Practical Dynamic Element Matching Techniques for 3-level Unit Elements

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Outline

- Brief background
  - Motivations and Applications
  - 3-level vs. 2-level unit element: advantages and challenges
  - What problems DEM does and does not solve
- Practical dynamic element matching (DEM) techniques
  - 2-level DEM review
  - 3-level DEM
  - Limitations of each technique
  - Solution spaces
- Higher-order DEM
  - Issues in 2^{nd}-order DEM
  - Solutions
- Application specific concept of DEM

- Q and A

Applications of 3-level unit elements

What is Dynamic Element Matching?

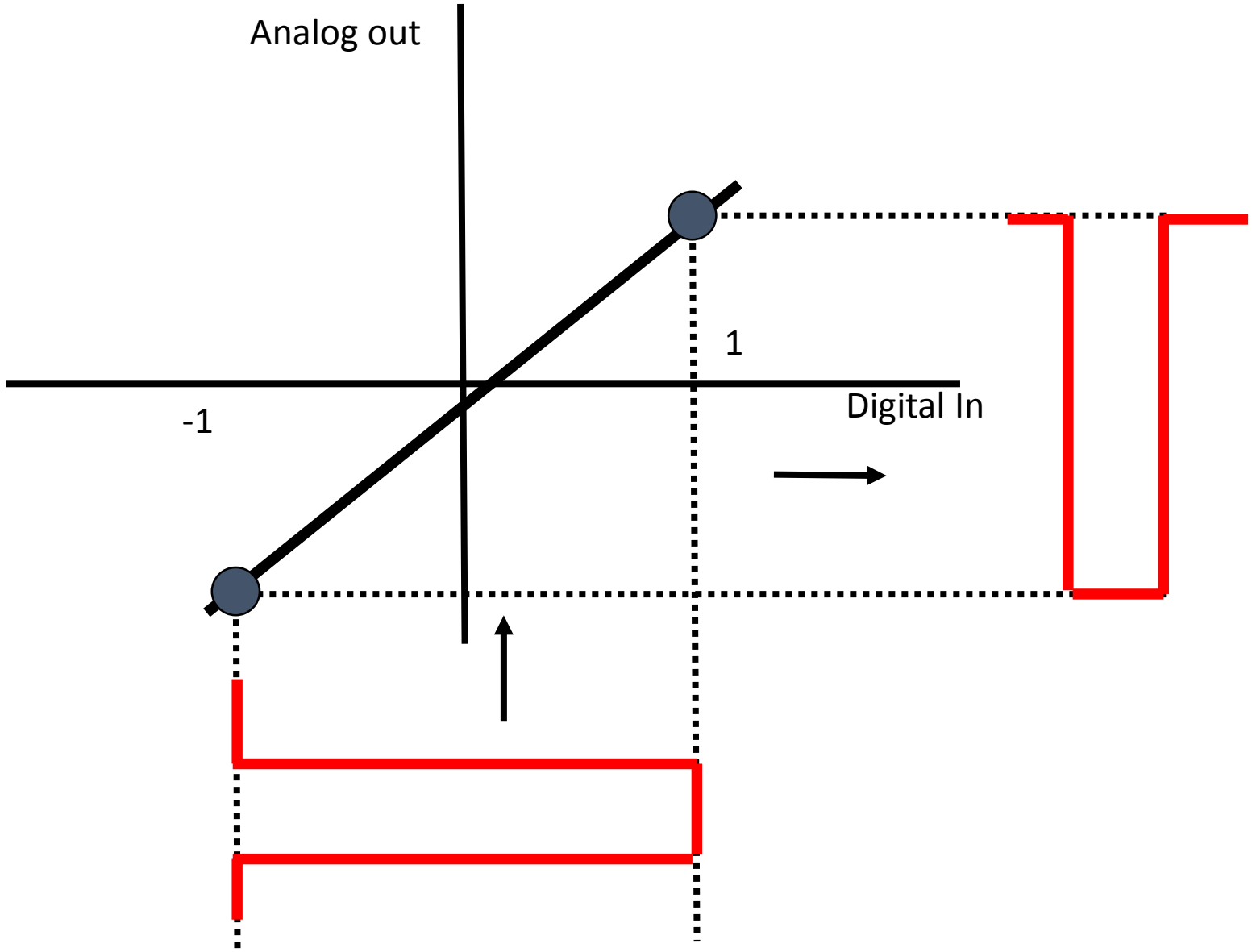
- A technique to achieve perfect matching of analog elements ***over time***.

Euclid's 5th definition for plane geometry

“Through a pair of points in space, there exists one and only one straight line”

What it means in the converter world ….

- Can achieve “perfect linearity” if the circuit output has only 2 states



Year 1995 .....

The “Perfect DAC” !

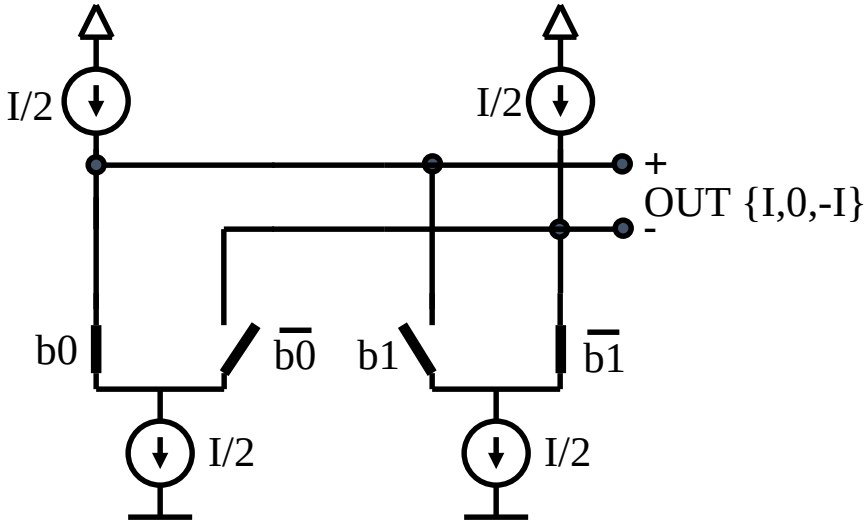
Why multi-bit ?

- Drawback of single-bit
  - High out-of-band noise → Requires stringent post-analog filter → costly, bulky
  - Limited usable input range with high-order noise shapers → Challenging to improve dynamic range
  - Stringent bandwidth and slew rate requirements for reconstruction amplifier → Challenging to reduce power consumption
- Multi-bit
  - Solves all the above but introduces linearity issue due to element mismatch → Mismatch shaping is the remedy
    - Each element is 2-level
- ***Why 3-level element ?***

Current steering DAC cell comparison

Digital input

b1	-1
b0	1

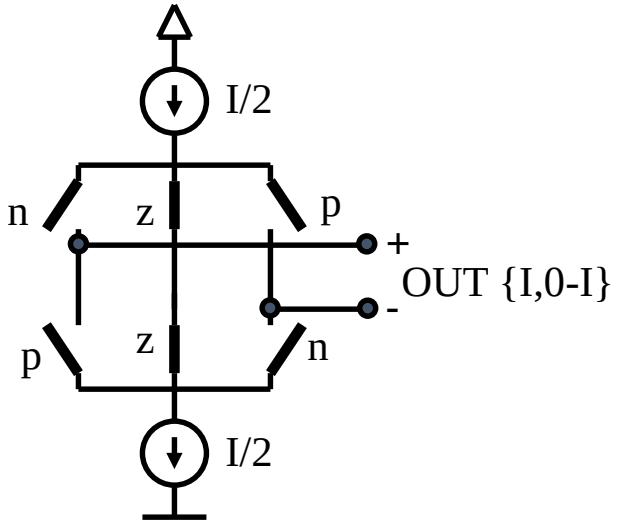


a) 2-level element architecture

Digital input

0	0
p	n

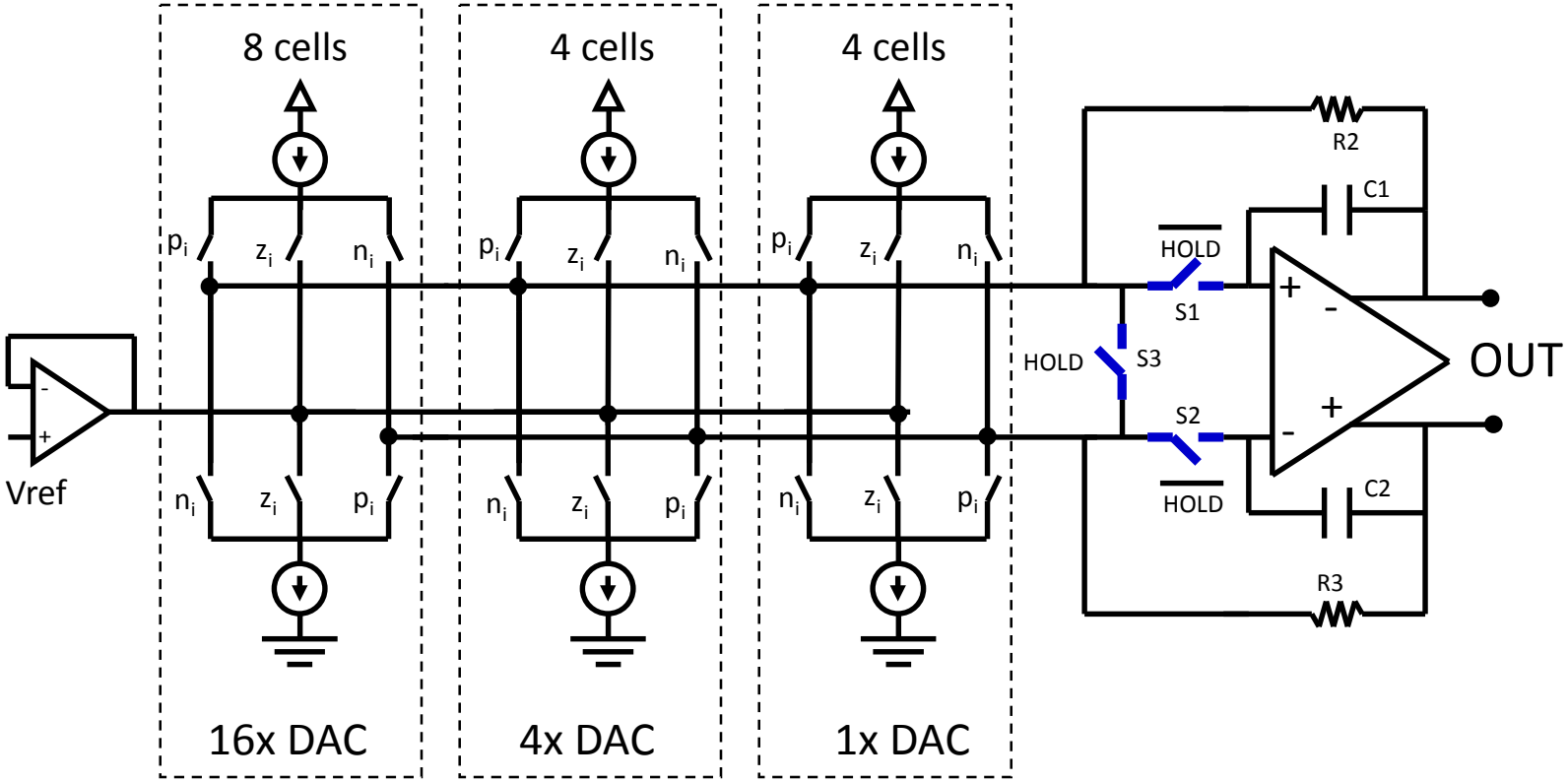
z = p NOR n



b) 3-level element architecture

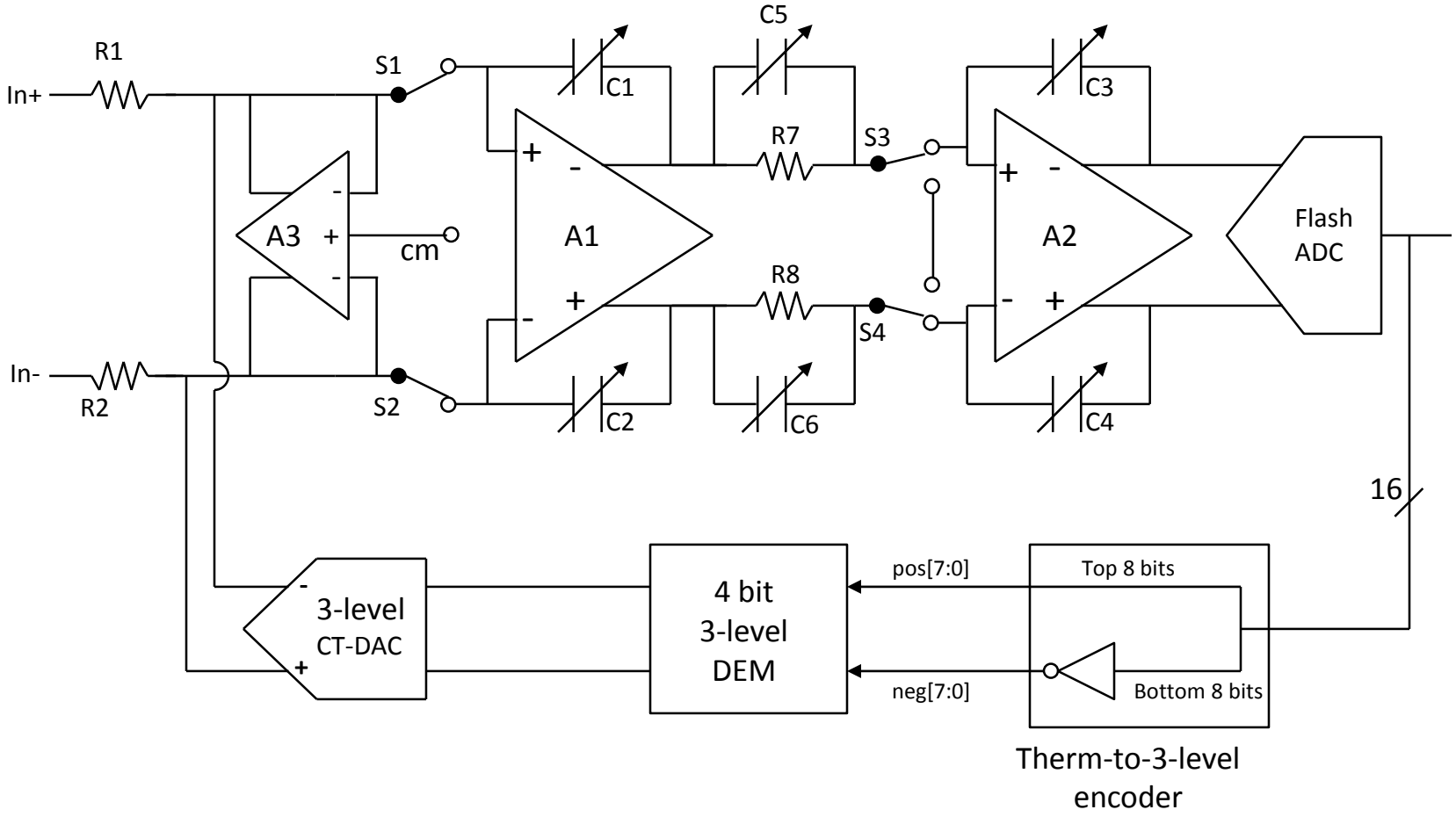
- **3-level element properties**
  - + Power efficient
  - + Best noise performance: No noise contribution in the “zero” state.
  - ***- Needs a new dynamic element matching logic***
  - - Needs a low power solution for ISI problem
  - - Drain voltage modulation degrades THD

Example 1: **High performance ΣΔ audio DAC**



Process	0.18μm CMOS
Supply	1.8 V
Full scale differential output	0.9 Vrms
Digital power consumption	0.4 mW / channel
Analog power consumption	0.7 mW / channel
OSR	64
Clock frequency	3.072 MHz
SNR (A-weighted)	108 dB
THD+N	-97 dB

Example 2: **High performance ΣΔ audio ADC**



Process	0.18μm CMOS
Supply	3.3 V
Digital power consumption	0.4 mW / channel
Analog power consumption	2 mW / channel
OSR	128
Clock frequency	6.144 MHz
SNR (A-weighted)	111 dB
THD+N	-97 dB

3-level element in ΣΔ ADC

- Additional advantages:
  - Minimum noise contribution from current steering DAC at low level signal (below -60dB full scale)
  - Equivalent to a current noise from a large resistor R, $i_N = \sqrt{4kt/R}$
    - I-DAC current noise is not the dominant source anymore
  - Dominant noise sources : input R and amplifier
    - For the same SNR target : Larger allowable R → Smaller integration capacitor size → Silicon area saving
  - Less switching activity at low level → Less spectral leakage due to ISI
- Cautions
  - Signal dependent switching activity → A source of harmonic distortions
  - Slight noise modulation due to signal amplitude

DEM: What it does and does not solve

- Solves
  - Cell-to-cell static mismatch (born or due to aging)
    - Between the +1s’ and the -1s’
  - 1/f noise of cells

- Does not solve
  - Magnitude error between “+1” and “-1” of a single cell
    - Circuit design technique exists as remedy for this issue
  - Cell-to-cell mismatch due to switching dynamics

Recap

- Brief background
  - Motivations and Applications
  - 3-level vs. 2-level unit element: advantages and challenges
  - What problems DEM does and does not solve
- Practical dynamic element matching (DEM) techniques
  - 2-level DEM review
  - 3-level DEM
  - Limitations of each technique
  - Solution spaces
- Higher-order DEM
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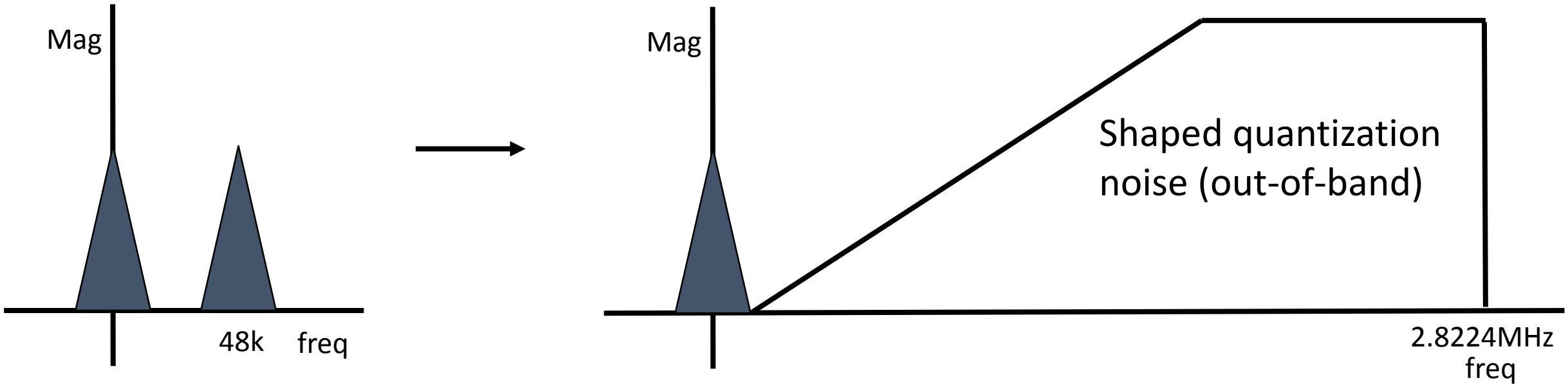
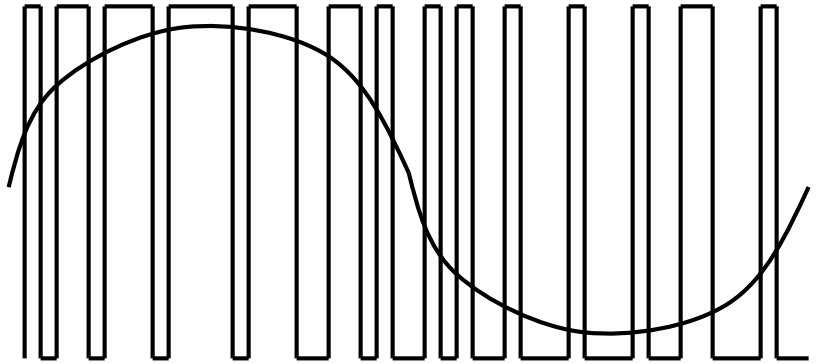
Review: Noise shaping concept

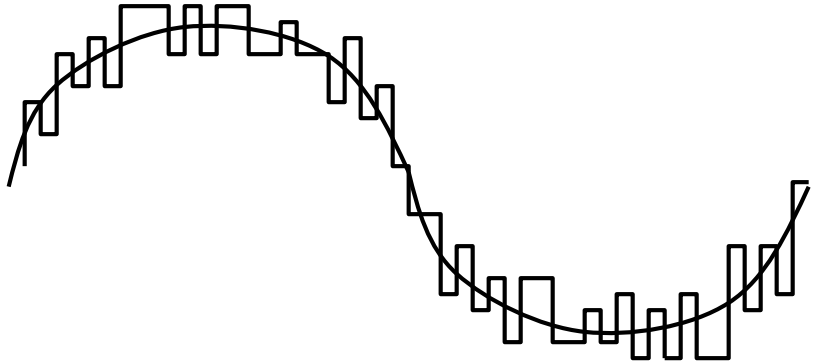
- High precision multi-level analog quantity is “difficult” to reconstruct
- Noise shaping: Trade off frequency band usage for word-width
  - 16b @ 44.1kHz → 1b at 5.6488MHz



