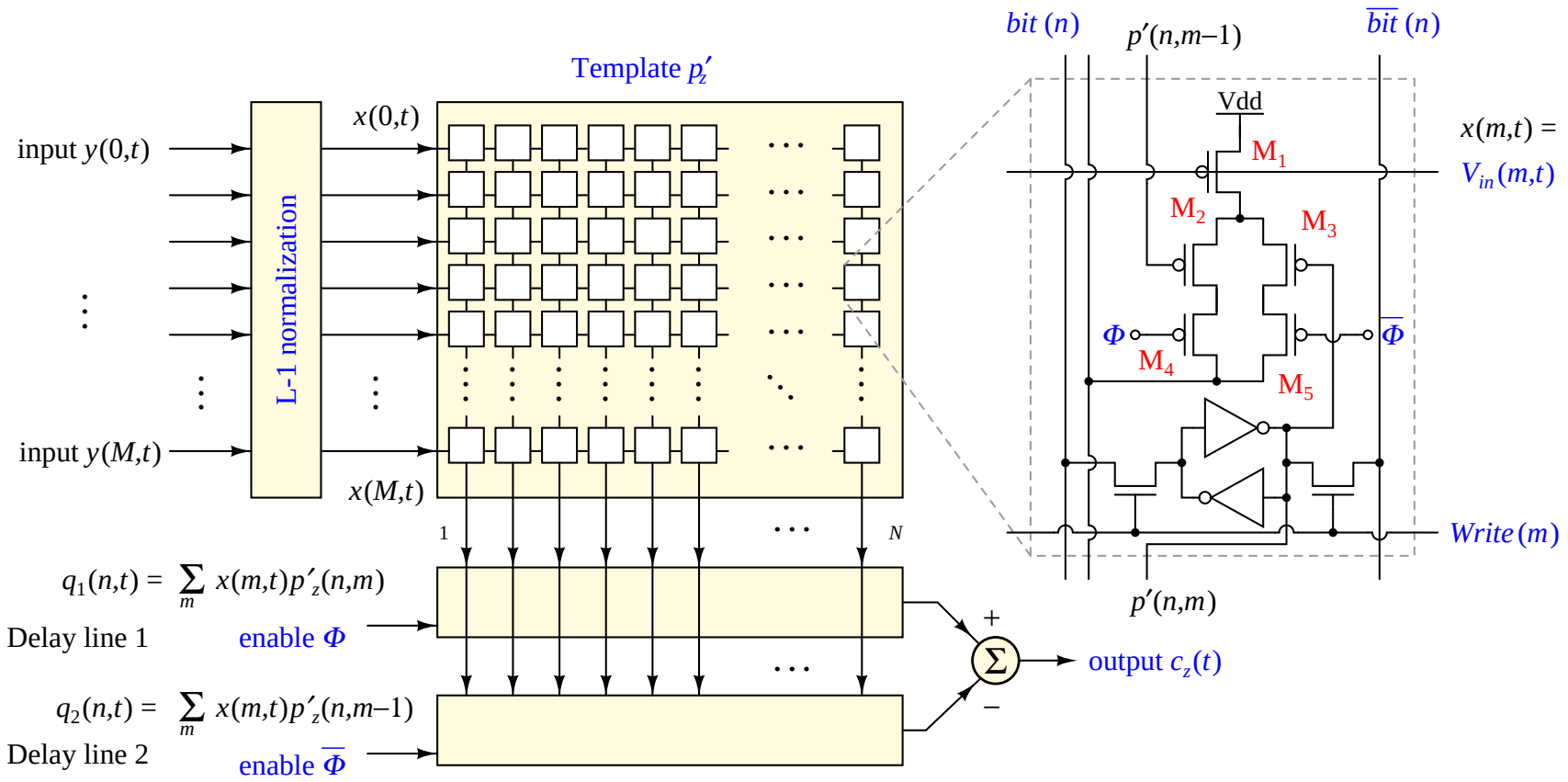
An Efficient Architecture for the Acoustic Transient Classifier

$$c_z[t] = \sum_{m=1}^{M} \sum_{n=1}^{N} \left(x[t-n, m] - x[t-n, m-1]\right) p'_z[n, m]$$

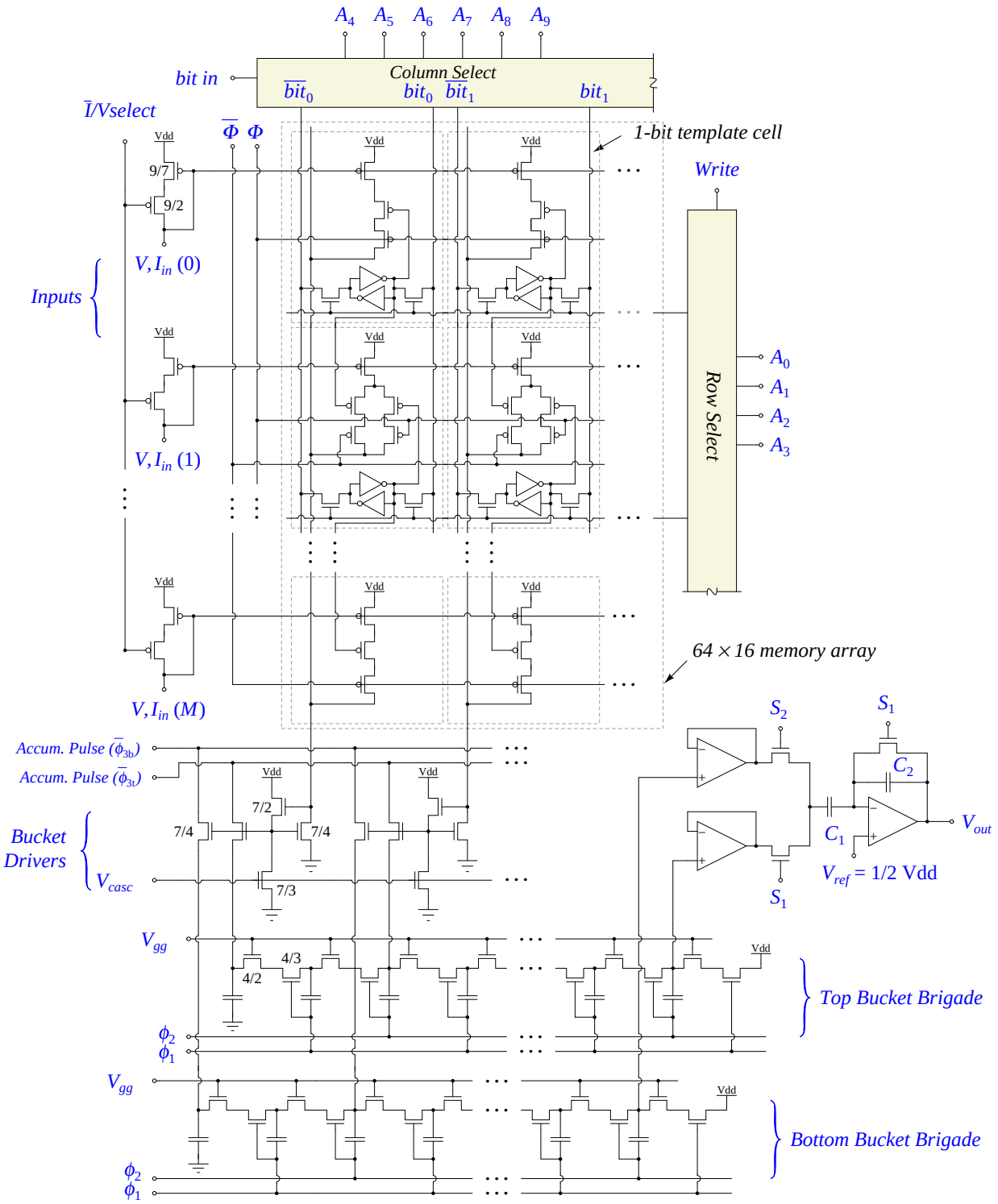
$$p'_z[n, m] = \begin{cases} 1 & (p_z[n, m] - p_z[n, m-1]) > 0 \\ 0 & (p_z[n, m] - p_z[n, m-1]) \leq 0 \end{cases}$$