1-bit versus multi-bit DAC

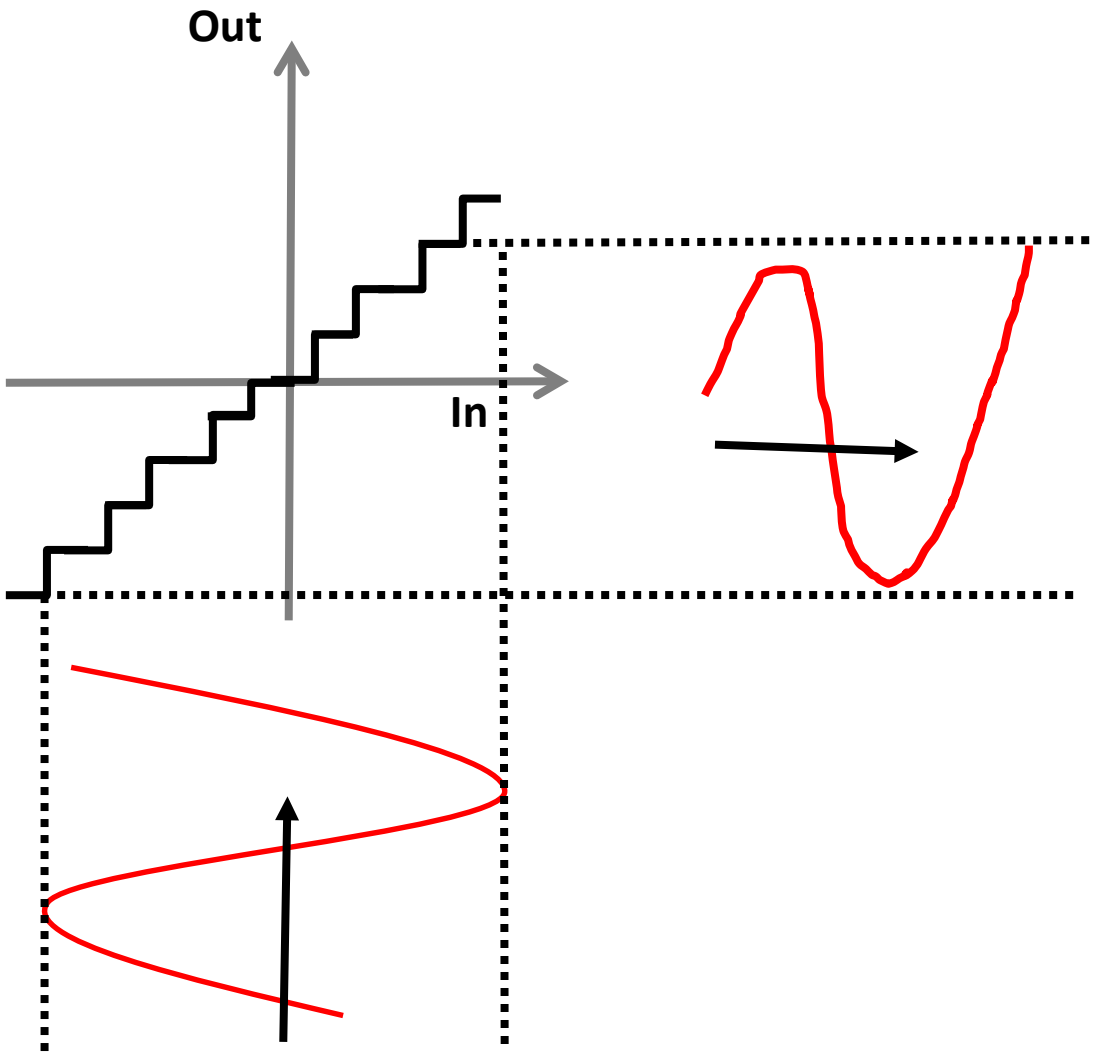


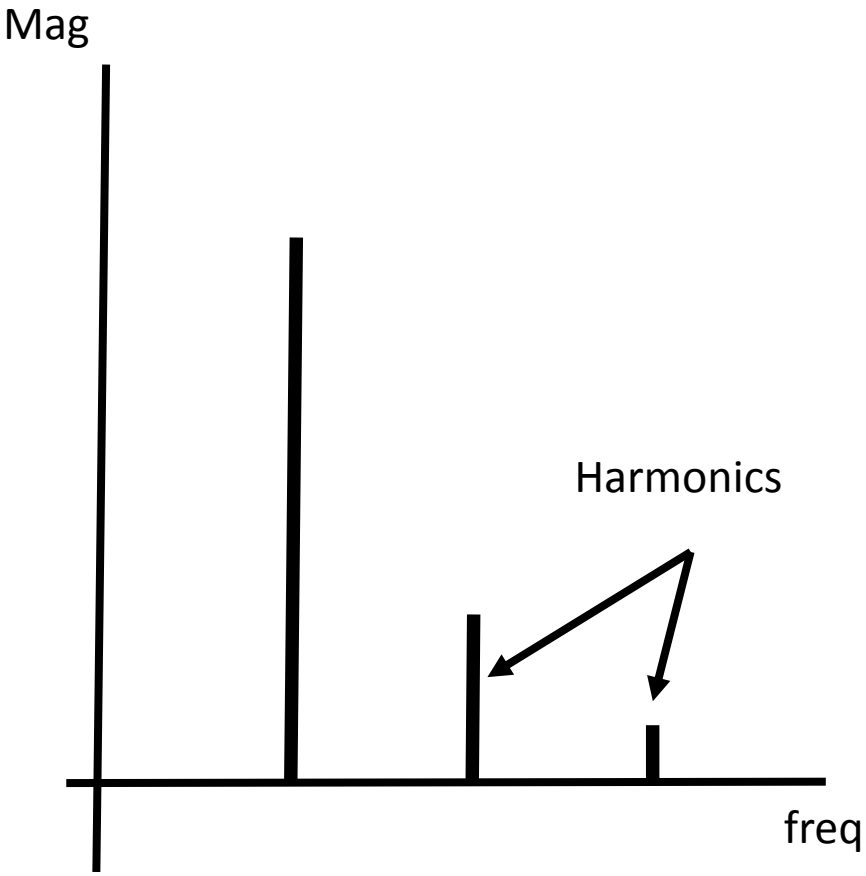
- **1-bit Advantages**
  - Linear – no matching issue
- **1-bit problems**
  - Large step size → jitter sensitivity
  - Tonal quantization noise can cause "idle tones" (quantizer can't be dithered properly)
  - High-order loops become unstable with large inputs



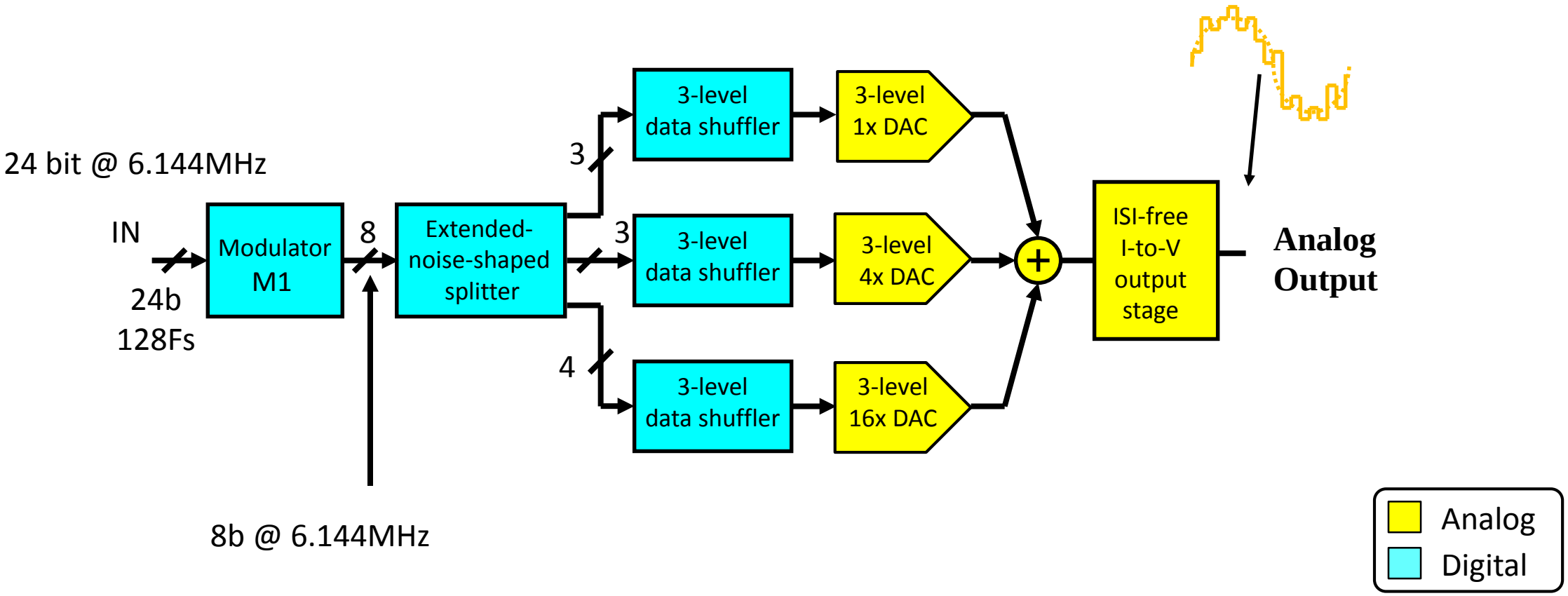
- **Multi-bit advantages**
  - Tone-free quantization noise (can be dithered)
  - Lower-order loops can often be used (easier stability)
  - Small steps (low jitter sensitivity, less filtering required)
- **Multi-bit problems**
  - Matching; DAC element errors cause distortion + noise

Multi-bit with element mismatch





Example of multi-bit audio DAC

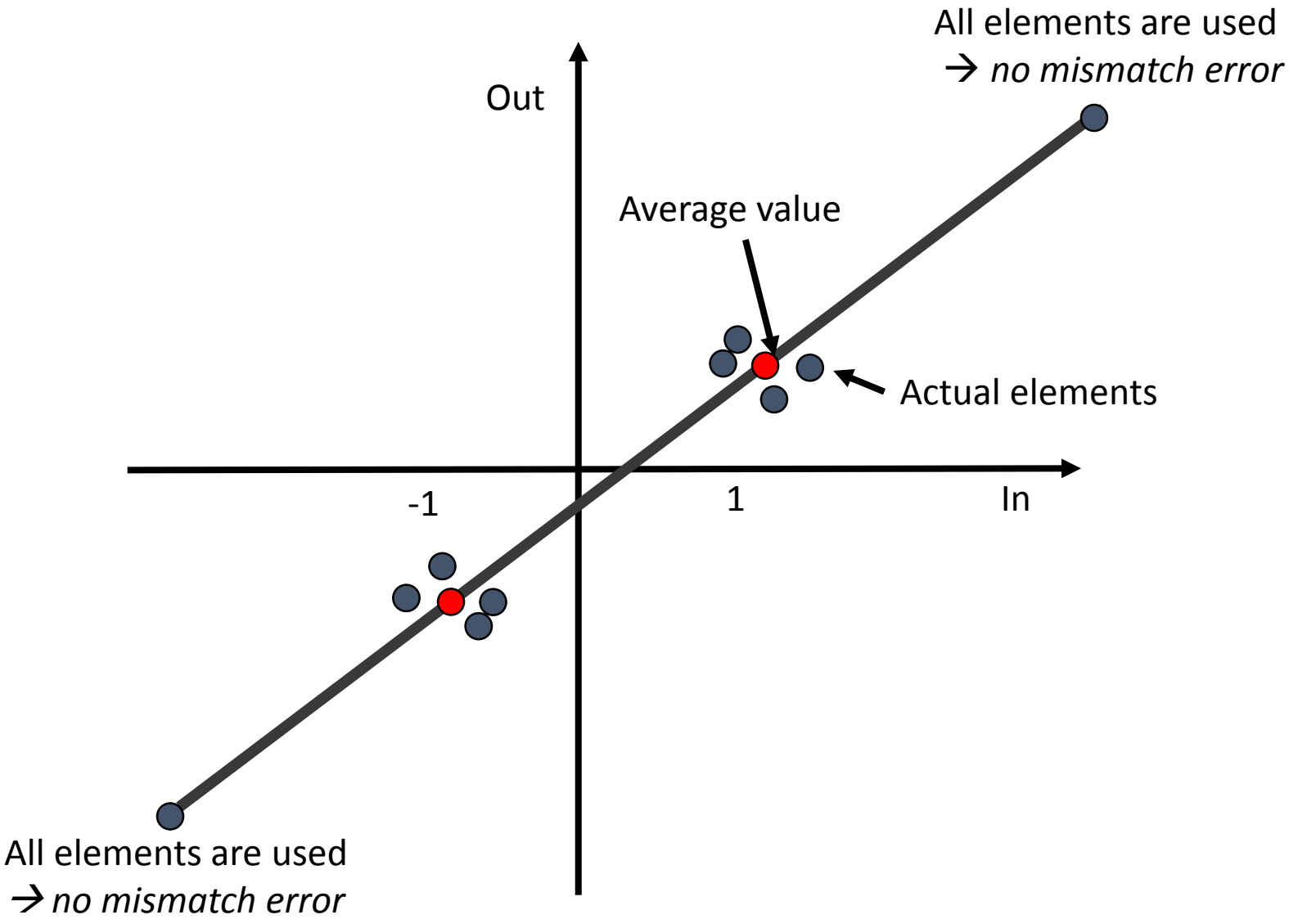


The essence of DEM

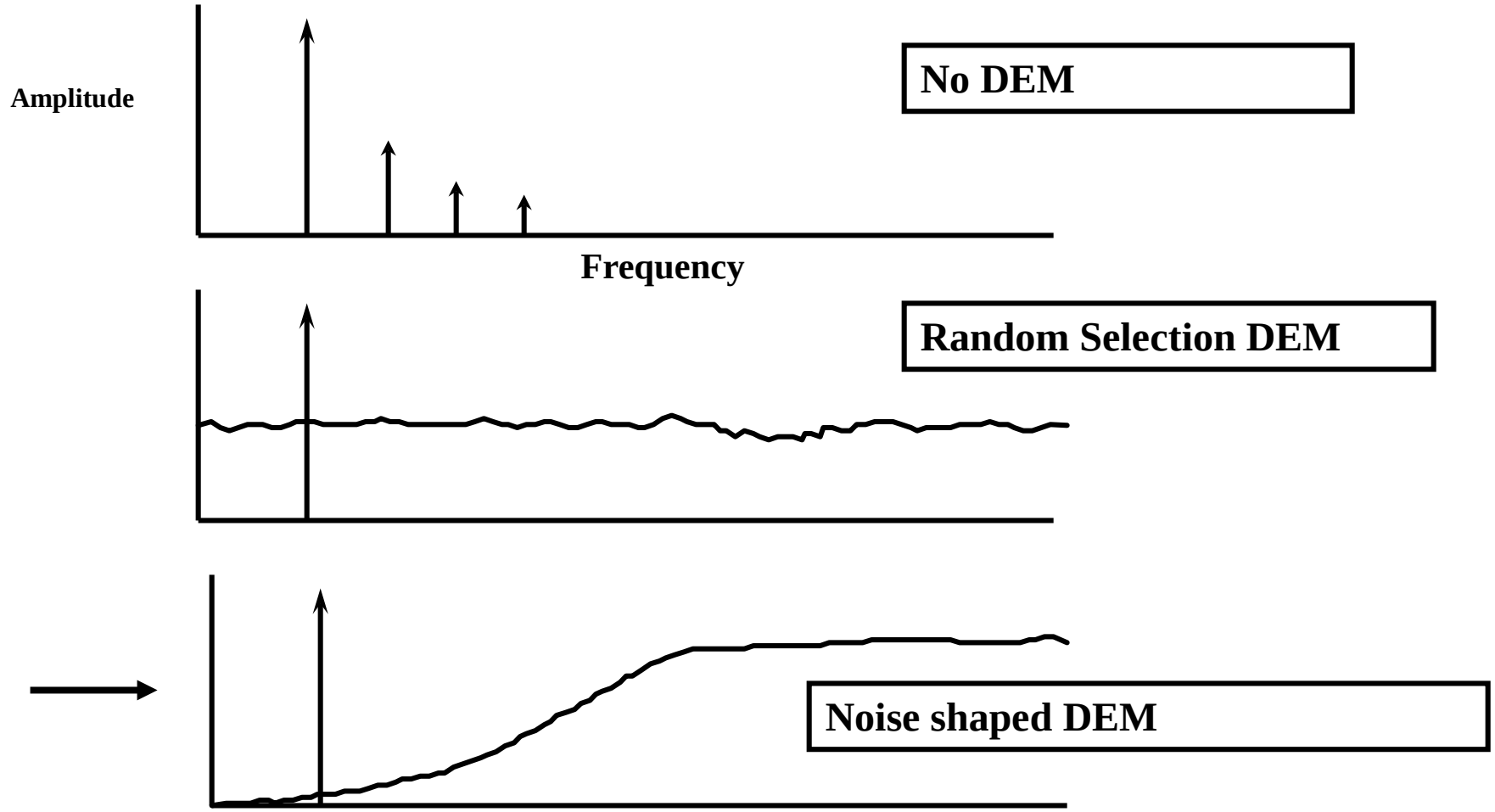
- Linearizing the transfer function
  - Making each element appears as average value → Reconstructed values are "perfectly" linear in the band of interest

- Requirements
  - Use thermometer coded data (uniformly weighted elements)
  - Must have multiple ways (redundancy) to reconstruct any value
  - Have an "out-of-band" region to push shaped mismatch errors to. i.e., oversampling ratio larger than 1 (practical OSR >= 16)

Multi-bit transfer function



Spectral contents with and without DEM



Approaches to 2-level unit element DEM

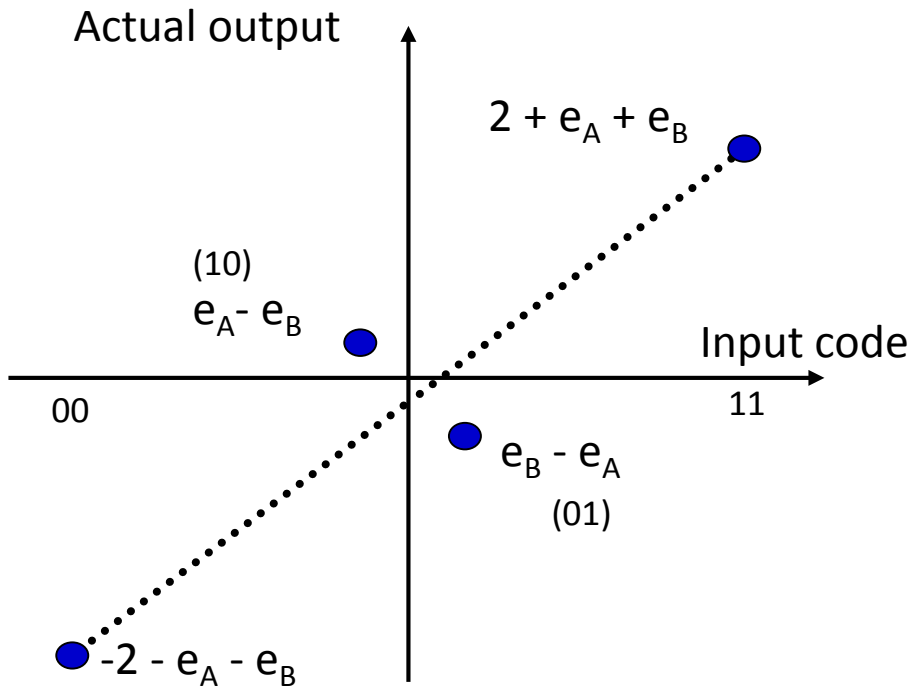
1. Data directed
2. Rotational
3. Tree structure
4. Vector quantization
5. Real-time

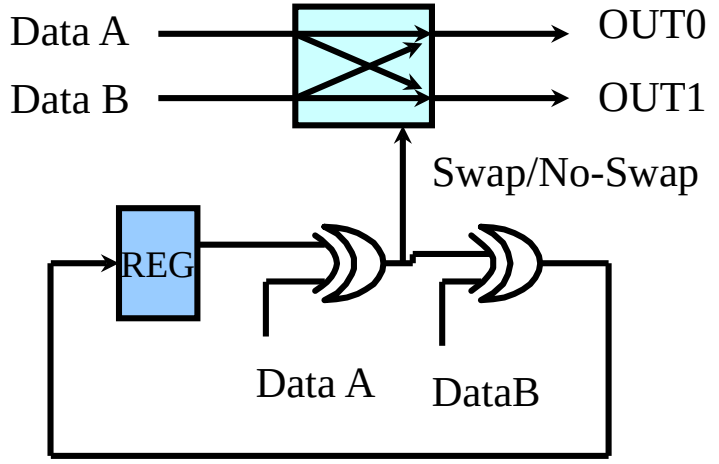
1. Data directed shuffling

- Consider a 2-bit thermometer code DAC
  - Cell A = 1 + e1
  - Cell B = 1 + e2

AB	Out	Instantaneous error (ei)
00	-(2+e1+e2)	0
01	-e1 + e2	-e1+e2
10	e1 – e2	e1-e2
11	2+e1+e2	0

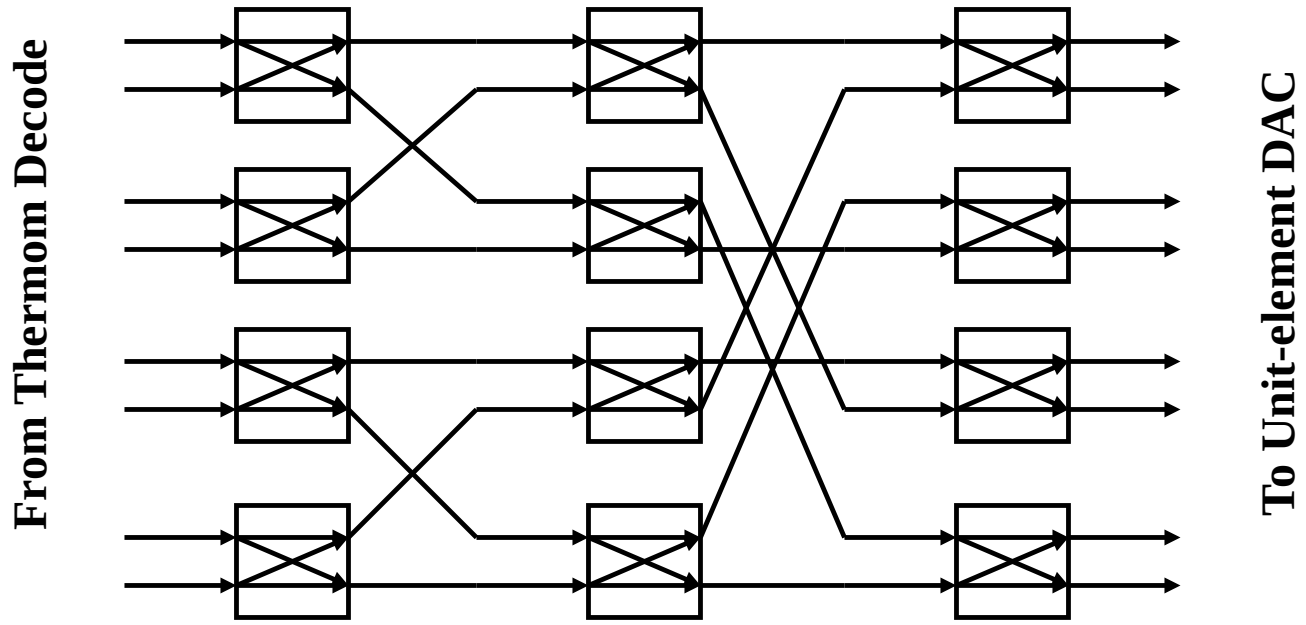
- Goal: Make the cumulative error approach zero.
  - *Done by alternating use of OUT1 and OUT2 when A ≠ B*