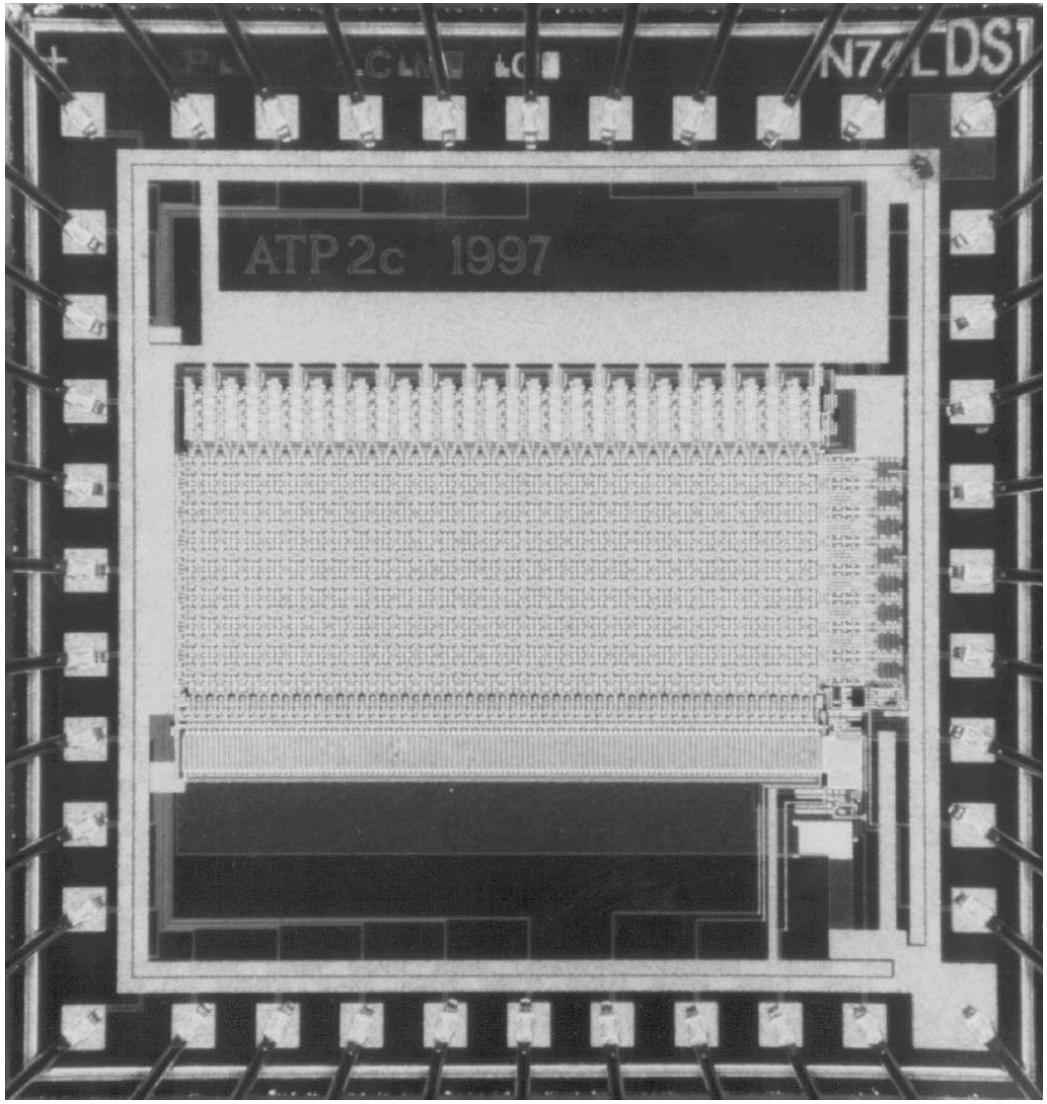
ATP Chip Architecture—Static Memory Core Cell



ATP—Complete Chip Architecture

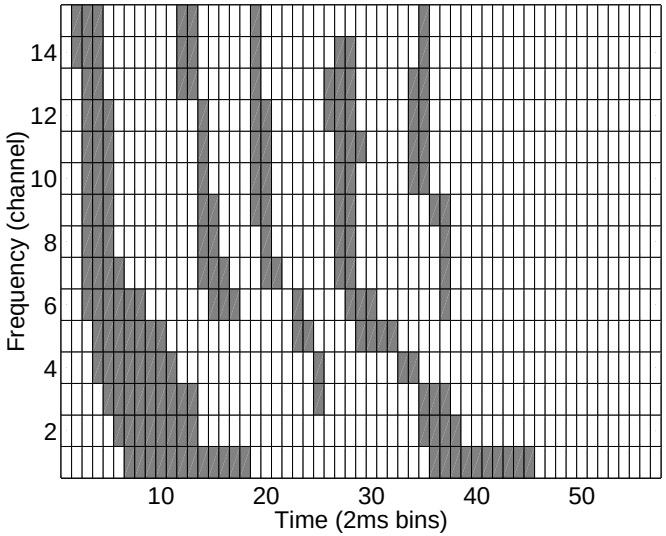


ATP—Photomicrograph



The acoustic transient correlator, a 2.2 mm $\times$ 2.2 mm die fabricated in a 1.2µm CMOS technology.