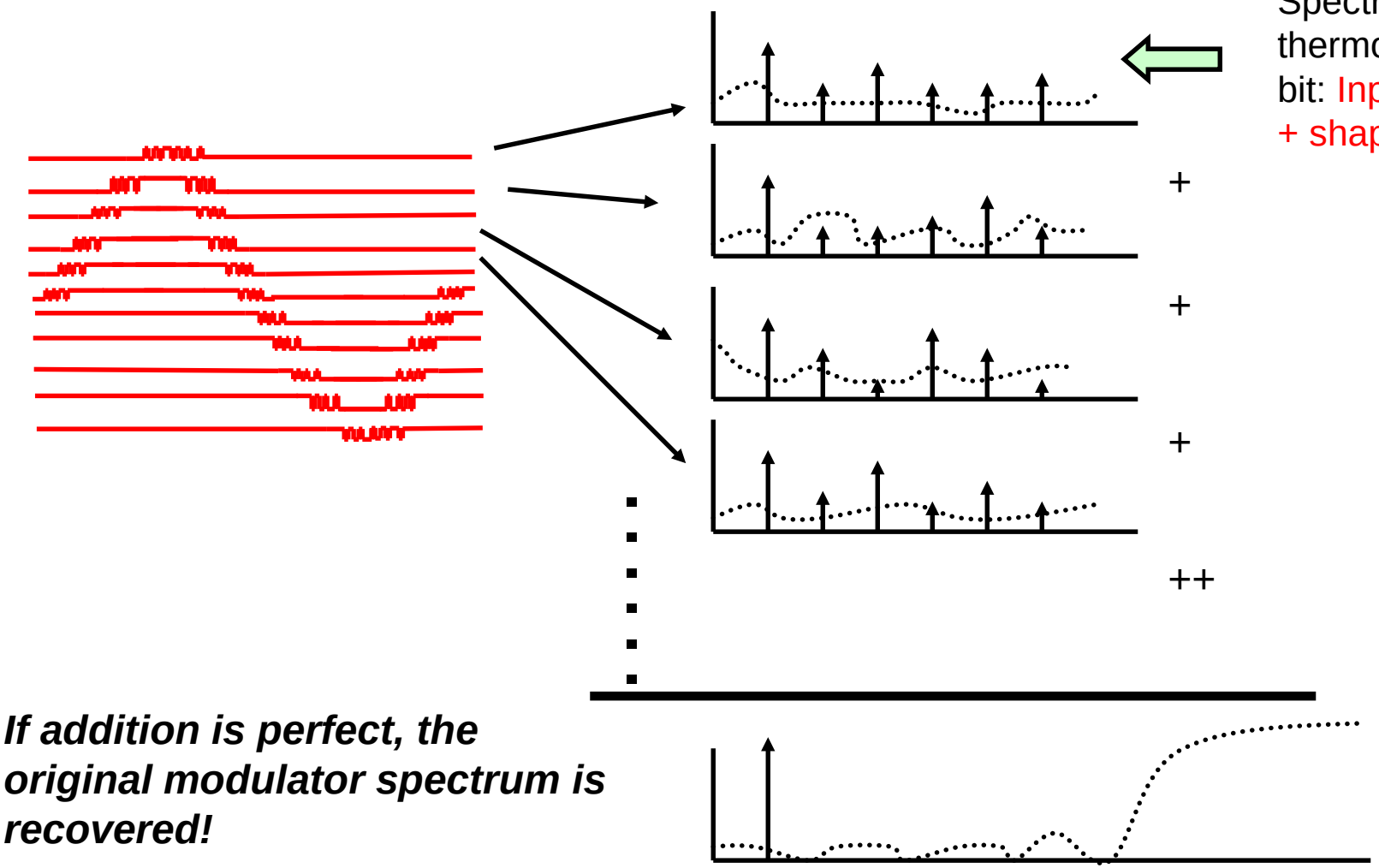
Swapper cell

How to make a multi-bit shuffler



- Butterfly network works as “usage” correlator
- Every input can reach every output
- Decision to swap is made by swapper cell

Spectral view of mismatch shaping

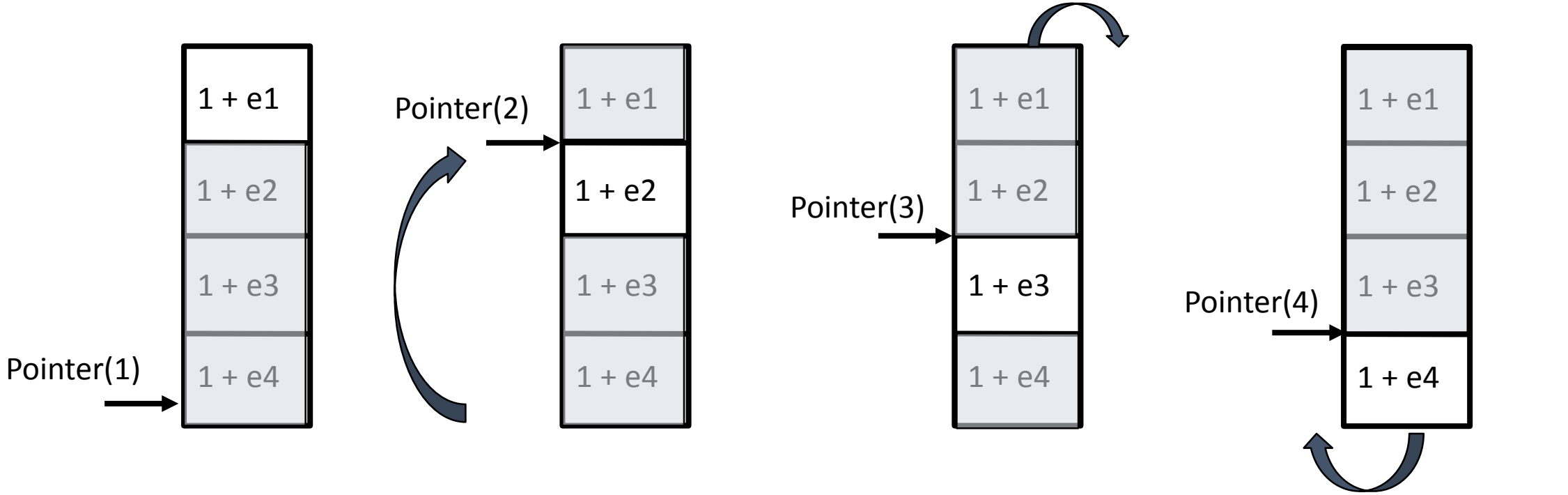


Spectrum of a single thermometer-encoded bit: Input + harmonics + shaped mismatch

If addition is perfect, the original modulator spectrum is recovered!

2. Rotational DEM

- Example: Digital in = 1, element selection in 4 clock cycles



E(1) = -e1 + e2 + e3 +e4

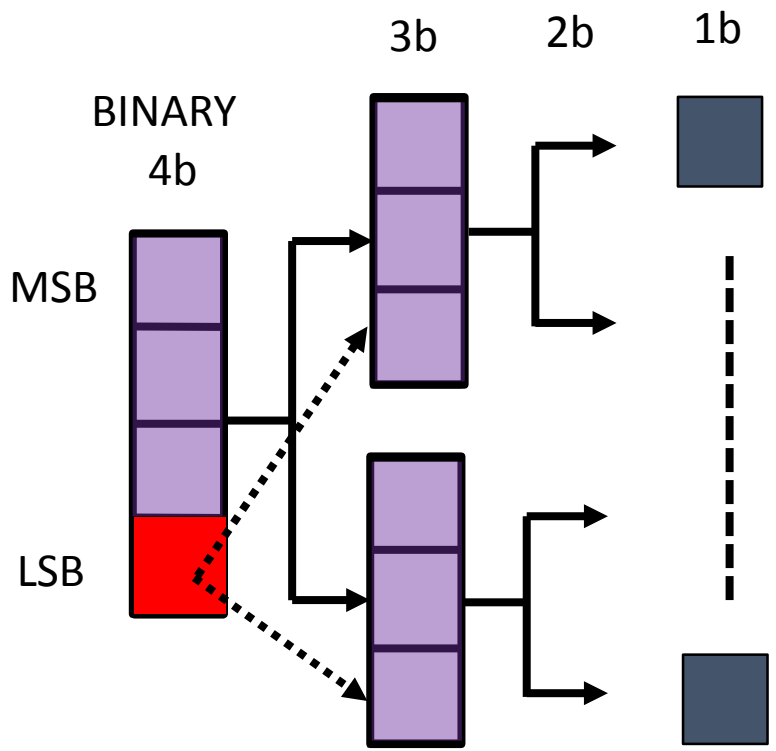
E(2) = e1 - e2 + e3 +e4

E(3) = e1 + e2 - e3 +e4

E(4) = e1 + e2 + e3 - e4

- **Cumulative error after 4 cycles = 2(e1 + e2 + e3 + e4)**
- **(e1+e2+e3+e4) : all elements are used equally → cumulative error = zero!**

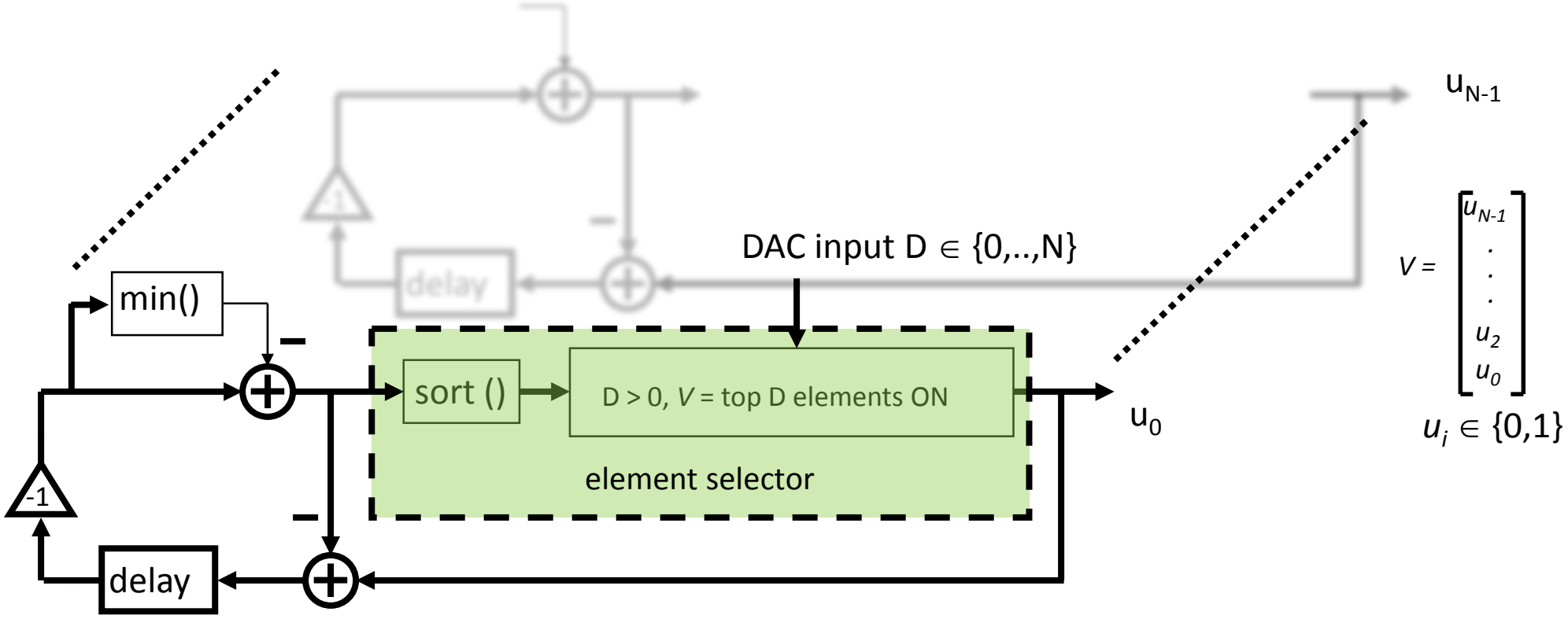
3. Tree structure DEM



- **DEM algorithm**
  - Start with N-bit binary word
  - Divide by 2 (shift left by 1)
  - If LSB = 1, use $\Sigma\Delta$ modulator to decide which sub-word to receive the LSB
  - Update modulator
- **Observation**
  - Difference between 2 words is a noise shaped sequence → Gain mismatch is high-passed
- **Note:**
  - Needs headroom to not overflow
  - Works fine for first–order shaping, what happens if input is EVEN for a while!

4. Vector quantization

- Generalized version of all DEM algorithms → Excellent model to study DEMs
- Hardware intensive

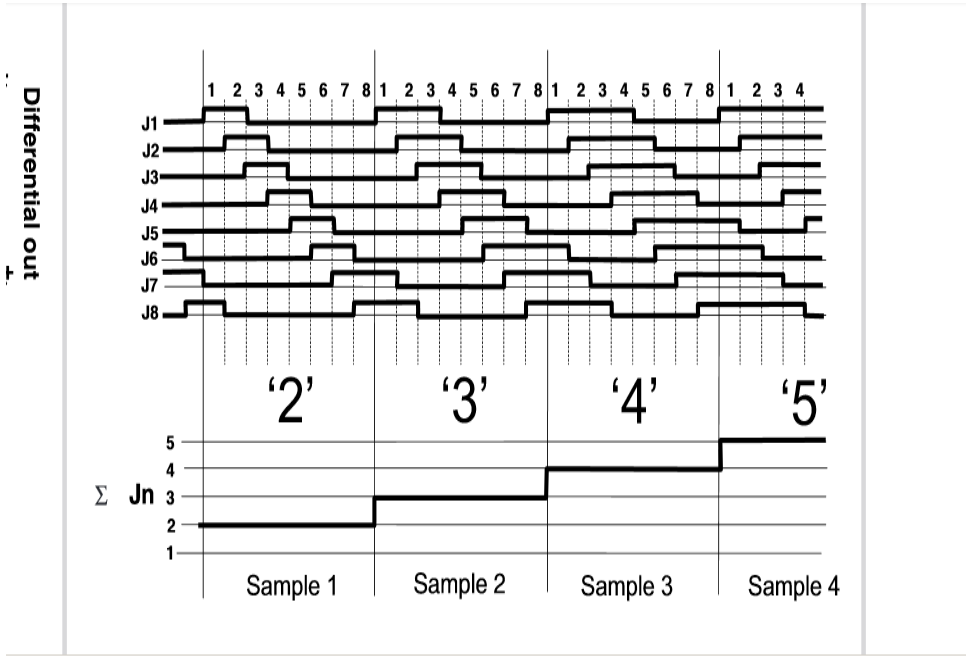


Example of a 1st-order DEM (using the error feedback ΣΔ structure)

Element selection logic

- Rank N input vectors with least used first
- Turn on (assert “1”) D output elements in output vector V
- Feedback the elements of V to the corresponding integrators (or loops)
- Can apply the use of a dithering vector to the input of the sorting routine to cure idle tone behavior

5. Real-time DEM



- Use all elements in every modulator clock cycle
  - Advantage:
    - Very simple logic
  - Drawbacks:
    - Need a fast clock (2^N times) for an N-bit DAC
    - Cannot go beyond 1^{st}-order shaping

Recap

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Approaches to 3-level unit-element DEM

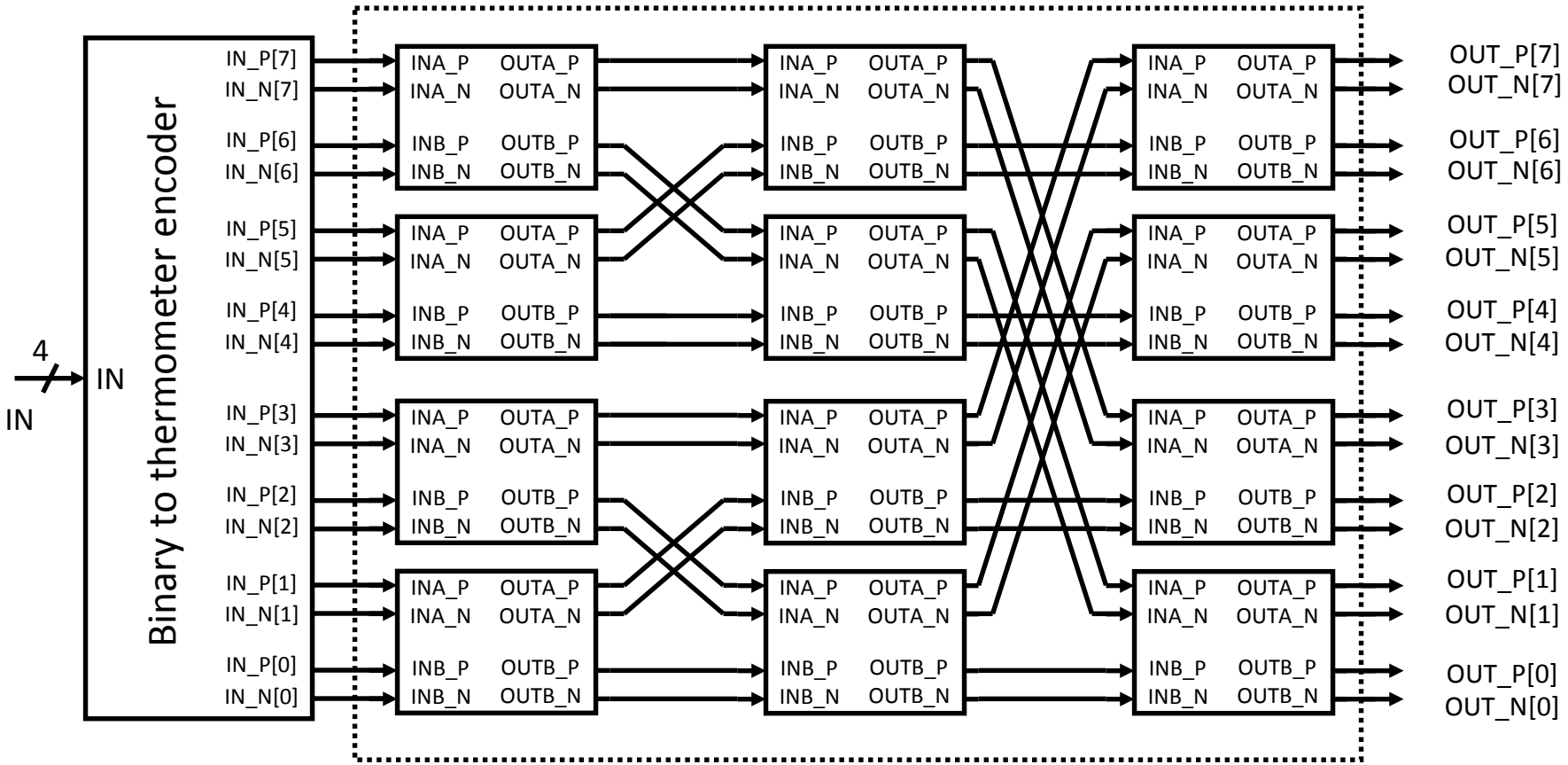
1. Data directed shuffling
2. Rotational
3. Tree structure
4. Vector quantization

Encoding style for 3-level data

- Best to treat data as **positive and negative thermometer codes** separately
- Results in simplest logic manipulation and decoding logic in the current steering cells
- Truth table

Positive thermometer code	Negative thermometer code	Analog value
1	0	+1
0	1	-1
0	0	0
1	1	Unused

Approach #1: Data directed shuffling

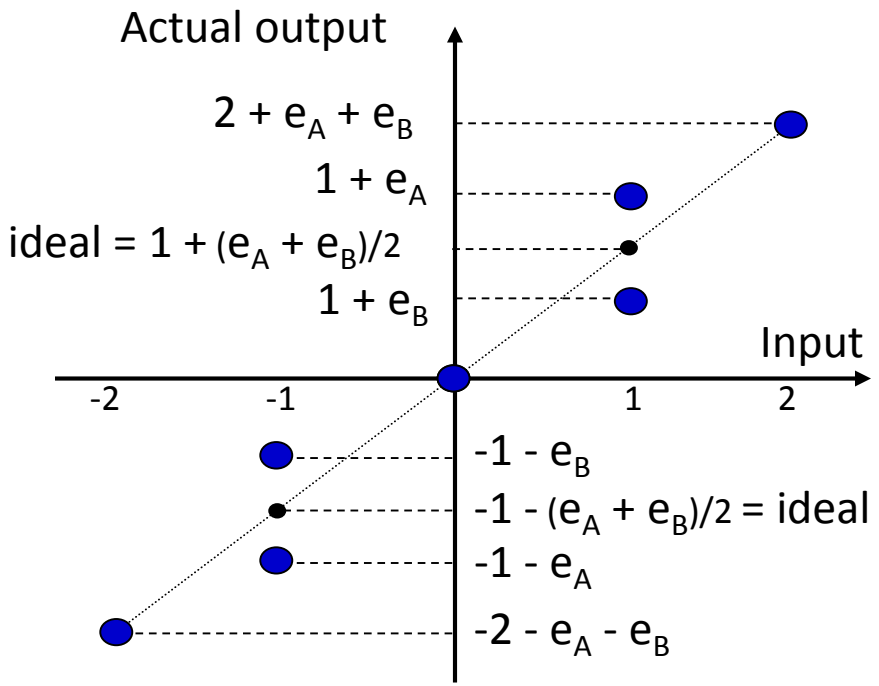


A 4-bit example

- Butterfly network serves as the usage correlator

$$\#\ of\ cells = \frac{N}{4}\log\left(\frac{N}{2}\right),\ for\ N+1\ output\ levels$$

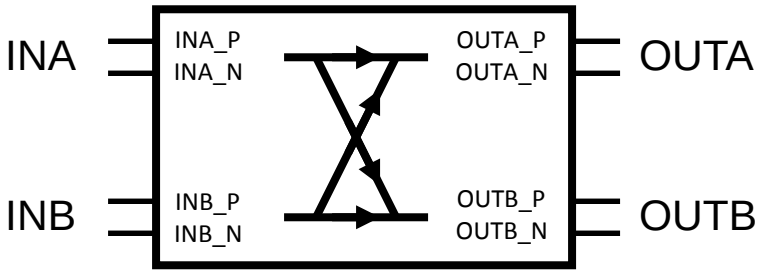
3-level mismatch error analysis



Transfer function of a DAC formed by a pair of analog elements A and B

- e_A and e_B: individual error of element A and B
- Error delivered:
  Ideal - Actual $\in \begin{cases} (e_A - e_B)/2 \\ (e_B - e_A)/2 \\ 0 \end{cases}$
- Goal: Select elements so that the long term average of each output level approaches its ideal value
- A 2b state machine to keep track of cumulative error

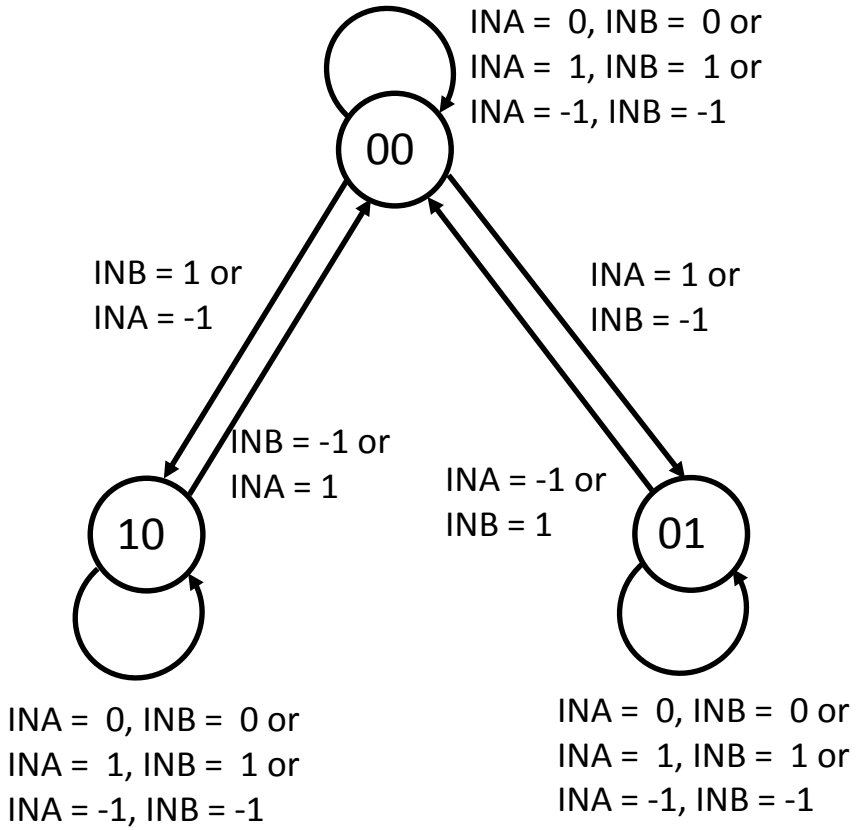
Cell implementation



INA, INB, OUTA, OUTB are 2b quantities	
Value	Code (PN)
+1	10
-1	01
0	00
unused	11

- Output value = OUTA + OUTB, $\in \{-2,..0..,2\}$
- Simple modification of thermometer code
  - A and B always have the same sign
- Input can be rerouted to either output
- Needs a state machine

State diagram



- Cumulative error:

  "00" : *zero*

  "01" : $(e_B - e_A)/2$

  "10" : $(e_A - e_B)/2$

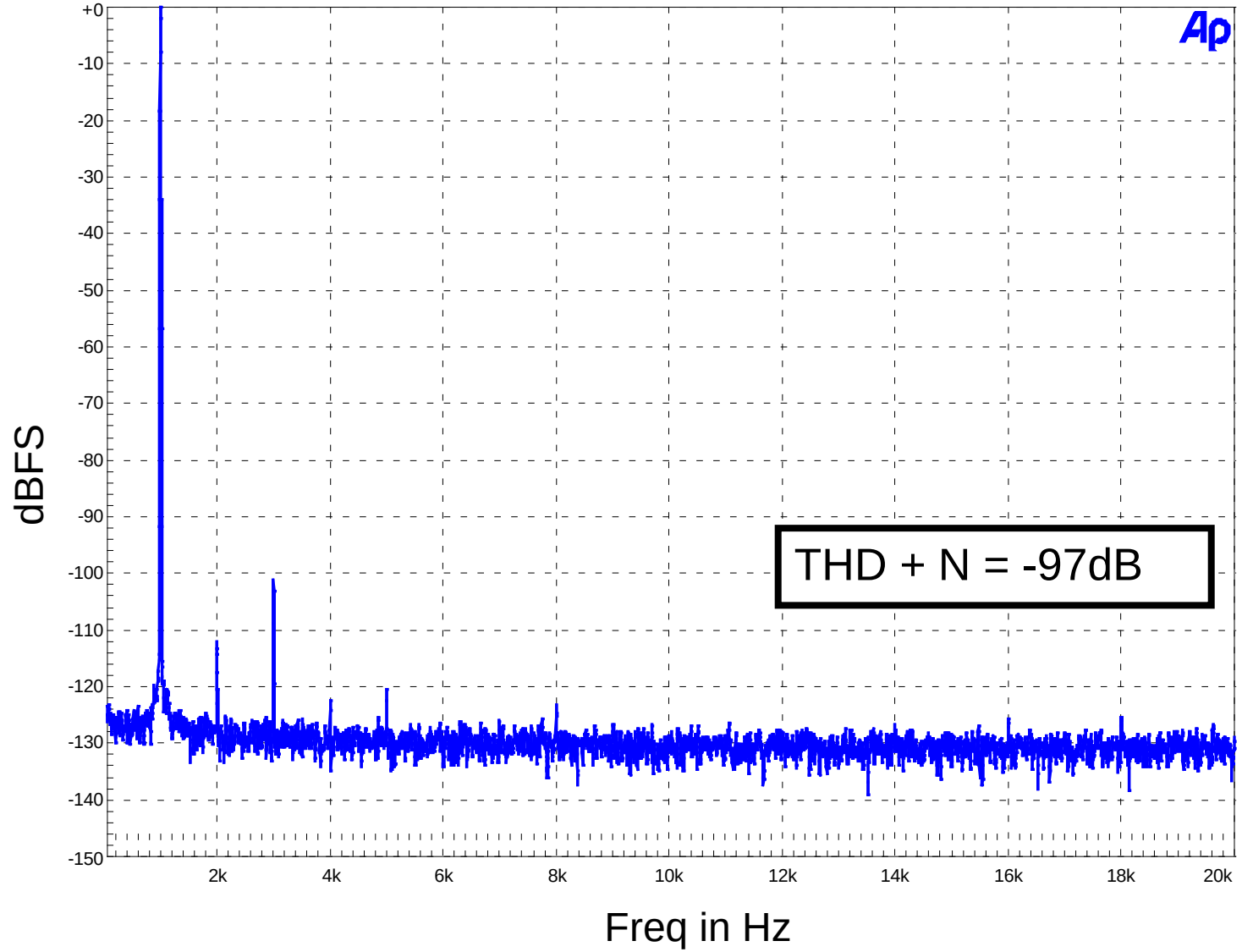
- Apply the DEM rules to reroute data and keep cumulative error at zero

- The shuffler cell operates similarly to the generalized DEM model

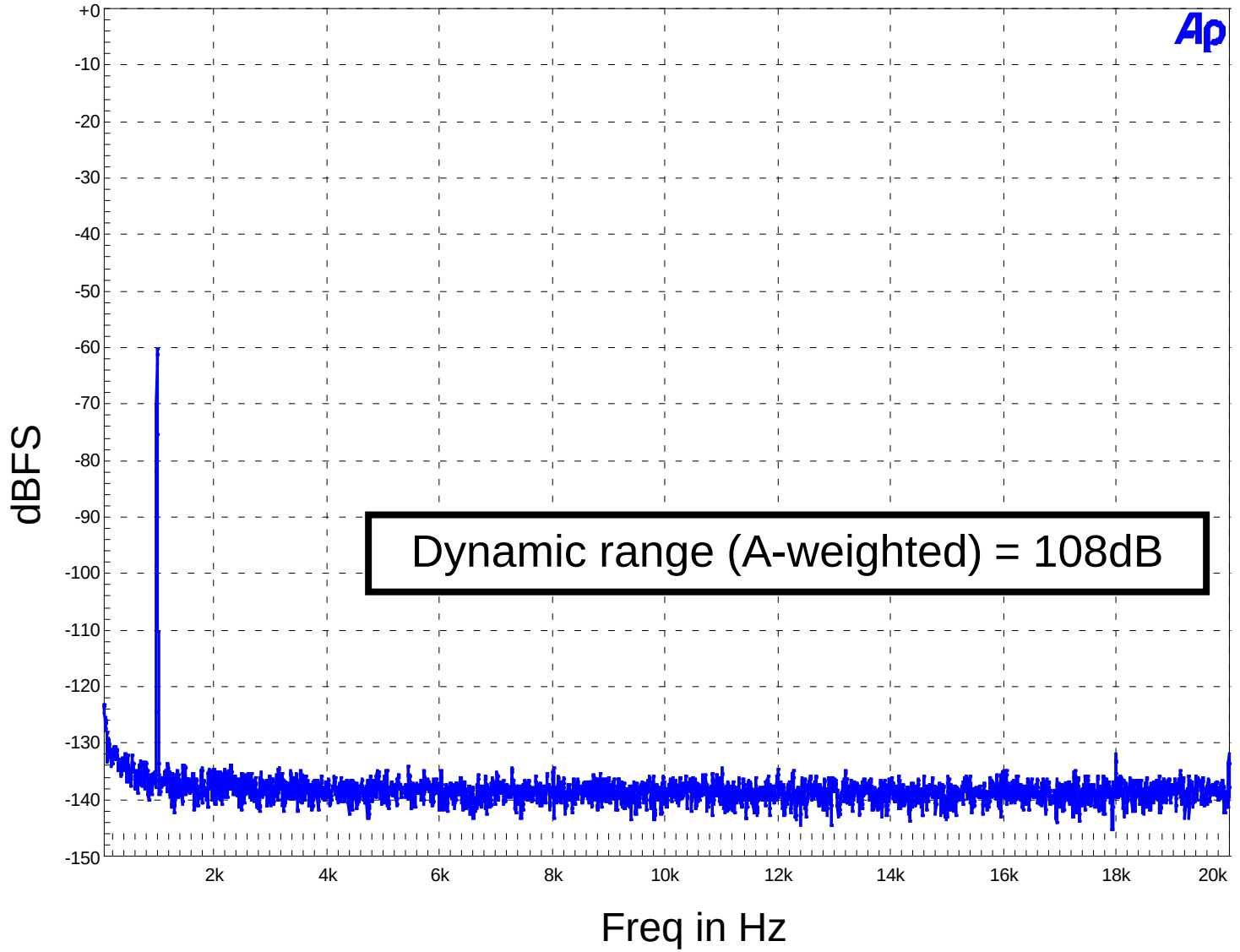
Idle tones in first-order data-direct shuffling

- Reasons:
  - Each shuffling cell is a 1st-order noise shaper (can create large inband tones)
    - With gain mismatch between cells, these result in idle tones
  - At low level (below -60dBFS), input has a tendency to travel through only a certain path due to the construct of the butterfly network
  - At low level input, some cells in the network become “starve” in activity
  - Can be detected by sweeping the input amplitude with small DC range
- Remedy
  - Precede the shuffler network with a randomizer
  - Ensure that each cell will have equal amount of data activity over time
  - Mismatch shaping effectiveness is slightly degraded but still can perform very well with high OSR (>=64)

Measured result ADAU1361 at -0.5dbFS

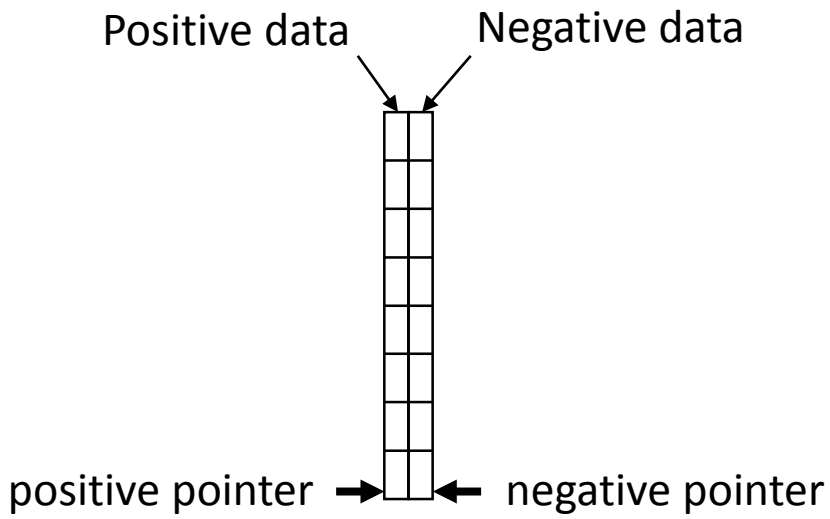


Measured result ADAU1361 at -60dbFS

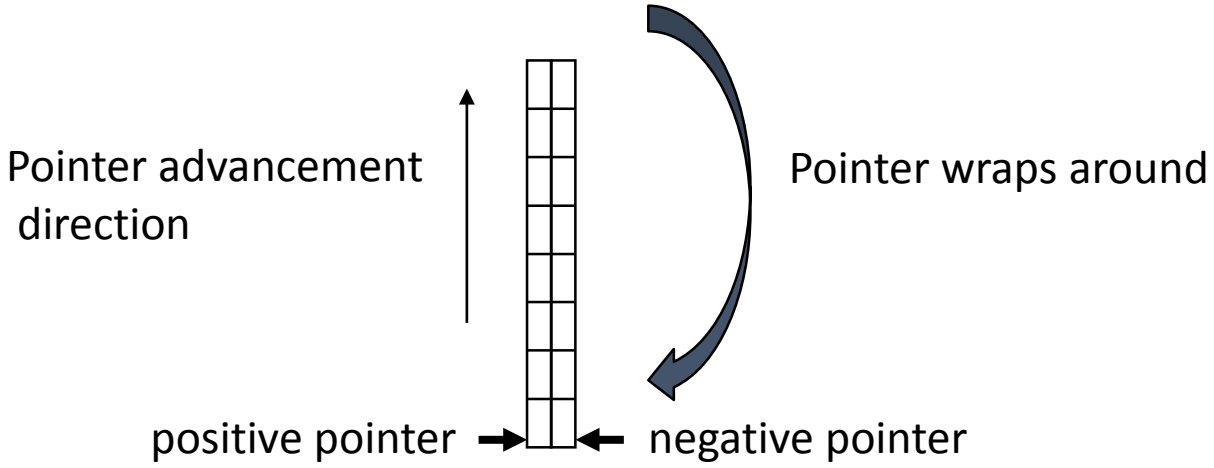


Approach #2a: Dual-pointer Rotational DEM

- Use 2 separate pointers: one for positive and one for negative thermometer data
- Use the same encoding scheme previously shown

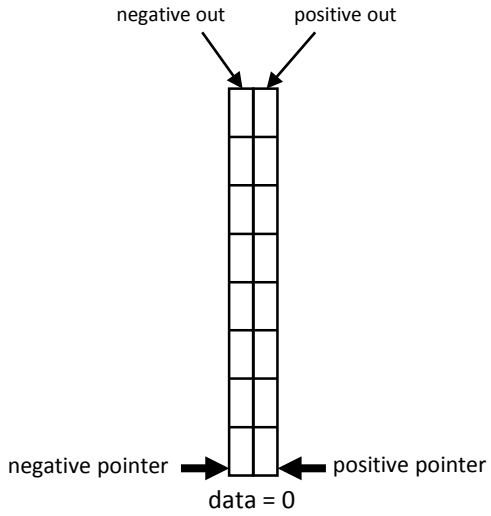


Rules for rotational DEM

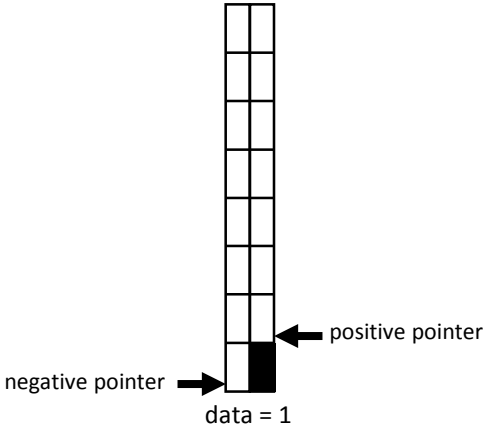


- Rules of DEM
  - For positive data, only positive pointer moves forward. Vice versa for negative data
  - Both pointers move in the same direction
  - Pointers wrap around in a circular manner
- Observations
  - If a pointer wraps arounds, the respective cumulative error is equal zero
  - If both pointers are at the same location, the cumulative error is equal to zero

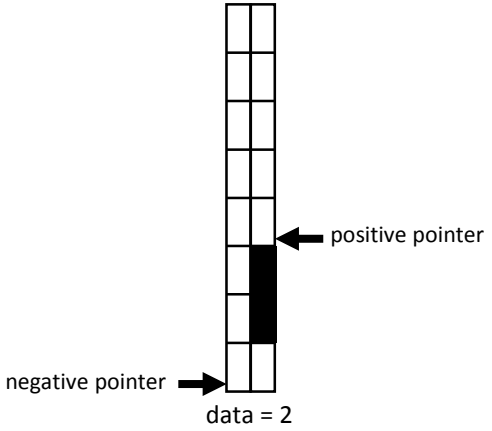
Example



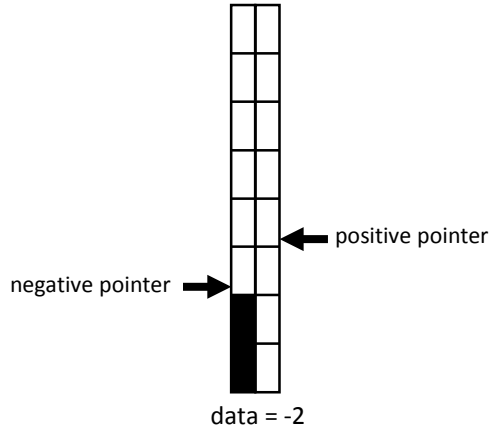
Cycle 0



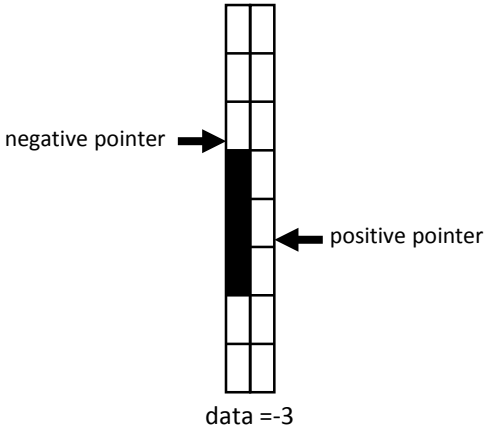
Cycle 1



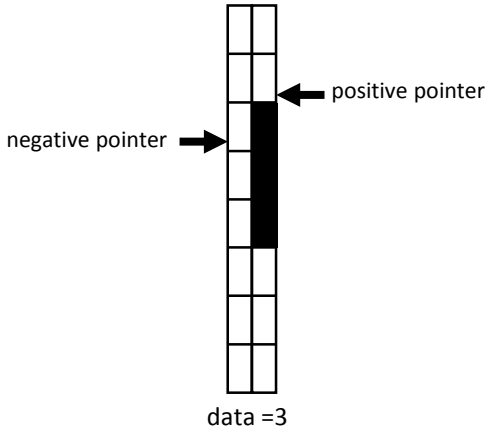
Cycle 2



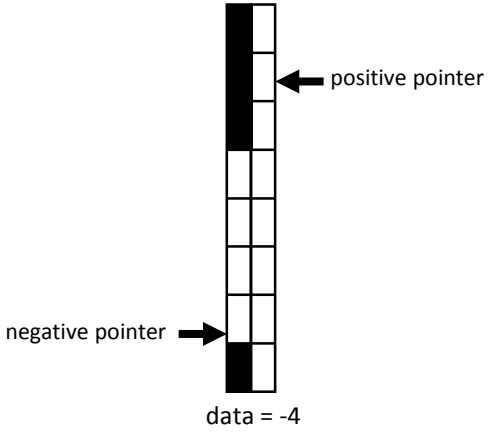
Cycle 4



Cycle 5

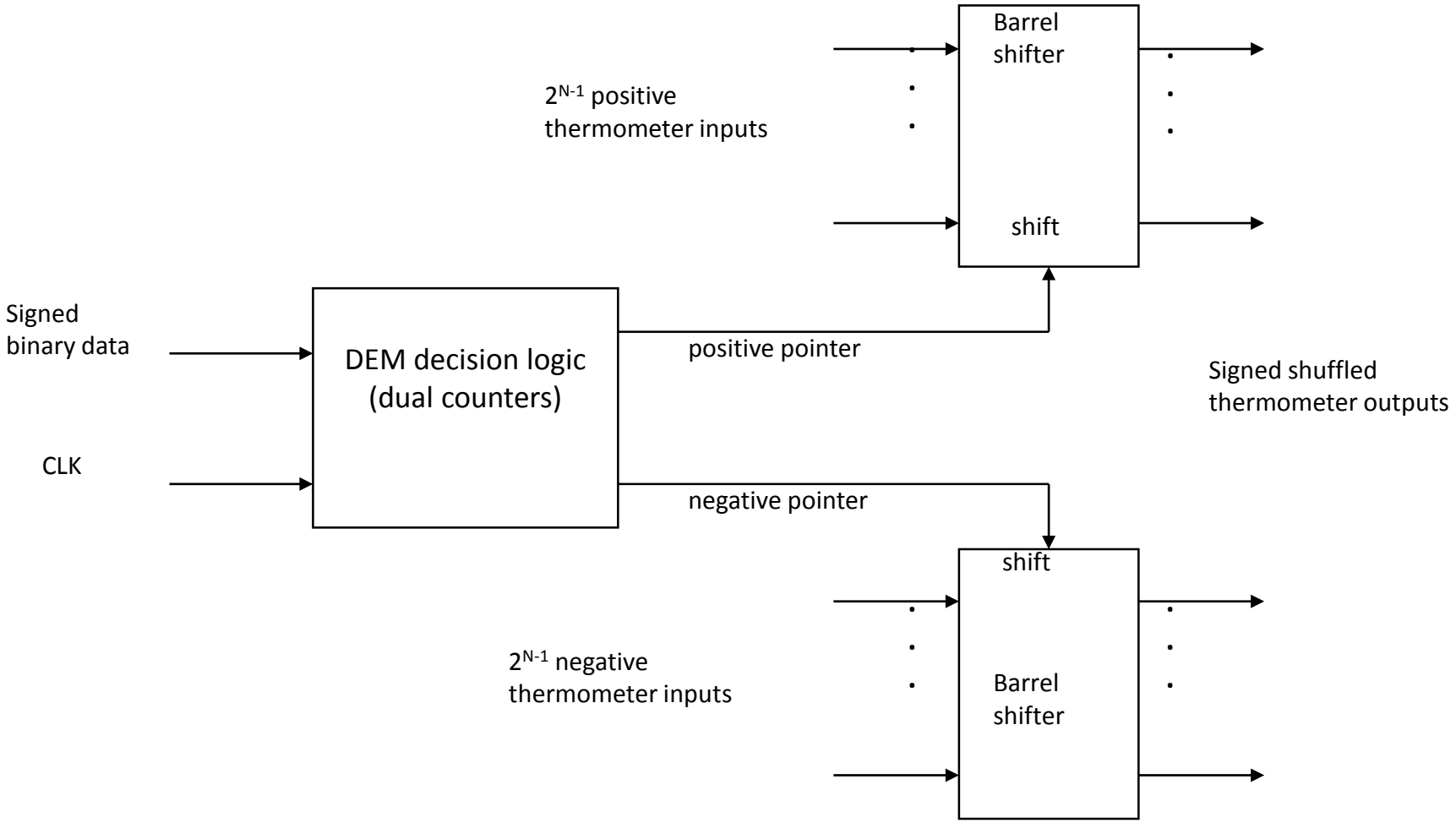


Cycle 6

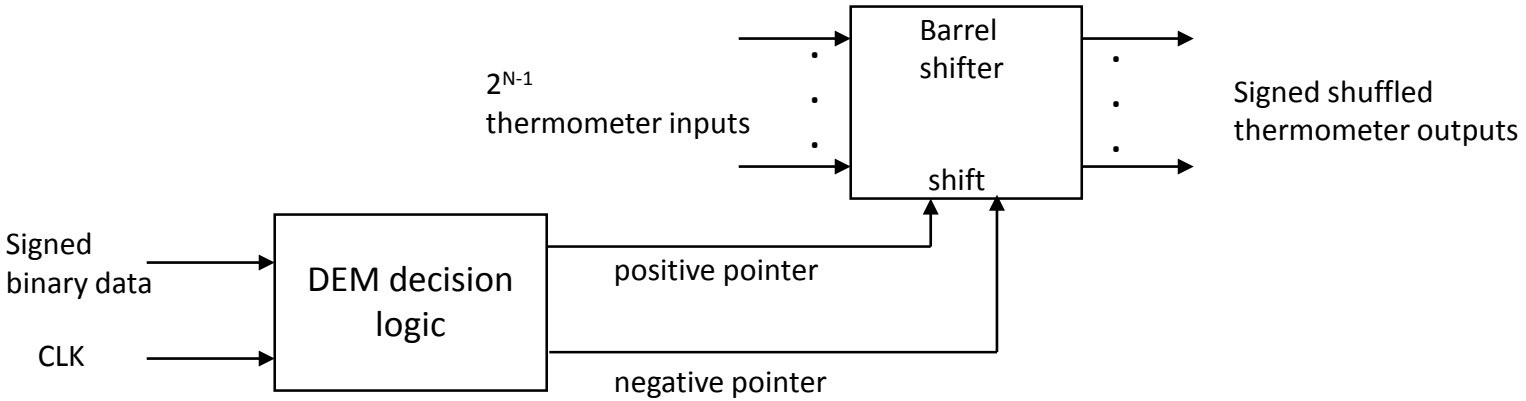


Cycle 7

Implementation of dual pointer DEM



Implementation of dual pointer DEM with sign-magnitude data

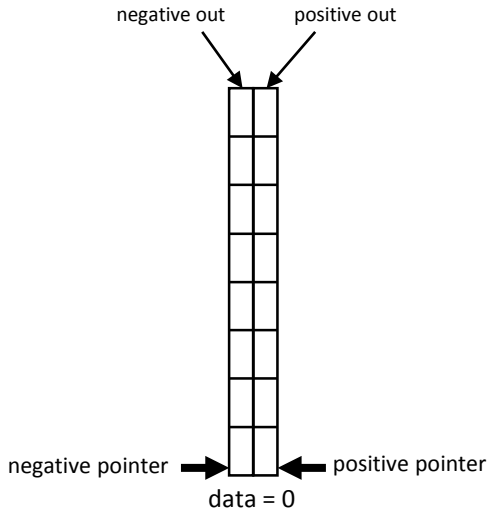


- Area efficient single barrel implementation
- Only 1 pointer is active and used at a time
- Barrel shift control is dependent on sign
- Barrel shifter only takes in magnitude
- Sign bit is used as a decoding

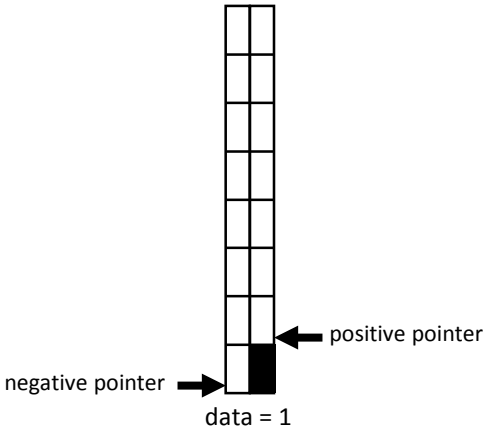
Idle tones in dual pointer DEM

- Reasons:
  - Similar to those found in 2-level single pointer DEM
  - Static born-mismatch pattern shows up at low input level
- Remedy
  - Observe that when both pointers are at the same location, the cumulative error is zero
    - **Both pointers can be repositioned to a randomly chosen location**
    - Static mismatch error pattern will be broken up
  - A slight degradation to the SNR due to the introduction of the randomness into the first-order single-bit noise-shaped sequences
  - Mismatch shaping effectiveness is still very good with high OSR (>=64)

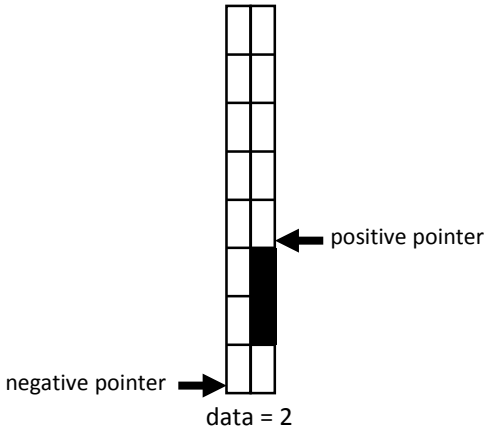
Example: With idle tone remedy



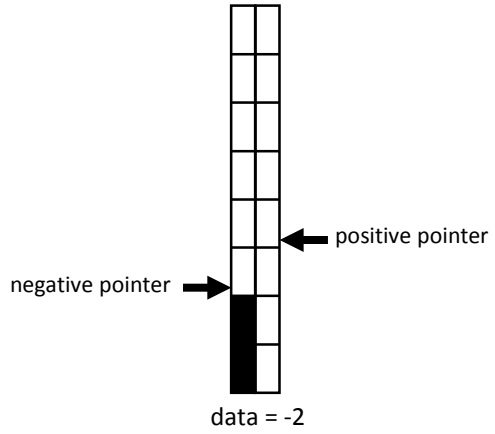
Cycle 0



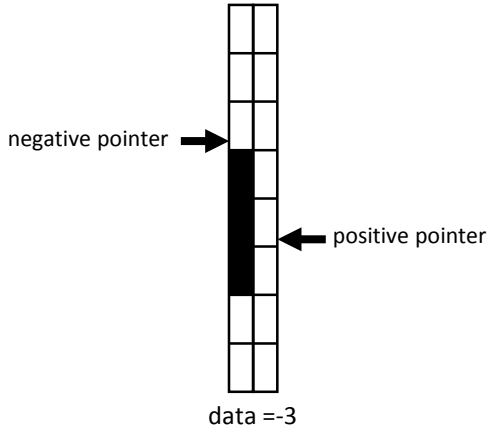
Cycle 1



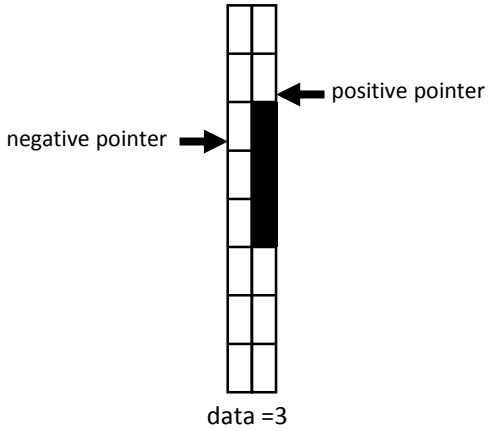
Cycle 2



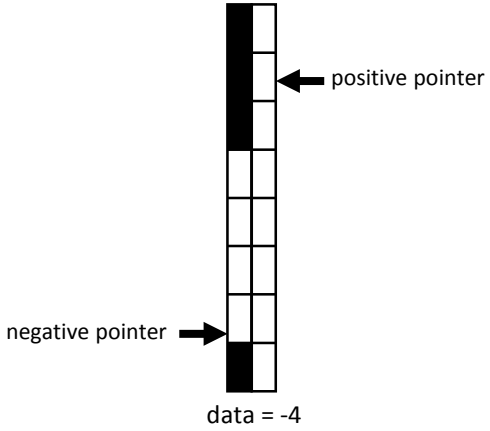
Cycle 4



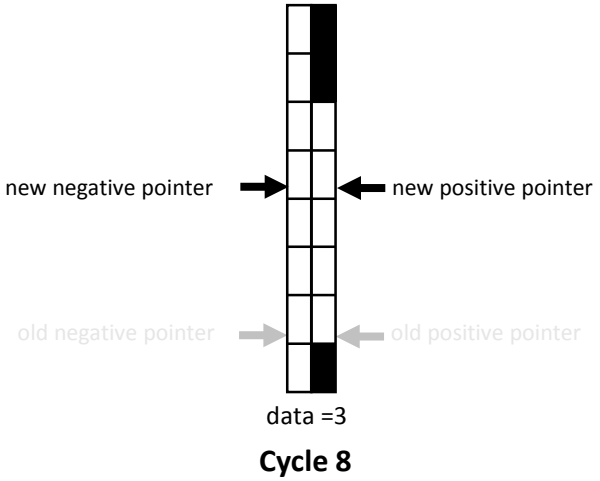
Cycle 5



Cycle 6



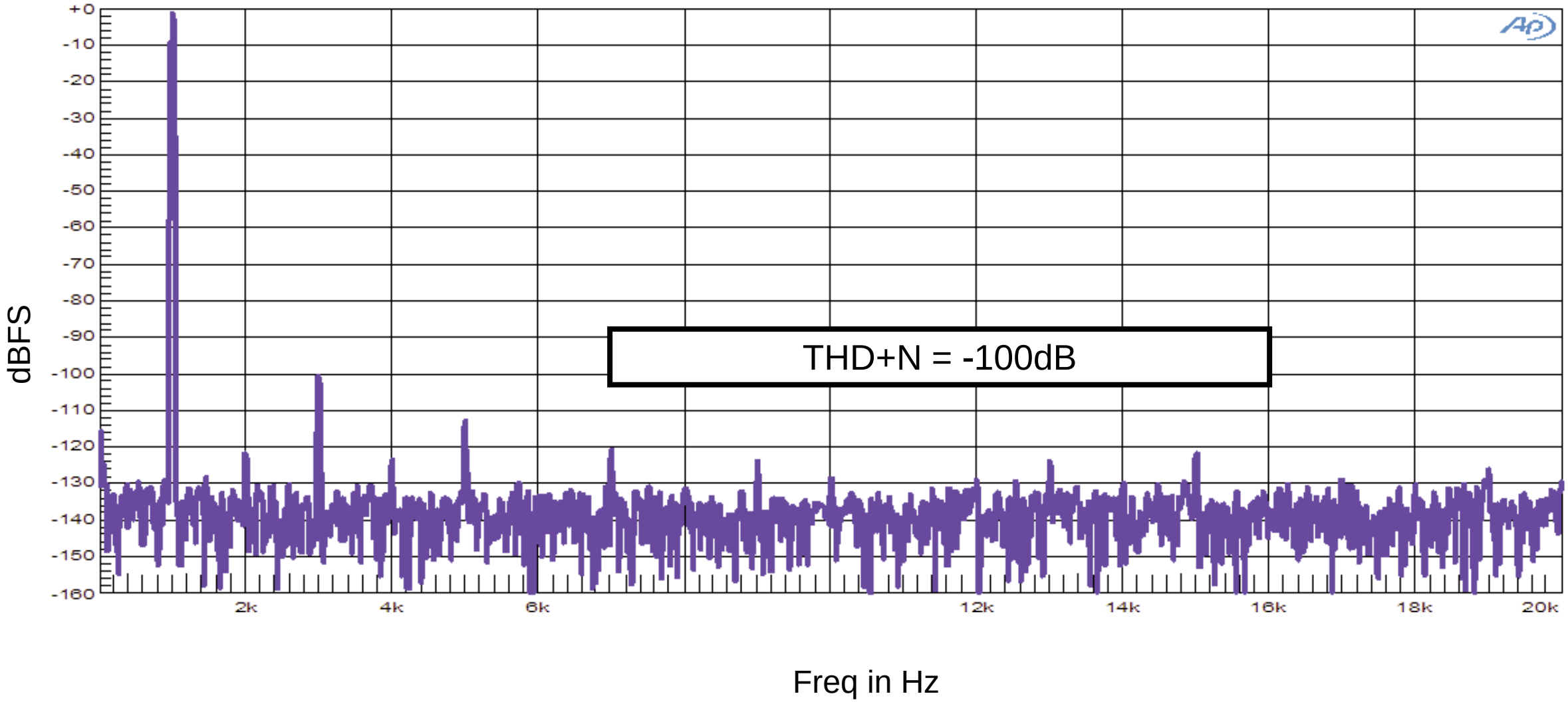
Cycle 7



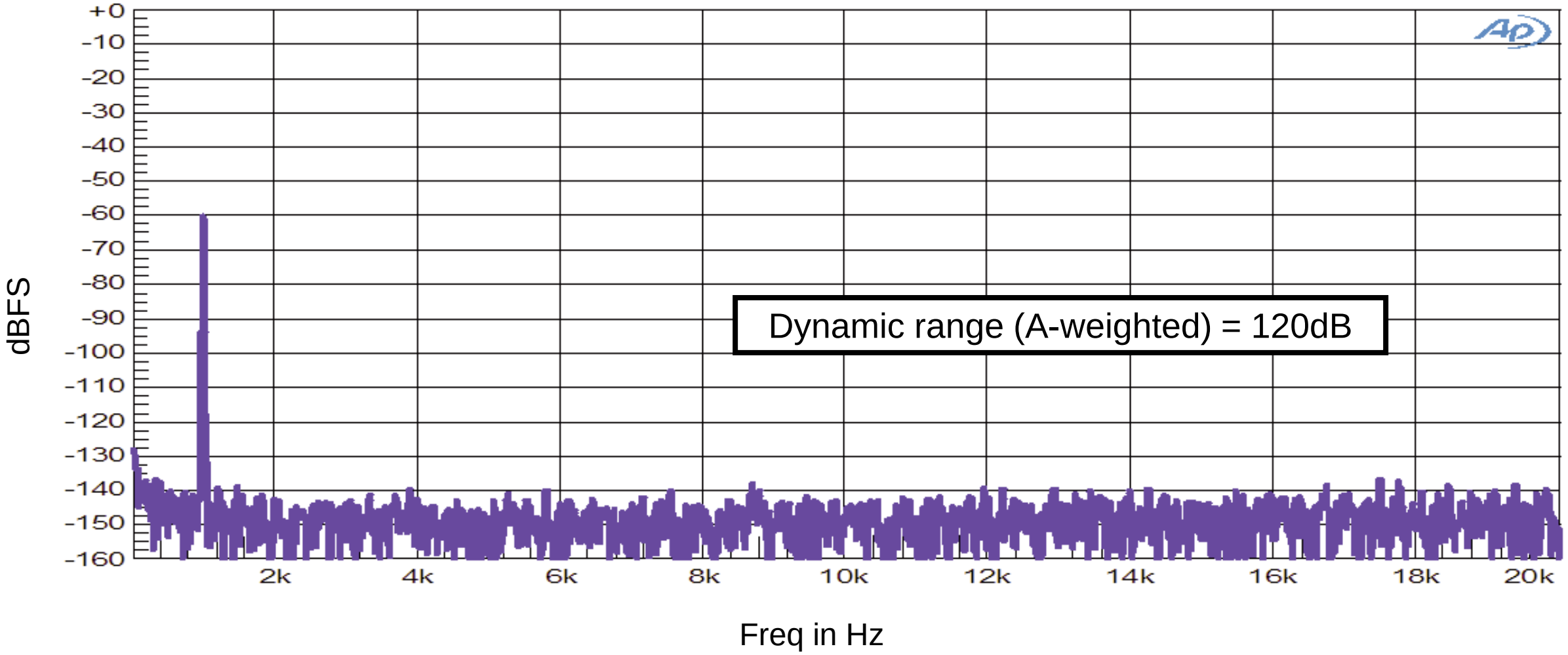
Cycle 8

When positive and negative pointers are equal, randomize the position of both pointers.

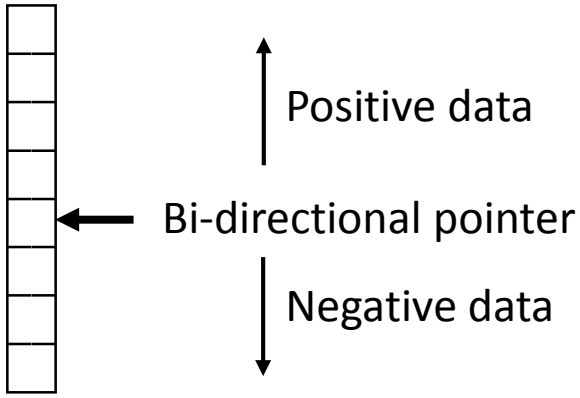
Measured result ADAU1966 at -0.5dbFS



Measured result ADAU1966 at -0.5dbFS



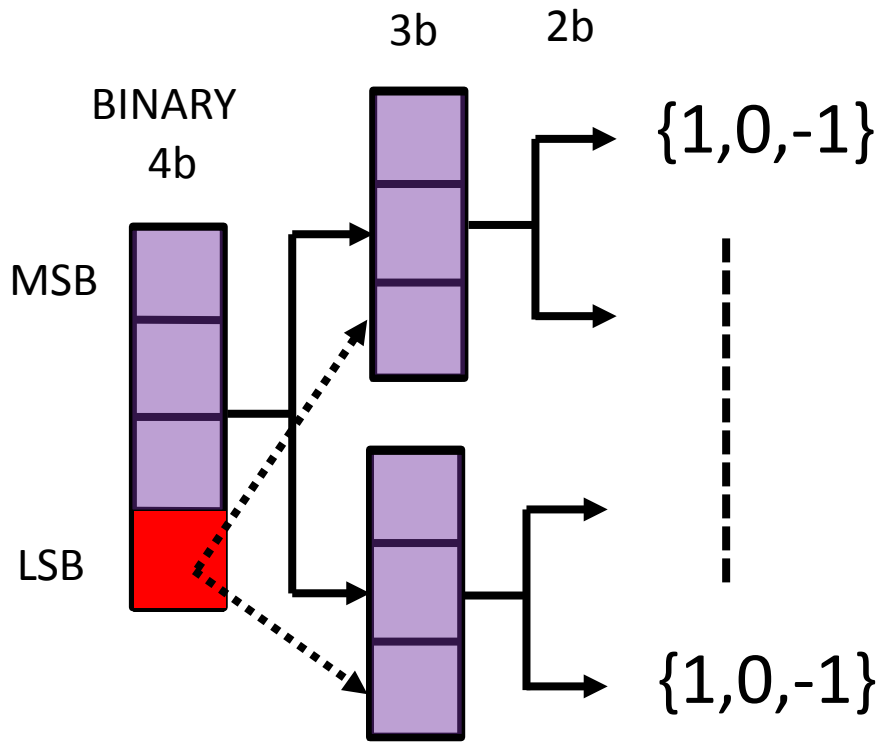
Approach #2b: Single-pointer rotational DEM



- One pointer that moves forward when data is positive and backward when data is negative

- Possible remedy for idle tone
  - Set up a reference point
  - Keep track of wrapping around the reference point
  - After wrapping around (single or multiple times) and ending at the reference point, reposition pointer to a new randomly chosen reference point.
  - Repeat the entire procedure

Approach #3: Tree structure DEM

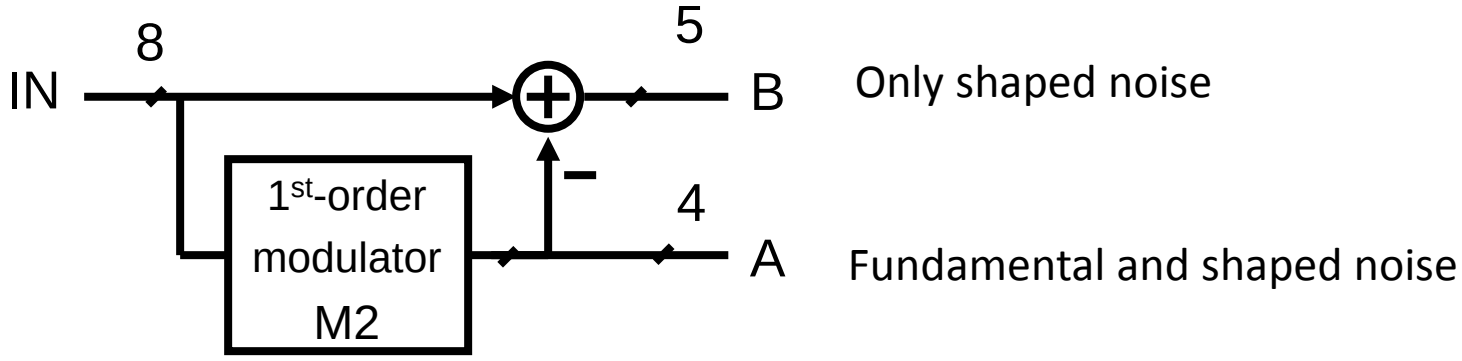


Example of a 4b implementation

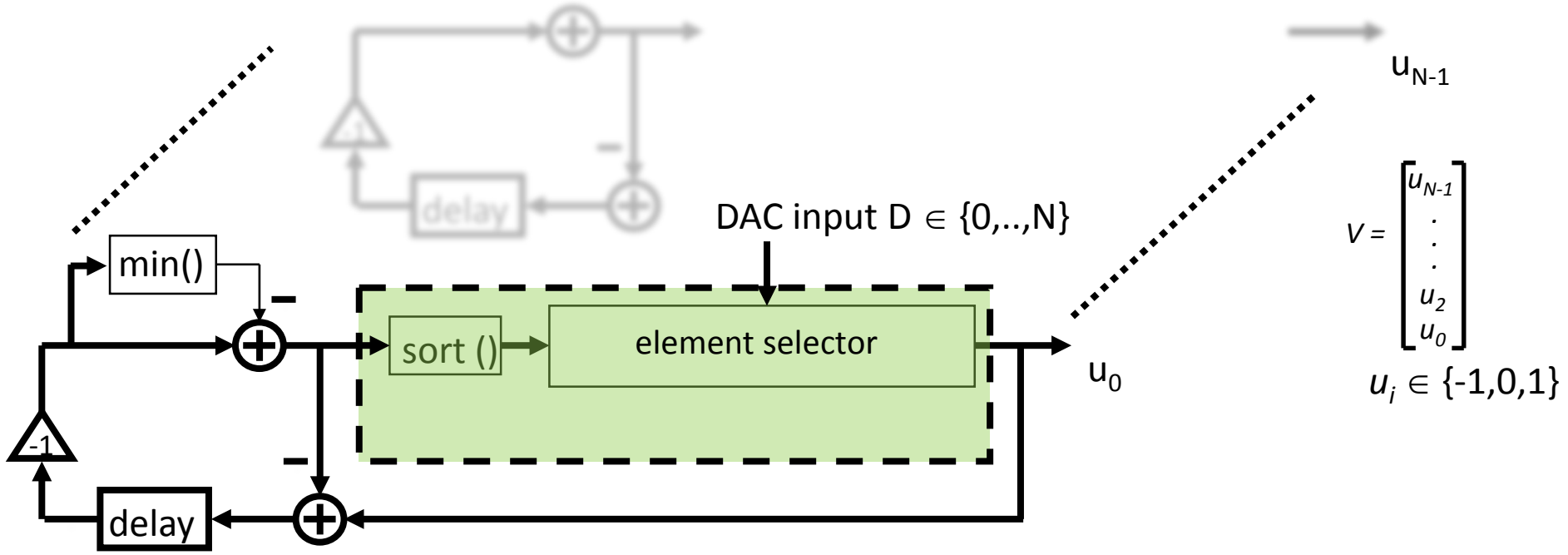
- Use the tree structure to split the word until the last 2MSBs
- Decode the leaf cells to get the {+1,0,-1}
- Remedy for idle tone
  - If data is even for a while, consider add 1 to one branch and subtract 1 in the other branch. This increases the data activity.
  - Watch out for headroom issue in the digital words
- **Note:** that each bit is still a 1st-order noise shaped sequence which has the fundamental component and shaped noise.

Other possible solutions to tree-structure DEM

- Applicable when input word width is large for any straight implementations of DEM
- Consider noise shaped segmentation principle
  - Only one component in the sub-level has the signal fundamental. Easier to derive solution for idle tones.
  - May be done recursively
  - A and B can then be followed by a butterfly, rotational or tree-structure shuffler



Approach #4: Vector quantization



- A slight change in the ESL to accommodate 3-level data
  - Rank N input vectors with least used first
  - ***Assert {-1,0,1} in D output elements in output vector V***
  - Feedback the elements of V to the corresponding integrators (or loops)
  - Can apply the use of a dithering vector to the input of the sorting routine to cure idle tone behavior

Approach #5: Real-time DEM

- Direct concept can be re-used
  - Requires fast clock
  - Switching loss due to logics may become significant to not be considered for low power implementation

Recap

- Brief background
  - Motivations and Applications
  - 3-level vs. 2-level unit element: advantages and challenges
  - What problems DEM does and does not solve
- Practical dynamic element matching (DEM) techniques
  - 2-level DEM review
  - 3-level DEM
  - Limitations of each technique
  - Solution spaces
- Higher-order DEM
  - Issues in 2nd-order DEM
  - Solutions
- Application specific concepts of DEM
- Q and A

Why need 2nd-order DEM

- 1st-order DEM
  - Effective when OSR >= 64x
  - At lower OSR
    - Shaped mismatch noise degrades SNR.
    - DEM tones appear inband.
    - Over-clocking DEM (2x) may offer small improvement (not enough). Switching dynamics become a source of noise.

- **Solution**: 2nd-order shaping

- Issues with 2nd-order:
  - Ineffective for low input amplitude.
  - Area intensive especially with number levels >8.