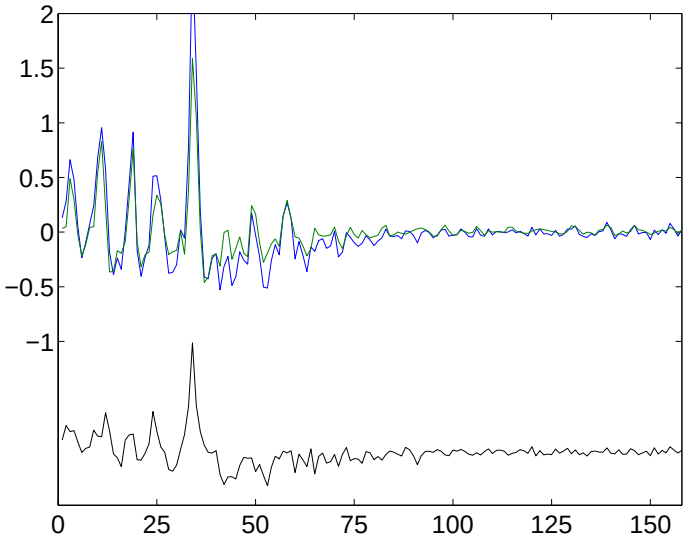
ATP Chip—Results

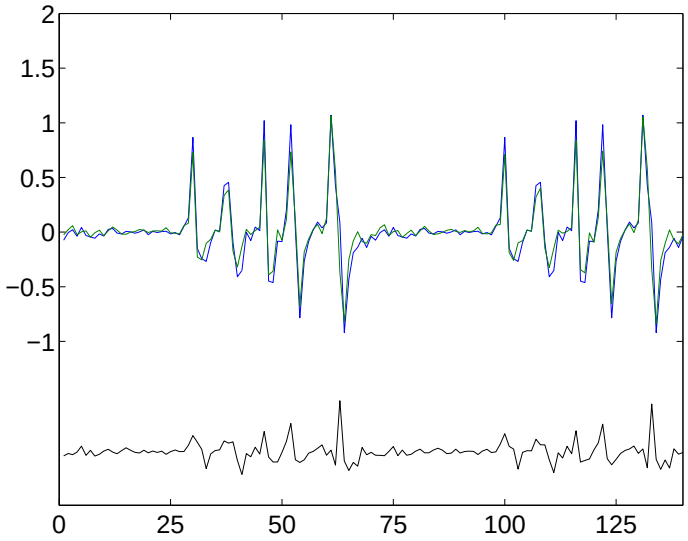


Simple template (left)
detects the transient “can” (bottom left)
but rejects the transient “snap” (bottom right).

Blue: numerical simulation.
Green: measured chip response.
Black: Residual error.