Approaches to 2nd-order DEM

- Data directed : Cannot produce second-order mismatch shaping effectively
  - When inputs are both 11 or 00, mismatch shaper cells get “overloaded”
- Rotational: Can produce a second-order, but extremely hardware intensive, tends to revert to first-order shaping
- Tree-structure: Can produce second-order shaping but tends to revert back to first-order in real life use case (signal conditions)
- Vector quantization: Very hardware intensive due to realization of sorter and element selector
  - ***Hardware implementation at size = 2-bit (4 elements) is affordable***

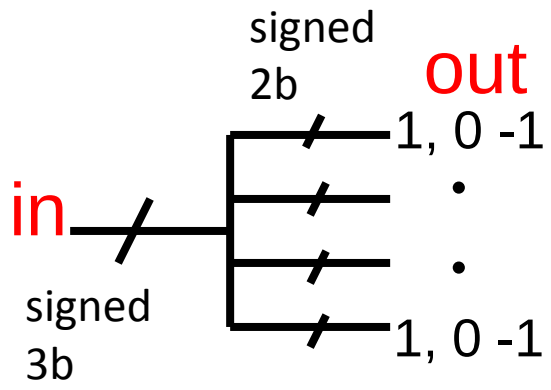
Design challenges and solutions

- Full implementation of vector quantization is extremely hardware intensive
  - Solution: Segmentation (or tree structure)
    - Break it down to smaller chunks where realization is affordable

2^{nd}-order DEM for 3-level unit elements

- Each leaf cell needs 2 bits: $\begin{cases} 00 \ for \ 0 \\ 01 \ for \ +1 \\ 11 \ for \ -1 \end{cases}$

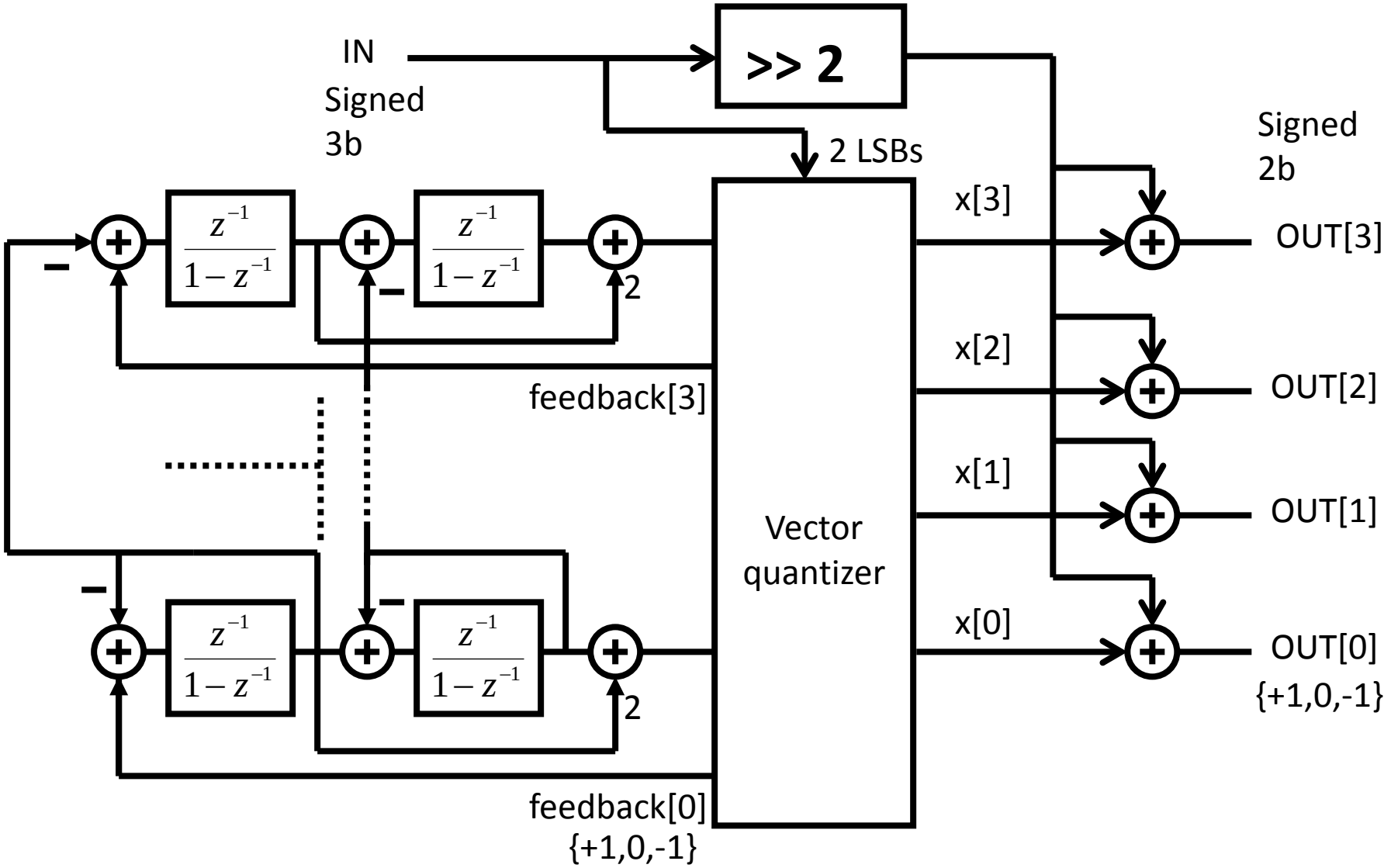
- At one level higher in the tree, minimum size = 3 bits
  - Will need 4 cells to represent {+3,…, -4}



Operations:

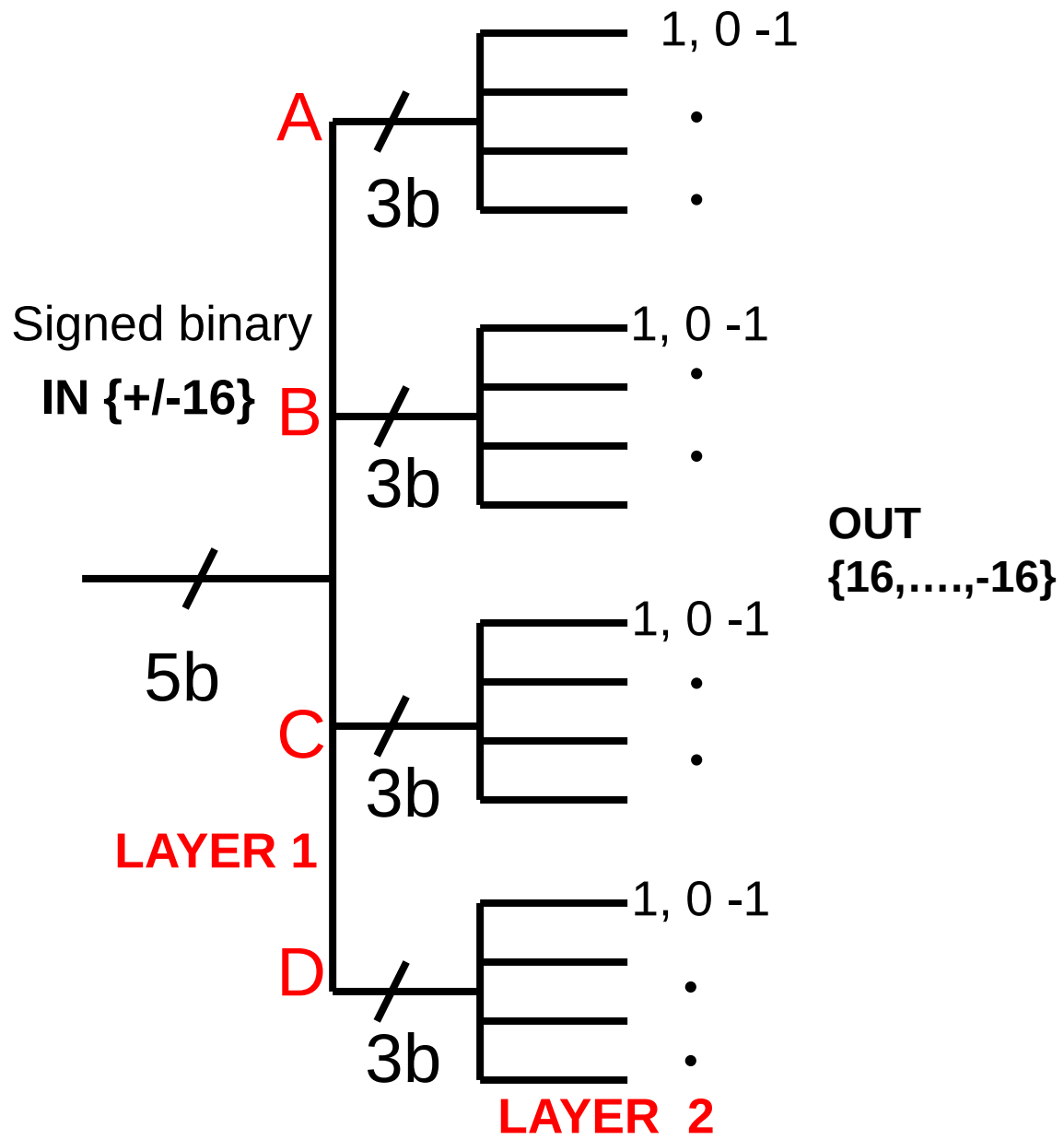
1) OUT[1:0] = IN >> 2
2) RESIDUE = 2 LSBs of IN
3) Use a 2^{nd}-order NS loop to decide how to distribute the residue to the outputs

Block diagram of a 3-bit, 2nd-order DEM



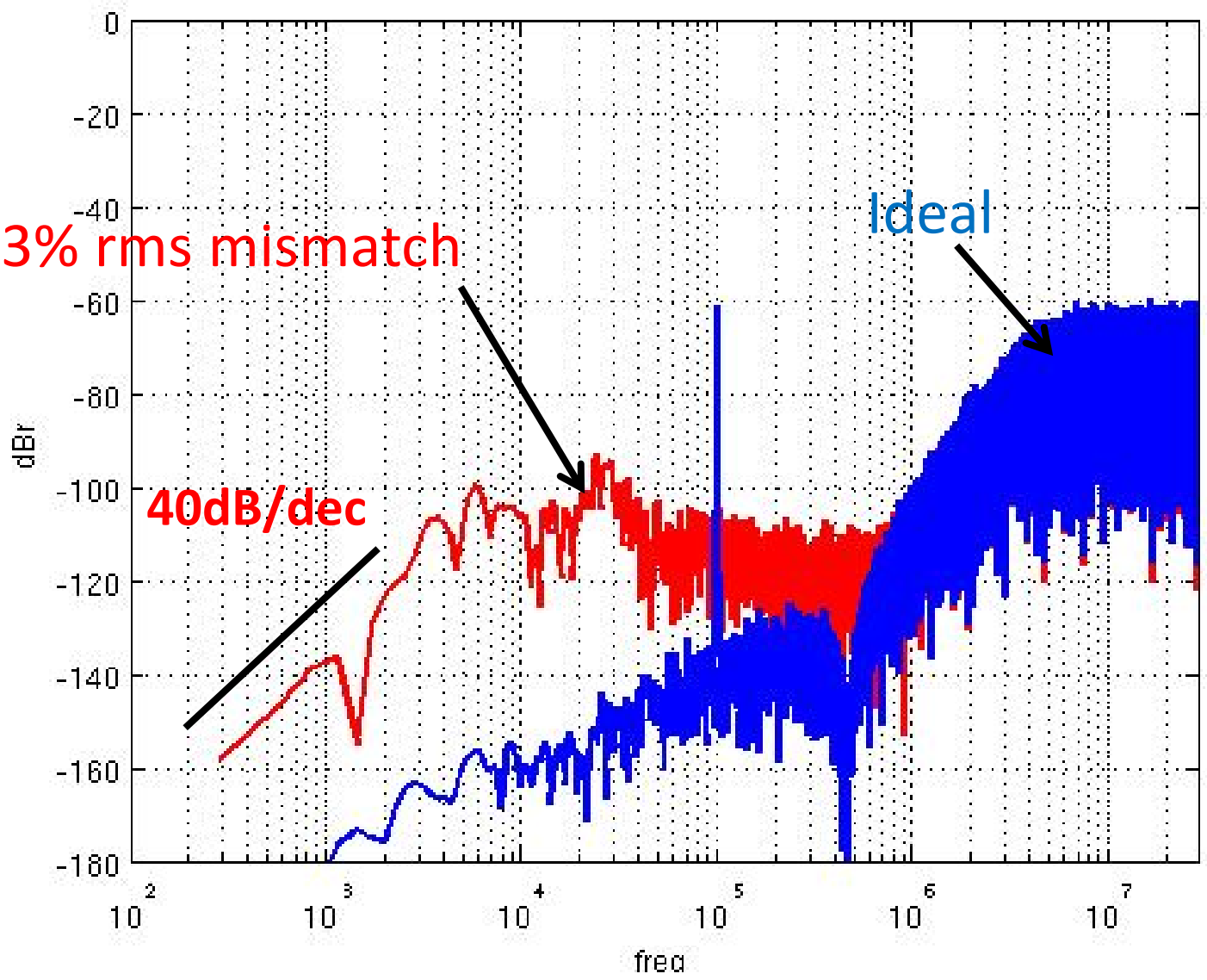
Feedback is ONLY produced when there is an instantaneous error made

Block diagram of a 5-bit, 2nd-order DEM



1. **A + B + C + D = IN.**
2. **The spectral difference between every pair in layer 1 must show a 2nd-order highpass function**
   - DAC-to-DAC gain error will be 2nd-order shaped.
3. **The spectral difference between any pair of unit elements in layer 2 must also show a 2nd-order highpass function**
   - Element mismatch will be 2nd-order shaped.

Simulation result

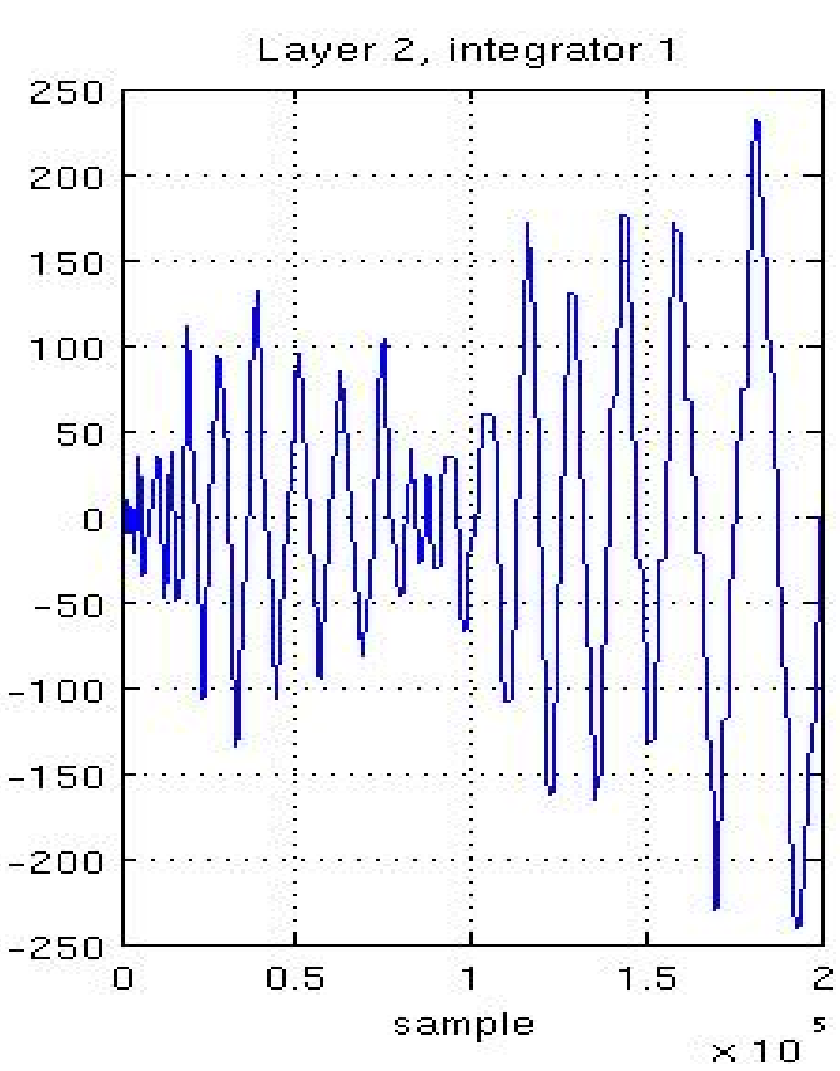


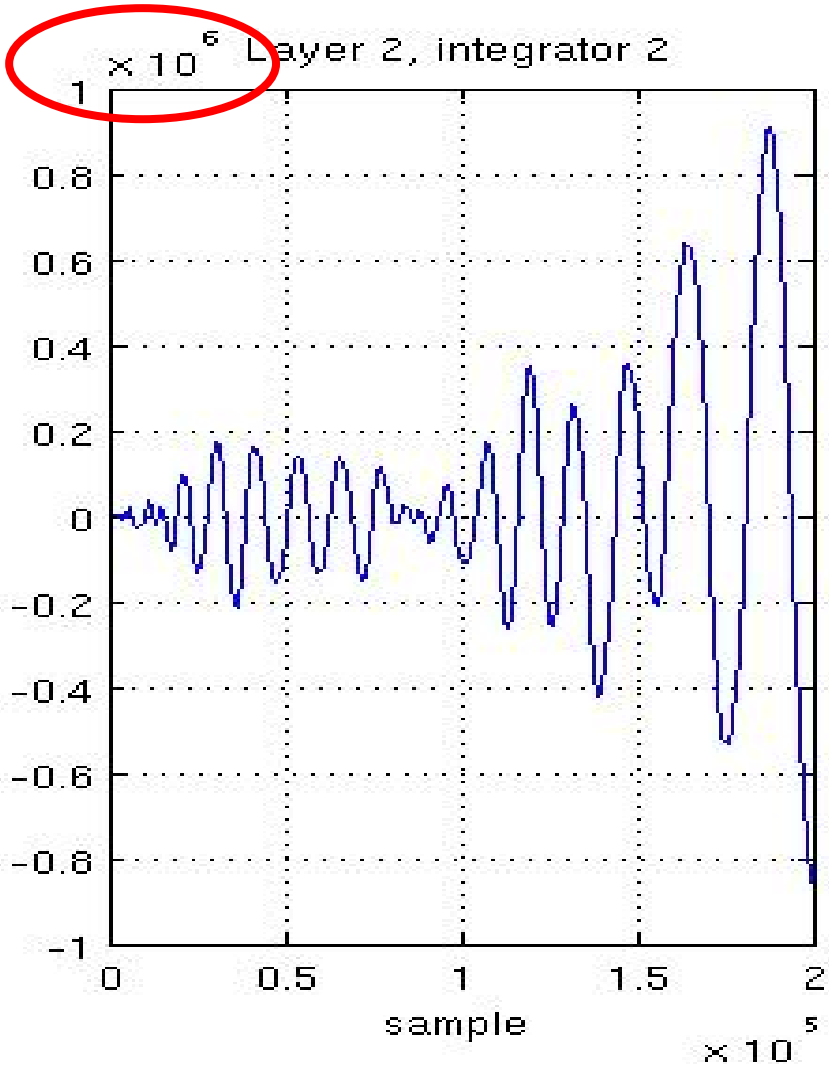
Input = -60dBFS at 100kHz

Fclk = 64MHz

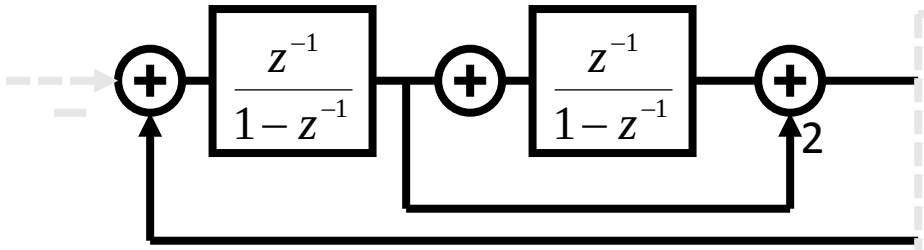
SNR is severely degraded !

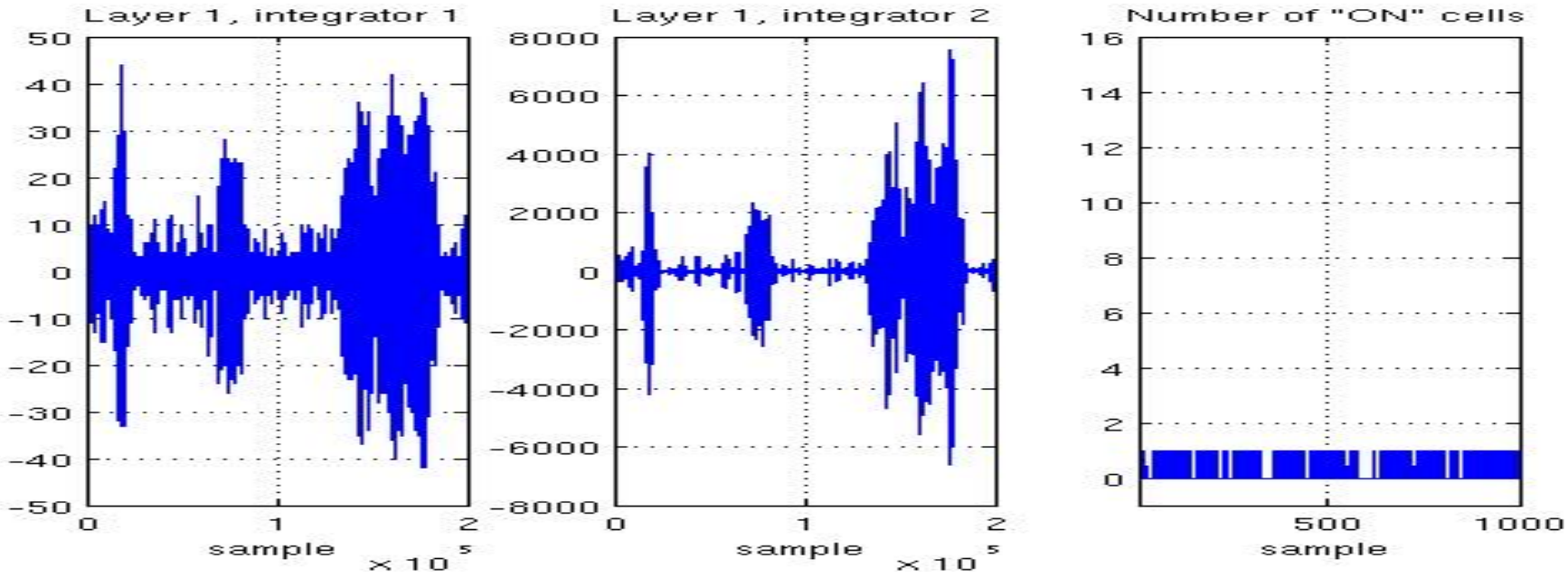
Closer look at the integrator outputs at low input level





The cause: low data activity





- Very large dynamic range integrator required
- Clipping makes the matter worse

Design challenges and solutions

- Full implementation of vector quantization is extremely hardware intensive
  - Solution: Segmentation (or tree structure)
    - Break it down to smaller chunks where realization is affordable

- Inadequate data activity: cause large growth in integrator word widths
  - Solution: Trade off a small thermal noise performance: Dynamics enhancement

Dynamics enhancement (DE)

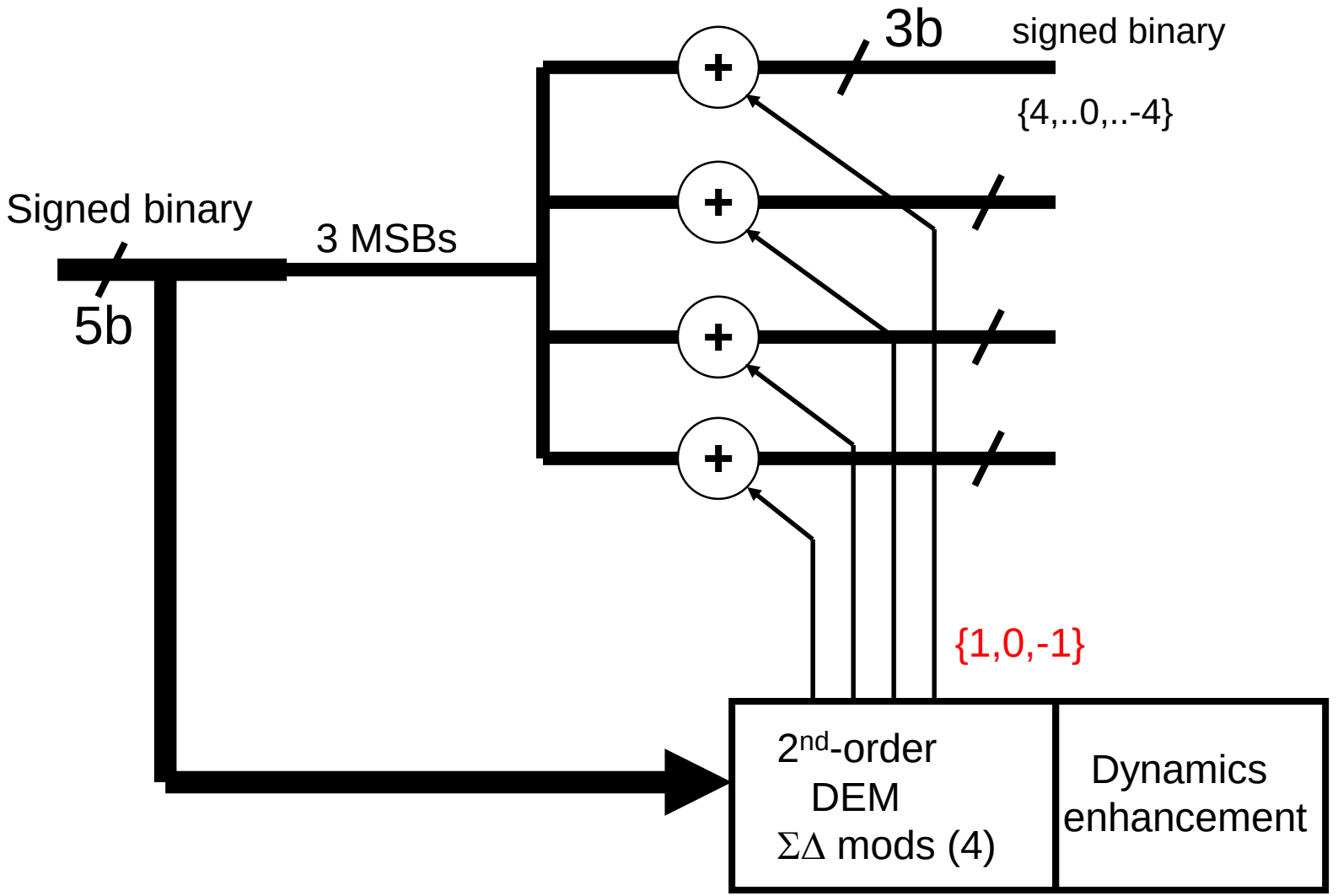
- Increases the data activities while maintaining the digital **value** unchanged.
  - Add +1 and -1 to digital input when possible
- Trades off thermal noise for mismatch
  - Goal: keep # of ON cells as low as possible
- Reduces the integrator output swing tremendously. Very hardware efficient.

Dynamics enhancement (DE)

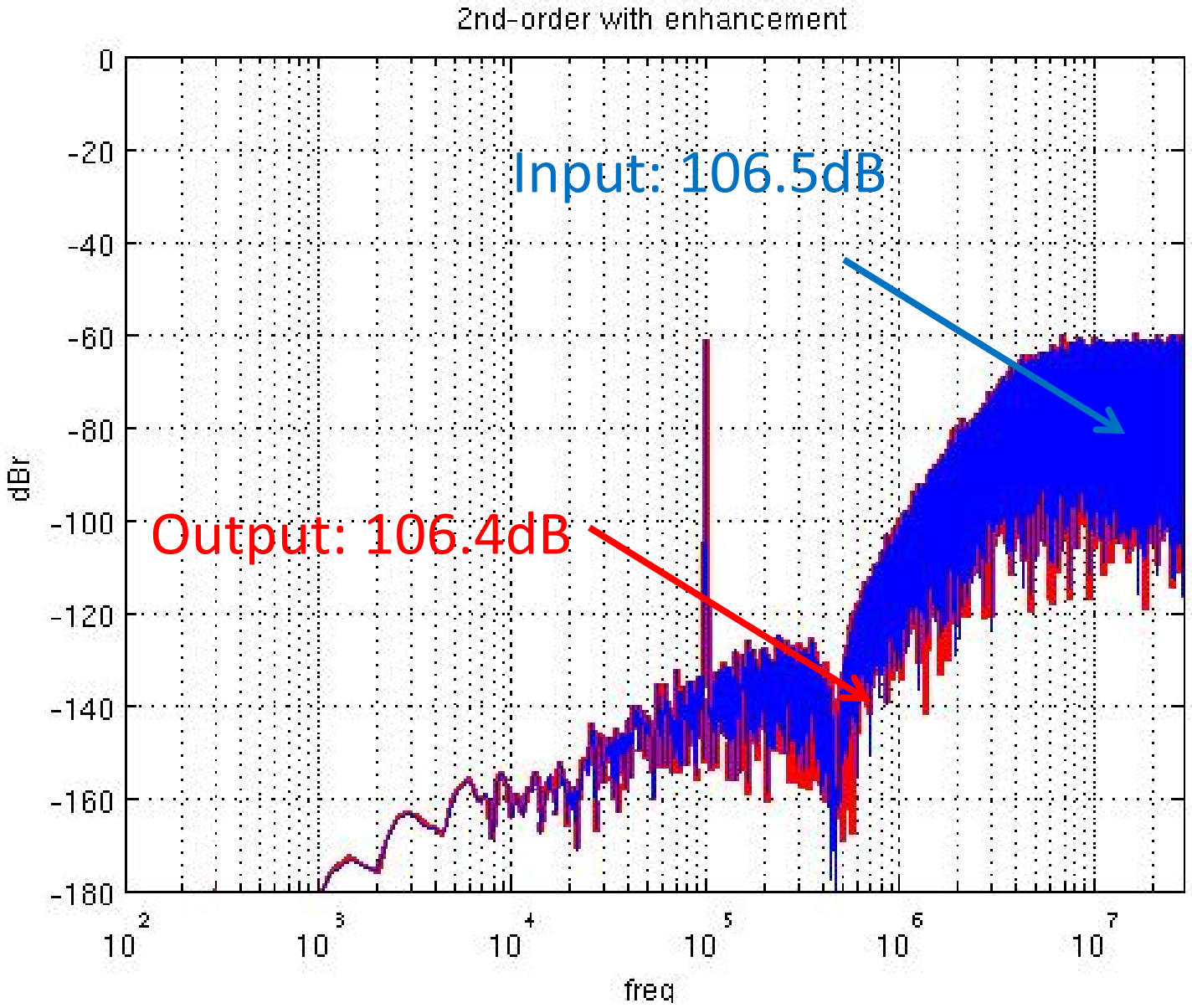
- If 2LSB = “00”, start counting
- If count exceeds a designated number “wait_time”
  - Check if signal(s) are in safe range
    - Add +1 and -1 to the branches. Reset wait_time.

- Parameters to adjust
  - Wait_time: affects integrators word width
  - Amount of +1/-1 added, restricted by thermal noise performance
  - Choice of where to direct +1 and -1 to.

Combining 2nd-order DEM and dynamics enhancement



Simulation: With dynamics enhancement

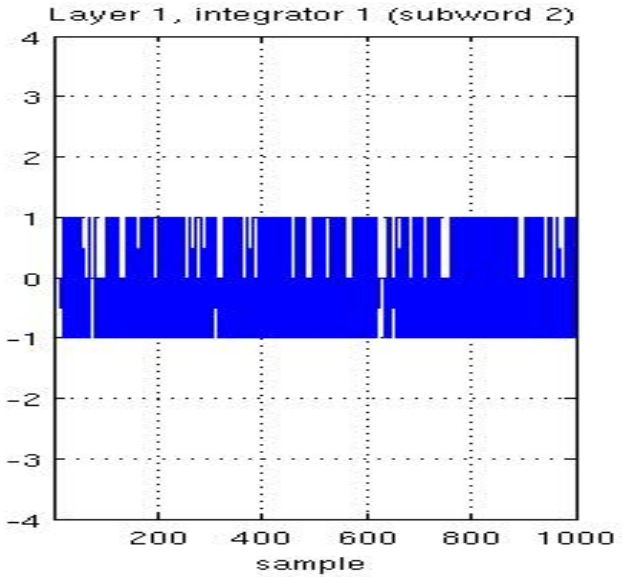


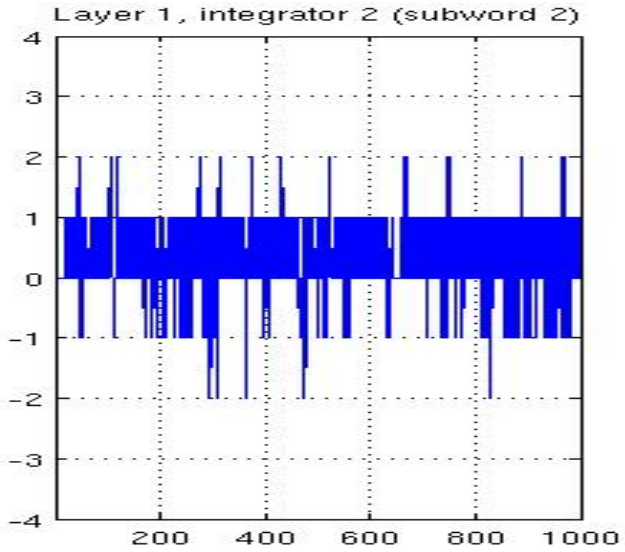
Input = -60dBFS at 100kHz

Fclk = 64MHz

Mismatch: 0.3% rms

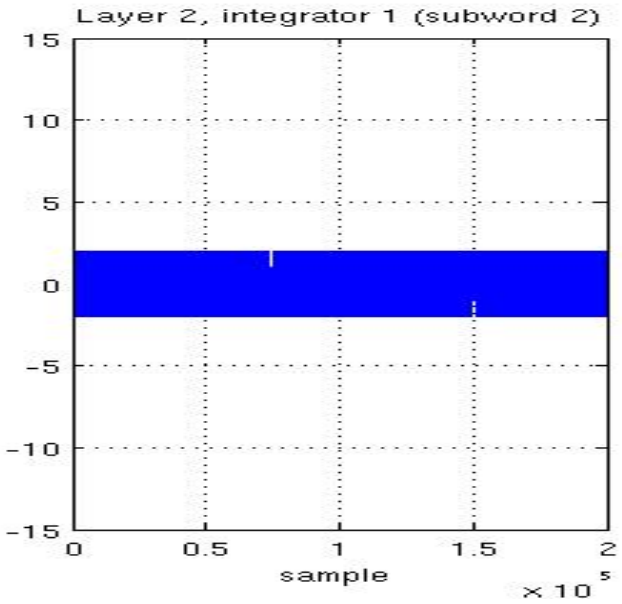
Integrator outputs with DE

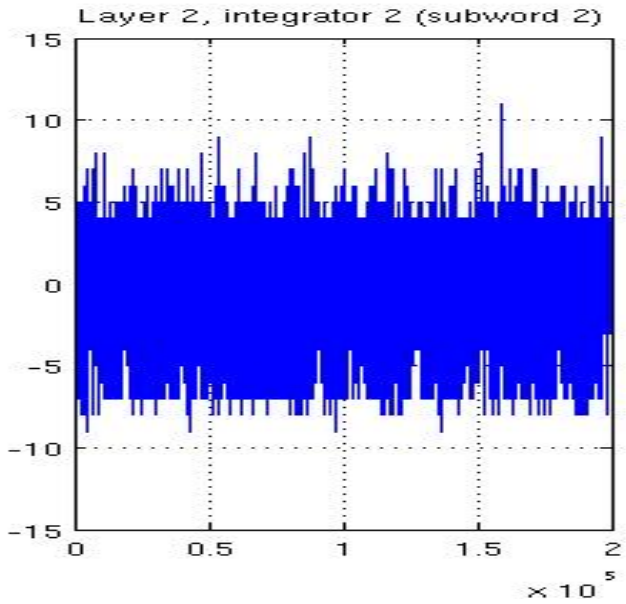




LAYER 1

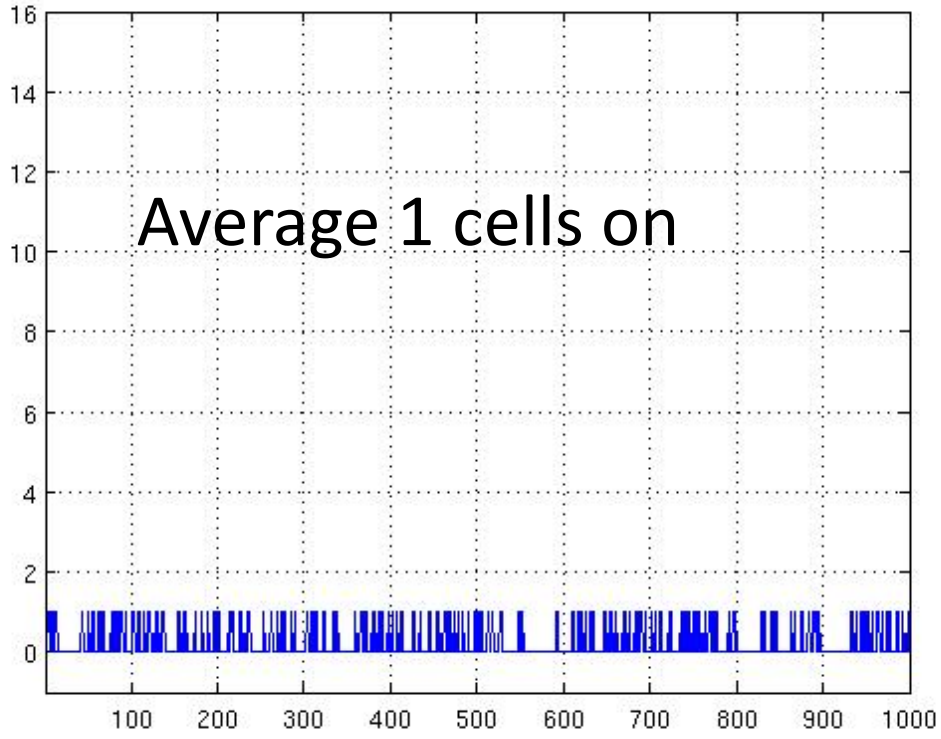
Much smaller dynamic range needed !



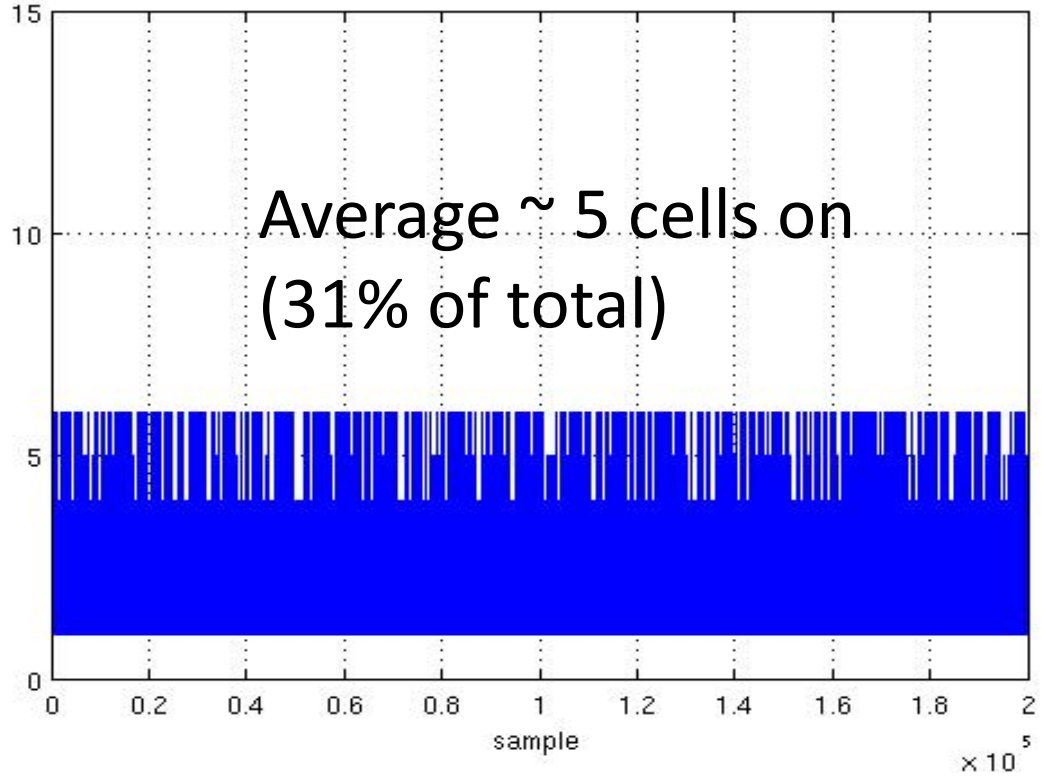


LAYER 2

Number of DAC cells used at -60-dB input

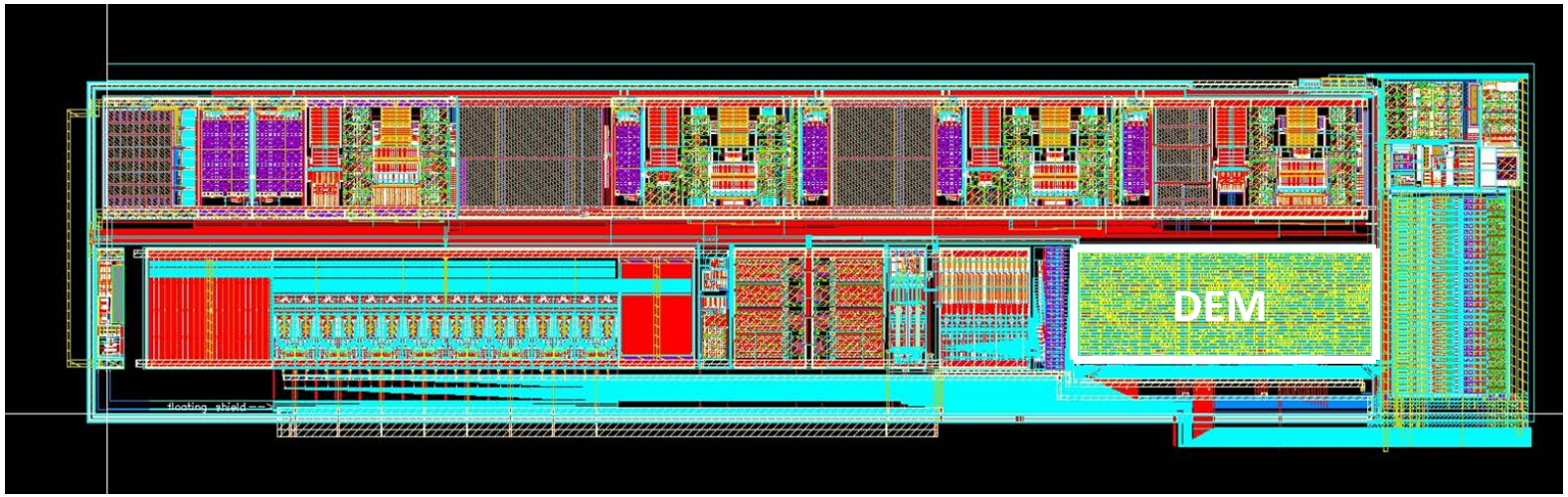


WITHOUT dynamics enhancement



WITH dynamics enhancement

Layout of a Multibit Continuous Time ΣΔ ADC”



A CT sigma delta 3rd-order modulator with 2nd-order DEM

Recap

- Brief background
  - Motivations and Applications
  - 3-level vs. 2-level unit element: advantages and challenges
  - What problems DEM does and does not solve
- Practical dynamic element matching (DEM) techniques
  - 2-level DEM review
  - 3-level DEM
  - Limitations of each technique
  - Solution spaces
- Higher-order DEM
  - Issues in 2^{nd}-order DEM
  - Solutions
- Application specific concept of DEM

- Q and A

Problem definition

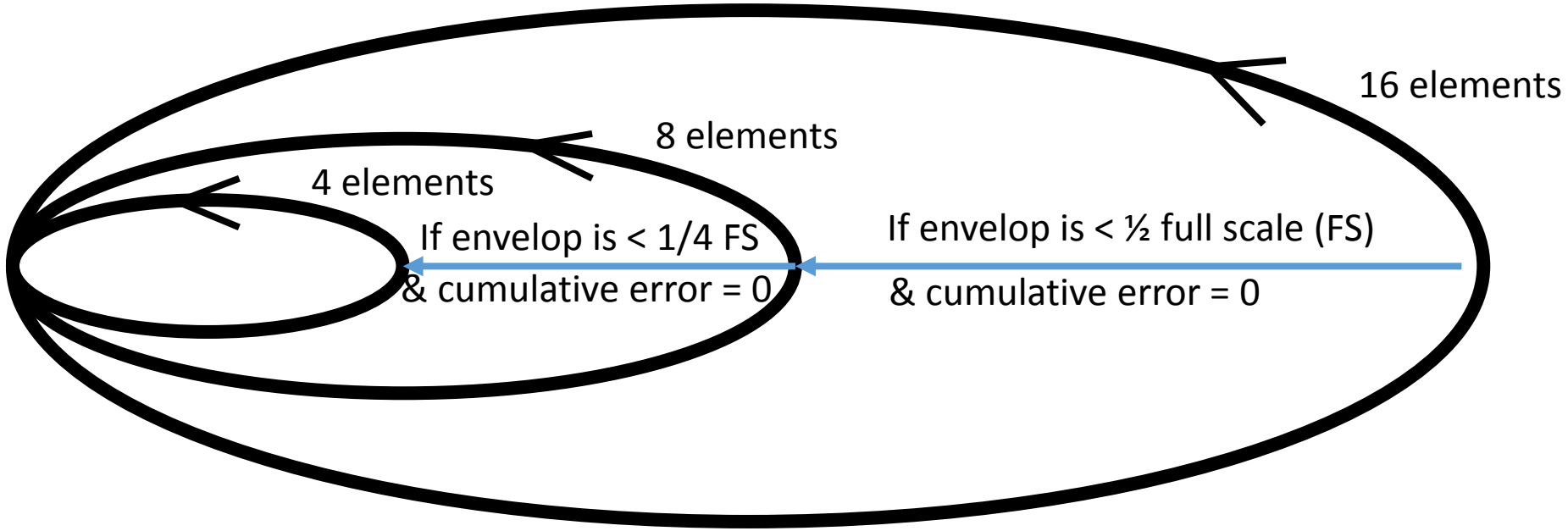
- **Reduce power consumption in the 3-level unit element DAC**
- In particular, when the input is small (-60dB) , only 1 or 2 cells are used, the rest of the cells are not used but still burn power.
- **Goal**: to turn off those unused cells without degrading performance.
- Note: *Dynamically turning off cells will cause degradation due to power consumption constraints and other dynamic effects.*

Variable-length DEM

- Group size changes according to the envelop of the input signal
- Depends on the input data amplitude, the full group, half-group or quarter-group of the elements is used to create the signal
- The switch over to smaller group sizes is done at the time when the CUMMULATIVE ERROR is zero → DOES NOT interfere with the DEM activities
- Once the smaller group is selected, the unused elements (outside of the smaller group) will be turn off to save power
- With small group of elements, there is LESS mismatch error → Smaller shaped mismatch error in output.
- With less elements, the dynamics of the DEM is more → the DEM becomes more effective!