Chip measured power consumption:
50 μW





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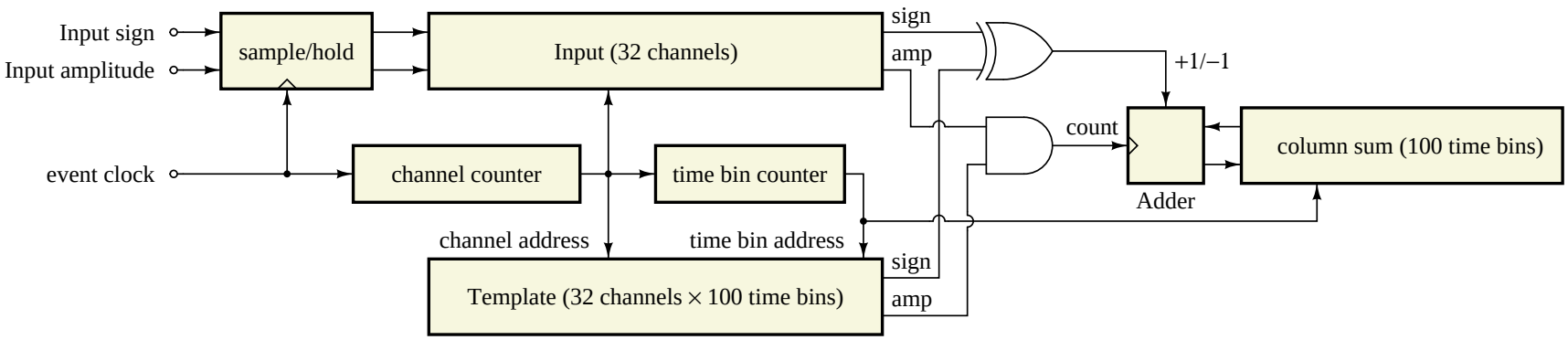
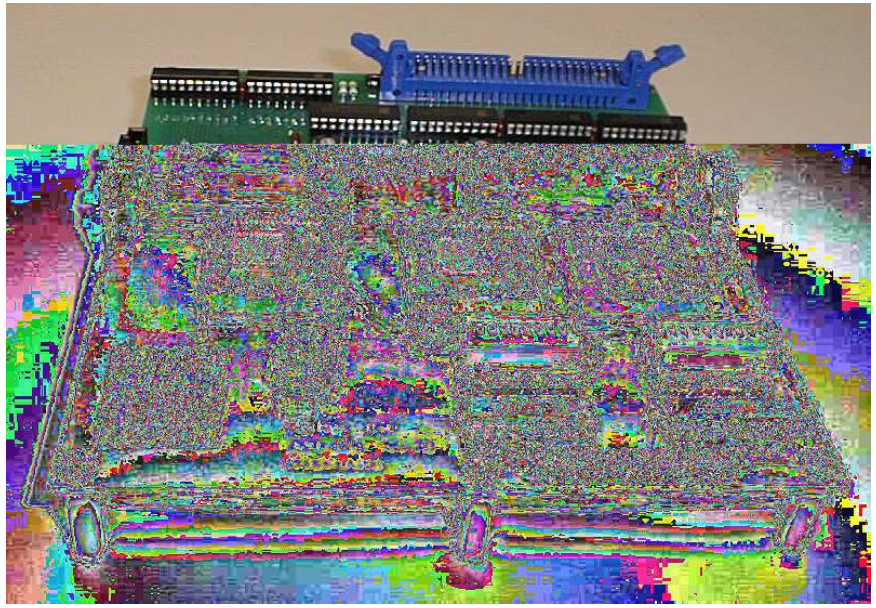
A Trinary-Trinary Correlator System