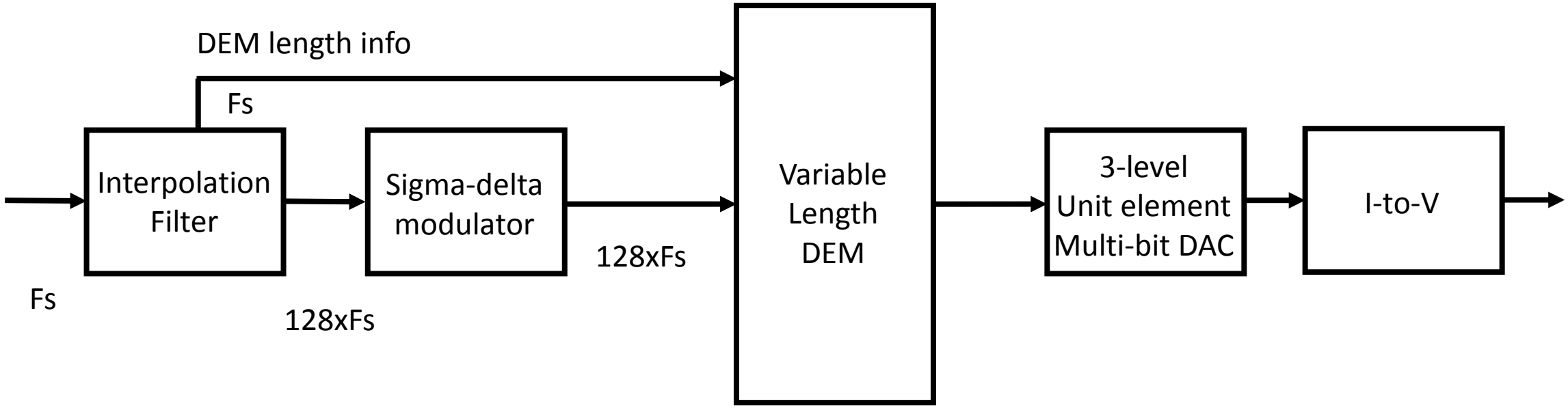
Variable-length DEM

- Example of a 16 units 3-level thermometer-code DAC.



Rotation rings of DEM

Example: Application in audio DAC

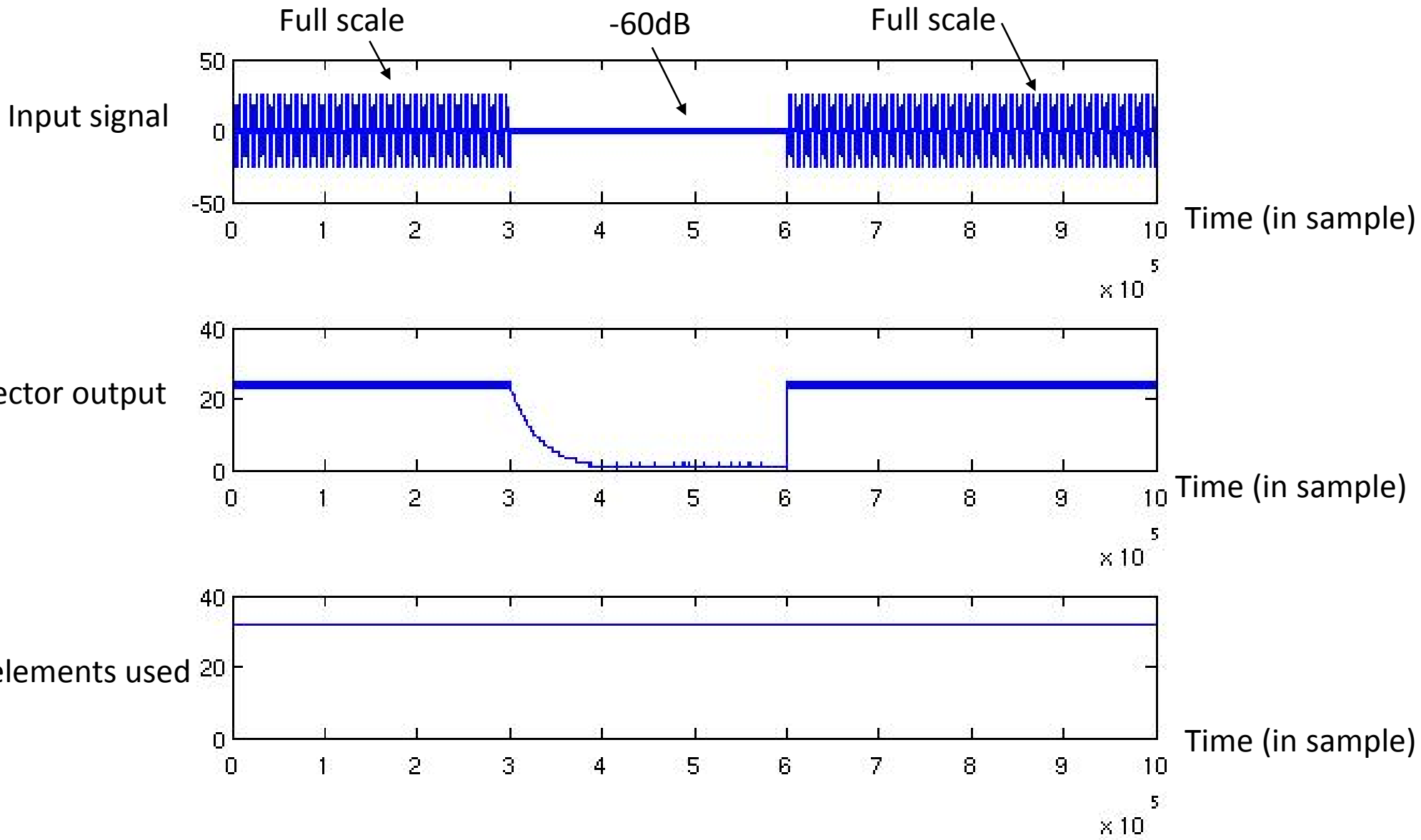


- Peak detector is used at the interpolation filter input
- Hysteresis is needed to avoid chatting (in and out of variable length mode)

Simulation case

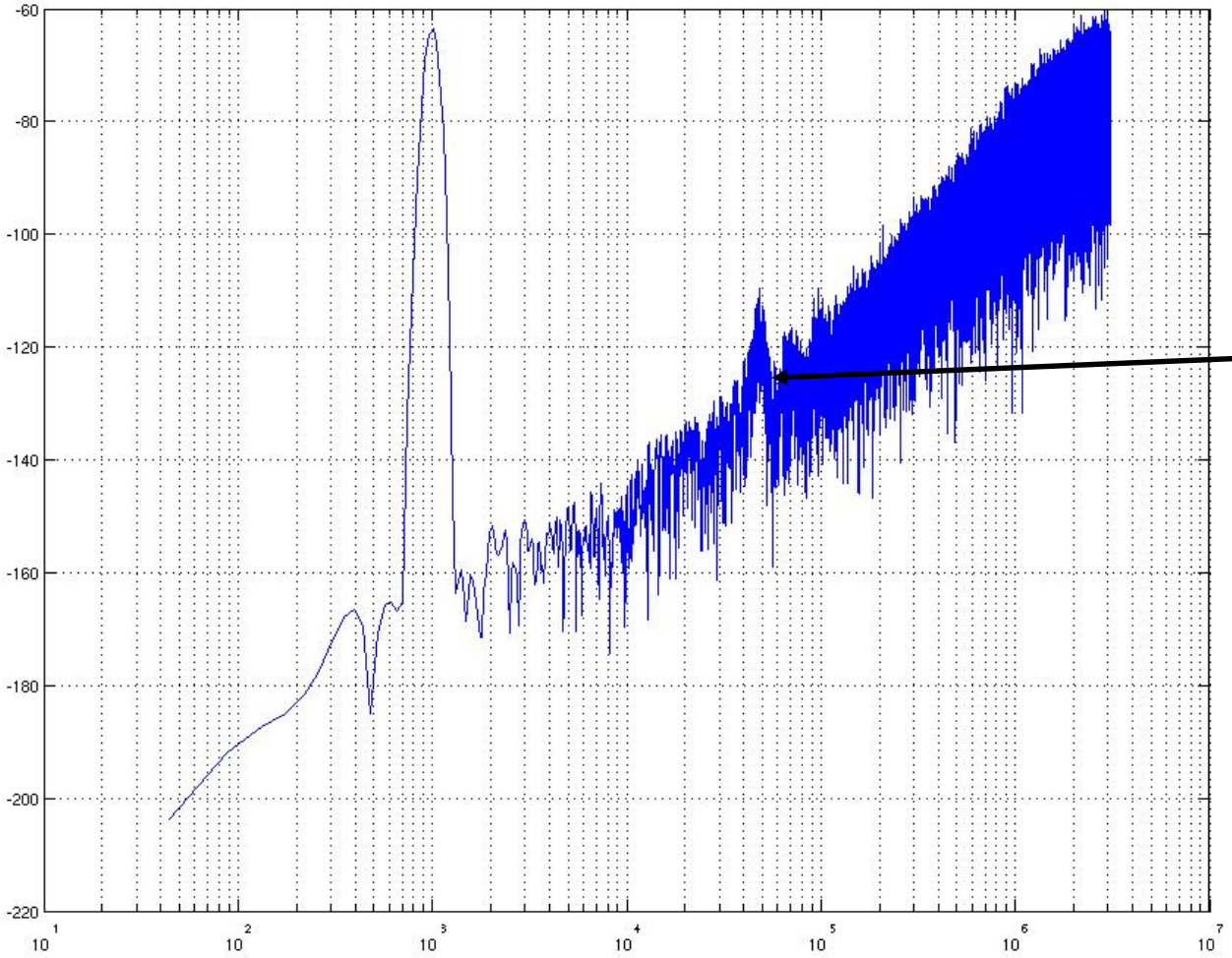
- 2^{nd} order sigma delta , 128x OSR, 6b output
- Input frequency = 1kHz
- Analog elements have 0.2% rms mismatch error
- Amplitude changes from full scale to -60dB FS
  - Demonstrate the switching from full-size group to quarter-size group
  - Demonstrate the improvements in SNR
  - Demonstrate the ability to turn off the unused elements to save power

Simulation result: No Variable-length



No Variable-length: FFT of the -60dB input

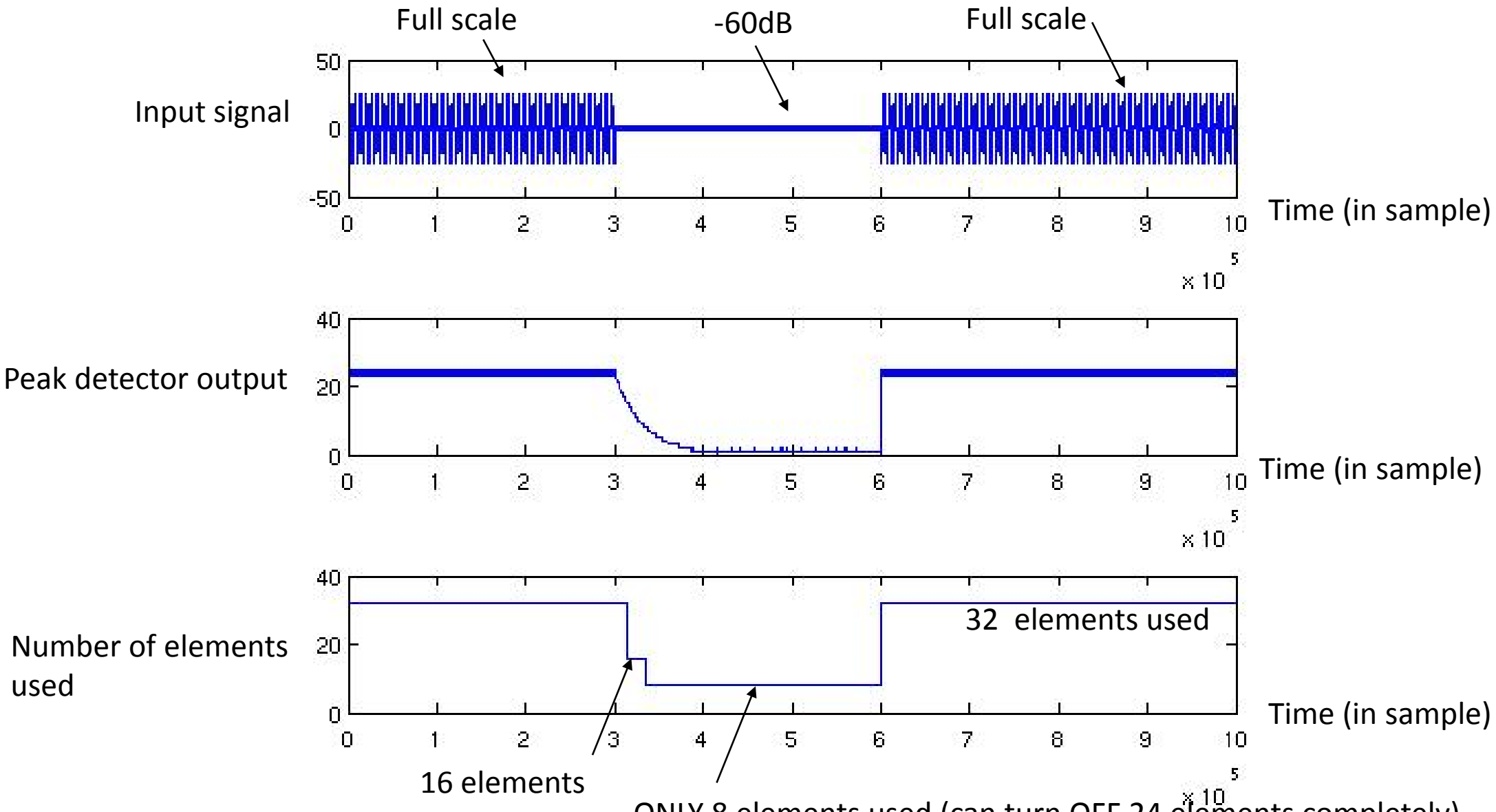
Amplitude (dB)



Tones due to large number of Elements -> had to wait for long time to apply remedy.

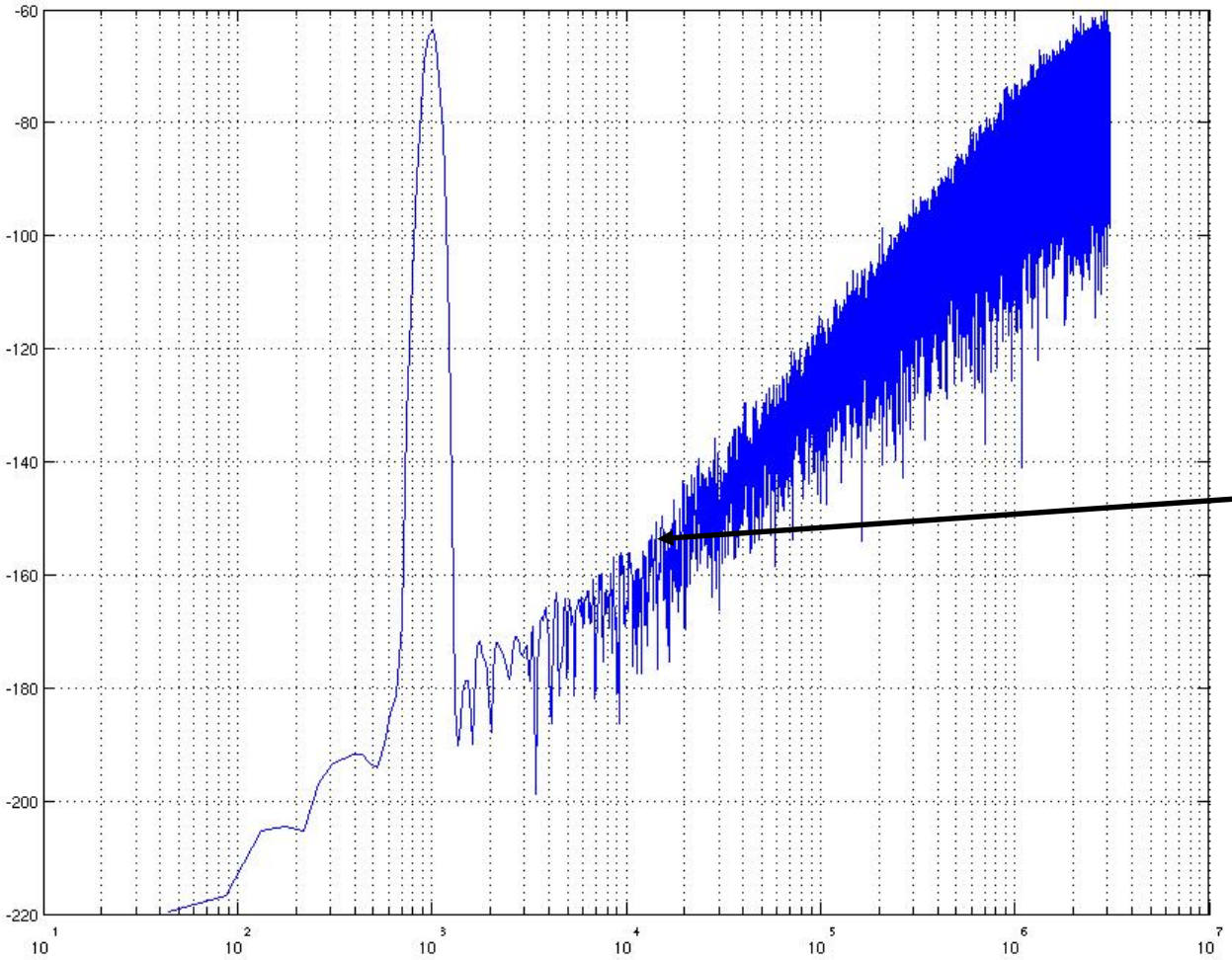
Frequency (Hz)

Simulation: With Variable-length DEM



With Variable-length: FFT of the -60dB input

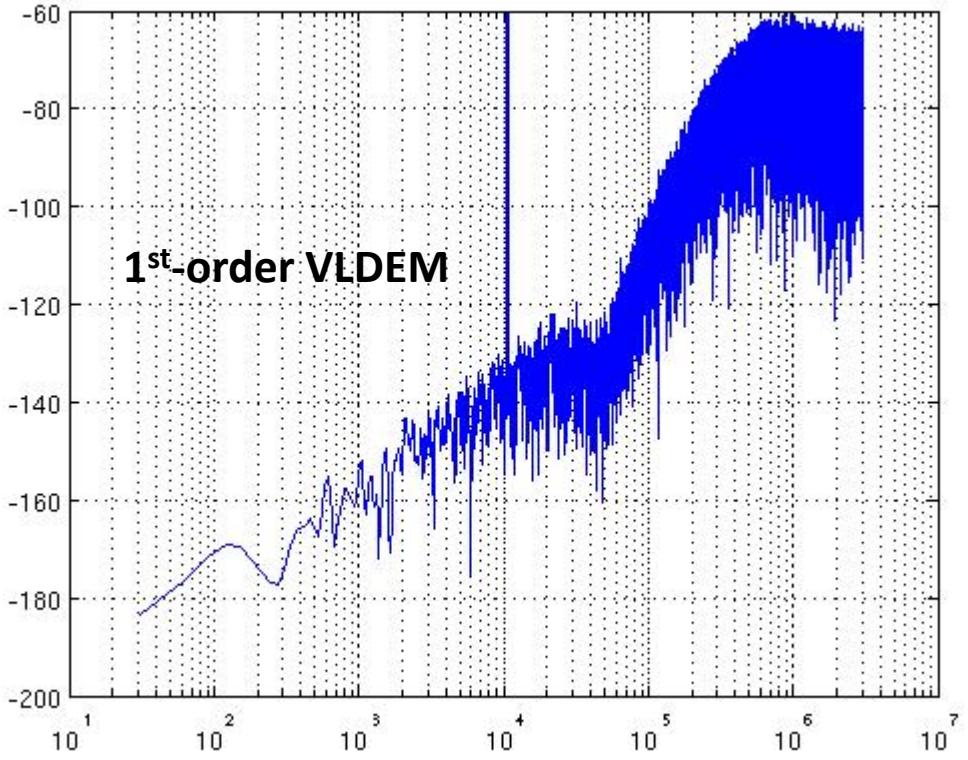
Amplitude (dB)

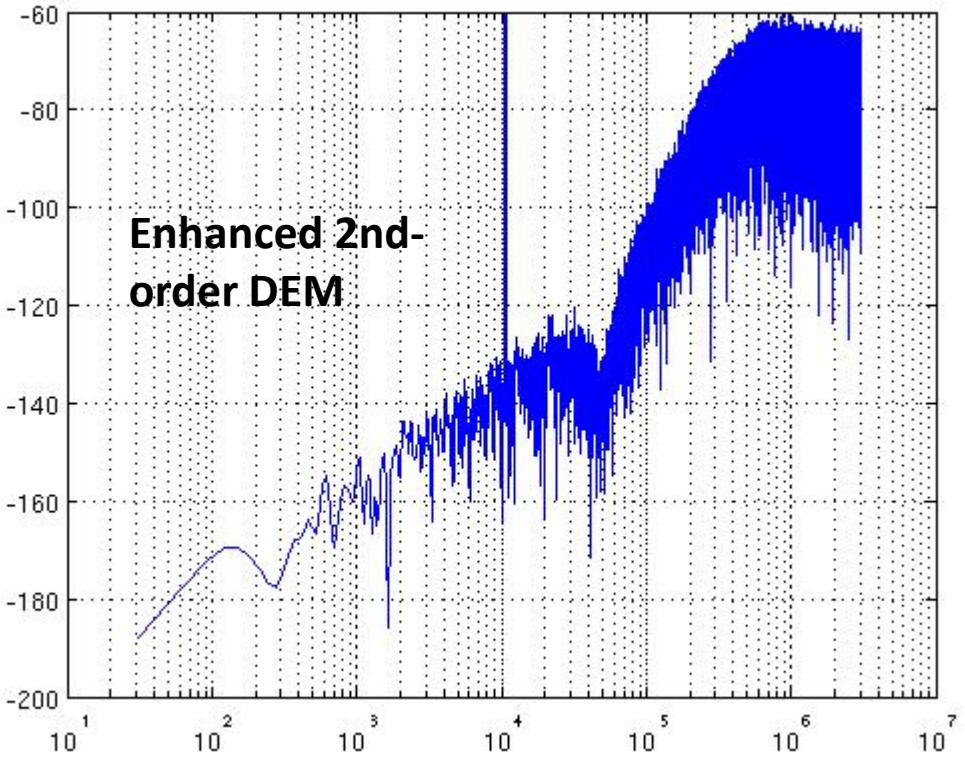


Very clean inband noise floor

Frequency (Hz)

Performance compared to 2nd order DEM @ -60dBFS, 0.25% rms mismatch





- Performs comparably to a **properly done** 2nd-order DEM (Both @ 103dB SNR)
- Much lower hardware requirement

Notes

- Optimized power consumption for DAC at low input level
- Very effective first order DEM for the sub segment(s)
- Very effective for DEM idle tone remedy
- Trade off the gain accuracy across signal amplitude range (there is NO distortion because there is no switching back and forth between smaller DACs and the large DAC , on the fly).
- Suitable for applications that require high AC linearity and not DC accuracy

Recap

- Brief background
  - Motivations and Applications
  - 3-level vs. 2-level unit element: advantages and challenges
  - What problems DEM does and does not solve
- Practical dynamic element matching (DEM) techniques
  - 2-level DEM review
  - 3-level DEM
  - Limitations of each technique
  - Solution spaces
- Higher-order DEM
  - Issues in 2^{nd}-order DEM
  - Solutions
- Application specific concepts of DEM

- Q and A

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