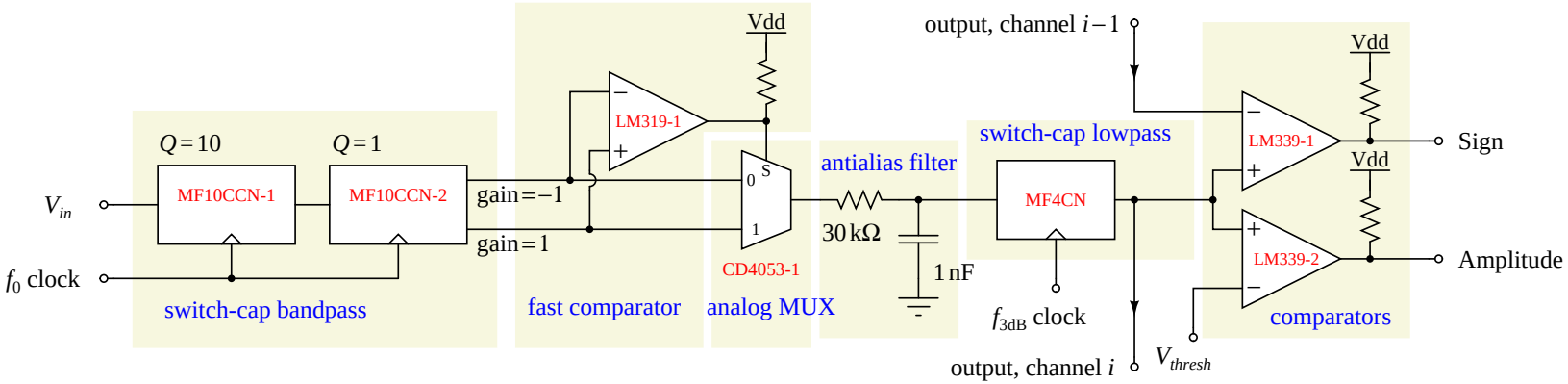


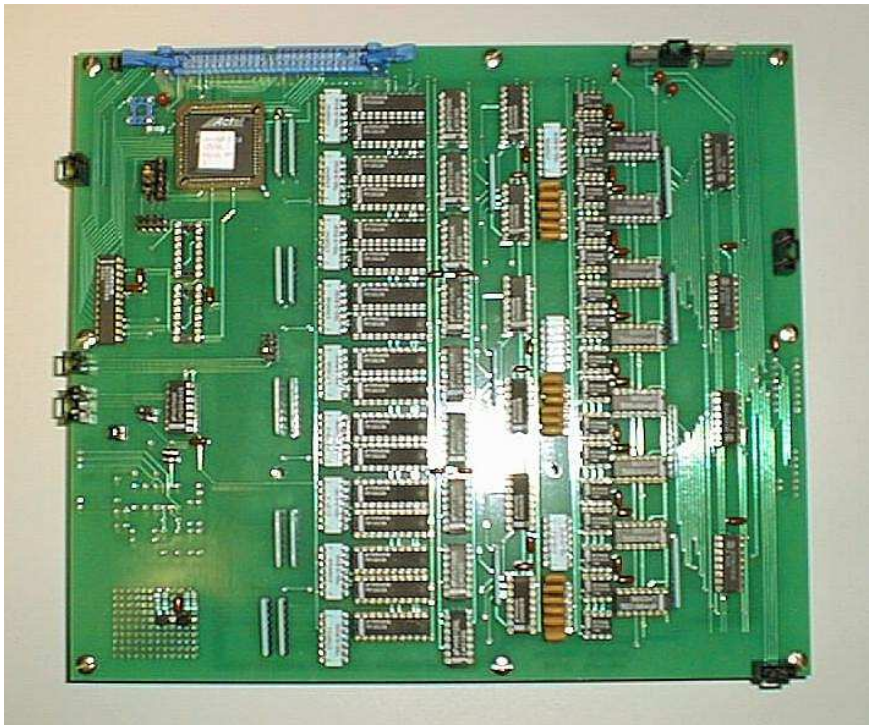


template ampl	template sign	input ampl	input sign	accumulate
0	X	X	X	0
X	X	0	X	0
1	0	1	0	+1
1	0	1	1	–1
1	1	1	0	–1
1	1	1	1	+1

Top: The “digital” acoustic transient correlator general architecture.
Above: Logic diagram for trinary-trinary correlation calculations.
Left: An FPGA and SRAM implementation of the correlation architecture.

A Switched-Capacitor Frontend System

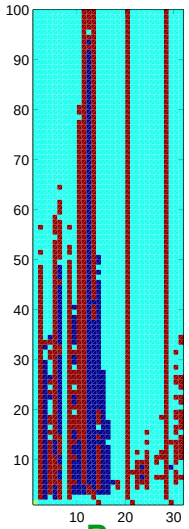


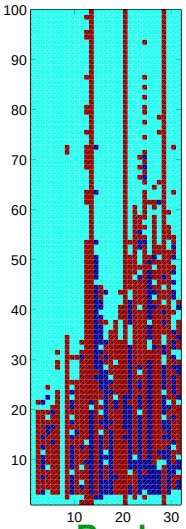


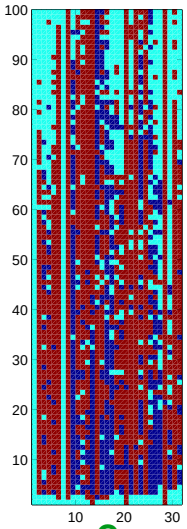
Top: The switch-capacitor frontend system architecture, with two-bit output for encoding trinary values.

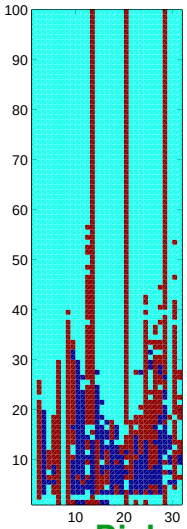
Left: A board-level implementation of the frontend architecture, with 17 channels (16 outputs), using a small FPGA to generate the frequency distribution across the filterbank.

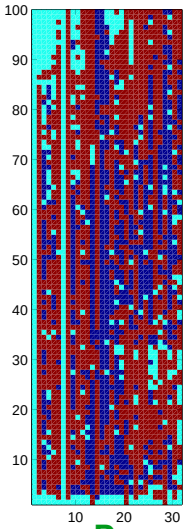
Example Templates Generated for all Classes

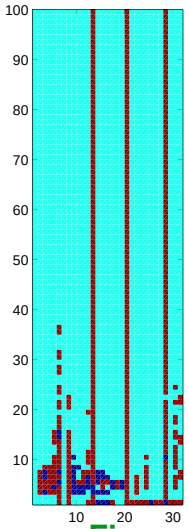


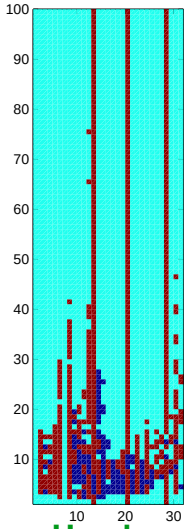


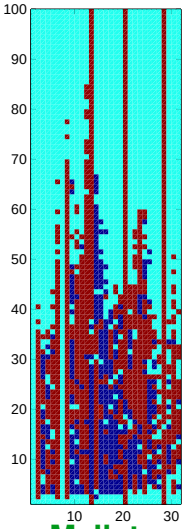


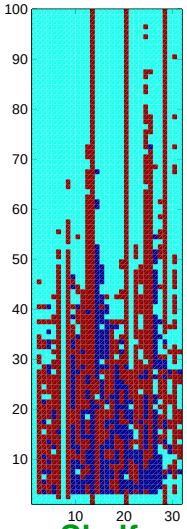


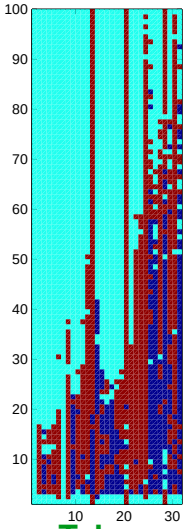


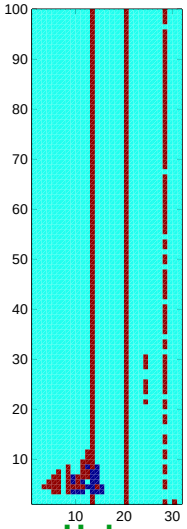


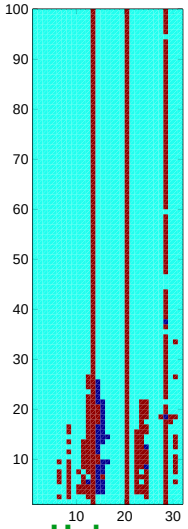




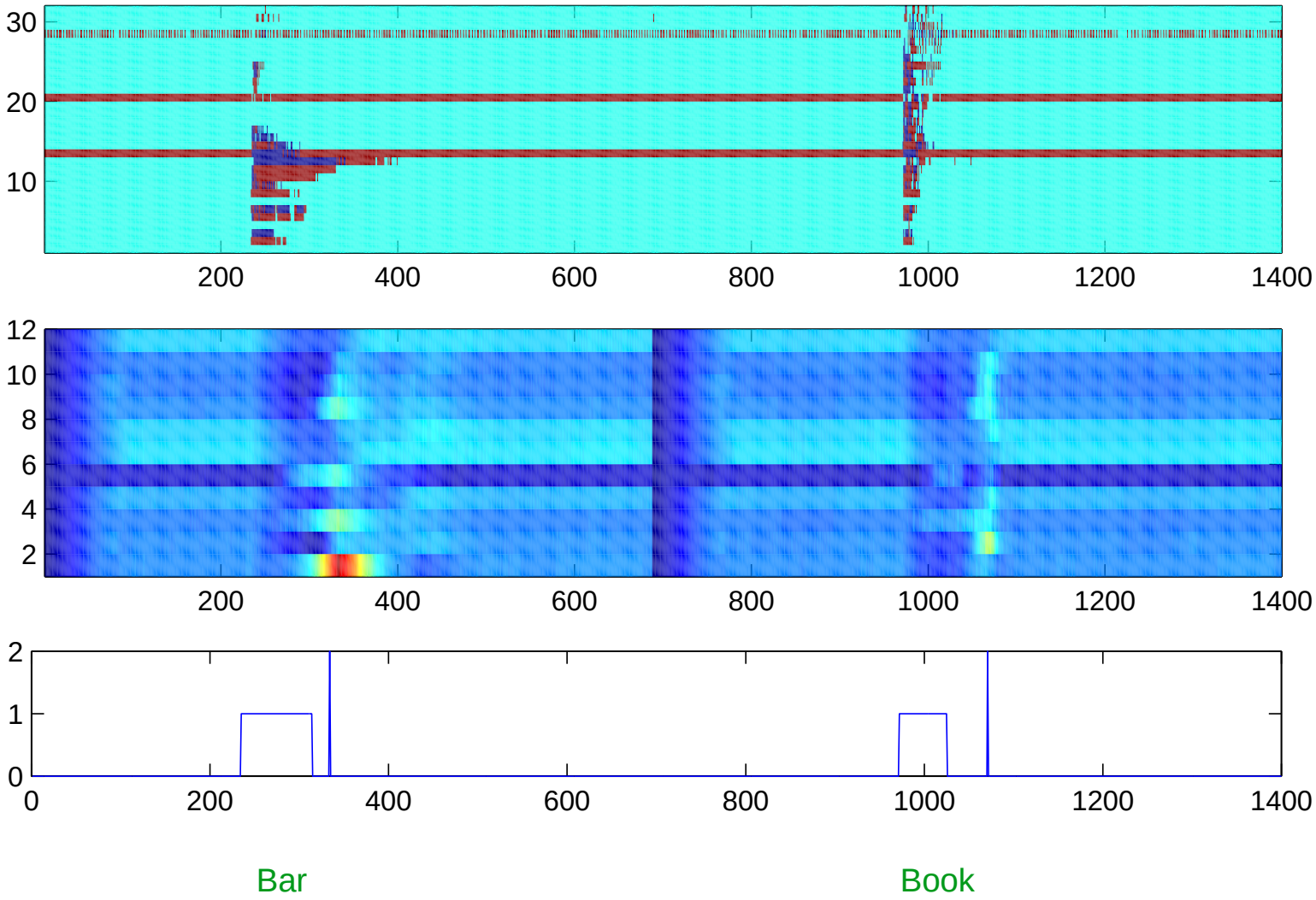








Example Correlation on Transient Data



Experimental Results of the Trinary Transient Classifier Hardware

Cross-Validation with Real-Time Segmenter

Hand-retagged data

Event	Bar	Book	Can	Dink	Door	Finger	Hand	Mallet	Shelf	Tub	Unknown	Unknown
Bar	20	0	0	0	0	0	0	0	0	0	0	0
Book	0	20	0	0	0	0	0	0	0	0	0	0
Can	0	0	24	0	0	0	0	0	0	0	0	0
Dink	0	0	0	20	0	0	0	0	0	0	0	0
Door	0	0	0	0	20	0	0	0	0	0	0	0
Finger	0	0	0	0	0	17	1	0	0	0	0	2
Hand	0	0	0	0	0	1	19	0	0	0	0	0
Mallet	0	0	2	0	0	0	0	18	0	0	0	0
Shelf	0	0	0	0	0	0	0	0	20	0	0	0
Tub	0	0	0	0	0	0	0	0	0	20	0	0
Unknown	0	0	0	0	0	3	0	0	0	0	0	0
Unknown	0	0	0	0	0	0	0	0	0	0	0	7

Statistics:

Total instances presented:	215
Total events found:	214
Correct:	205
Incorrect:	9
Missed:	1
Correctly identified:	95.3%
(In set of known targets):	97.2%
Incorrectly identified:	4.2%
Missed:	0.5%

Time-Frequency Acoustic Processing and Recognition: Analysis and Analog VLSI Implementation

- Introduction
- Template Correlation
- An Acoustic Transient Processor in VLSI:
  - Frontend Filterbank Systems
  - Template Correlation
  - Experimental Results
- A Trinary-Trinary Correlator
- Conclusion

Conclusion

Mixed Analog and Digital VLSI architectures

- promise efficient and robust implementations of acoustic signal processors
- can take full advantage of massively parallel architectures
- can pack considerable processing power into a small area
- are a good option for battery-powered, hand-held systems
- are useful as low-power systems used to continuously monitor the environment and alert a processor waiting on standby

We have developed efficient algorithms, architectures, and circuits for acoustic processing in mixed analog/digital hardware:

- log-domain synthesis and analysis
- a current-mode, log-domain bandpass filterbank
- a micropower current-mode template correlator for acoustic transient classification
- a trinary-trinary template correlator and acoustic transient classifier

Future Research Directions

- Hierarchical systems based on post-processing of acoustic transient features
- Small-vocabulary speech recognizer based on the transient classifier architecture
- Use of the architecture and hardware for sonar transient classification
- Simulate methods of processing in the auditory cortex
- On-chip automatic learning of templates