Switched-Capacitor Companding Filters

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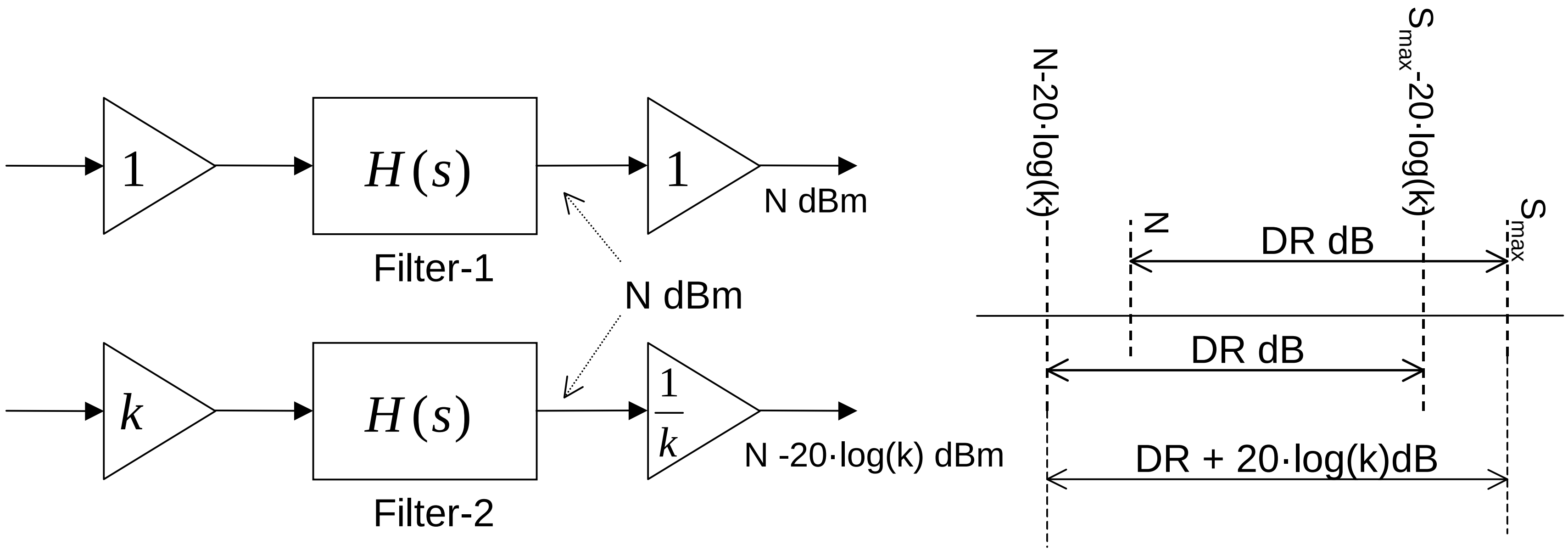
Outline

- Instantaneous companding.
- Companding using gain switching.
- Switched-capacitor implementation.
- Companding using a piecewise-linear exponential.
- Increase in dynamic range for a fixed power consumption.

Motivation

- Conventional linear filters consume a power that is proportional to the maximum S/N ratio and hence, the dynamic range.
- Companding is used to increase the dynamic range in transmission systems.
- Expected to do the same for filters without a proportionate increase in their power consumption.
- Try to keep the internal signals well above the noise and below the saturation limits in the filter circuit.

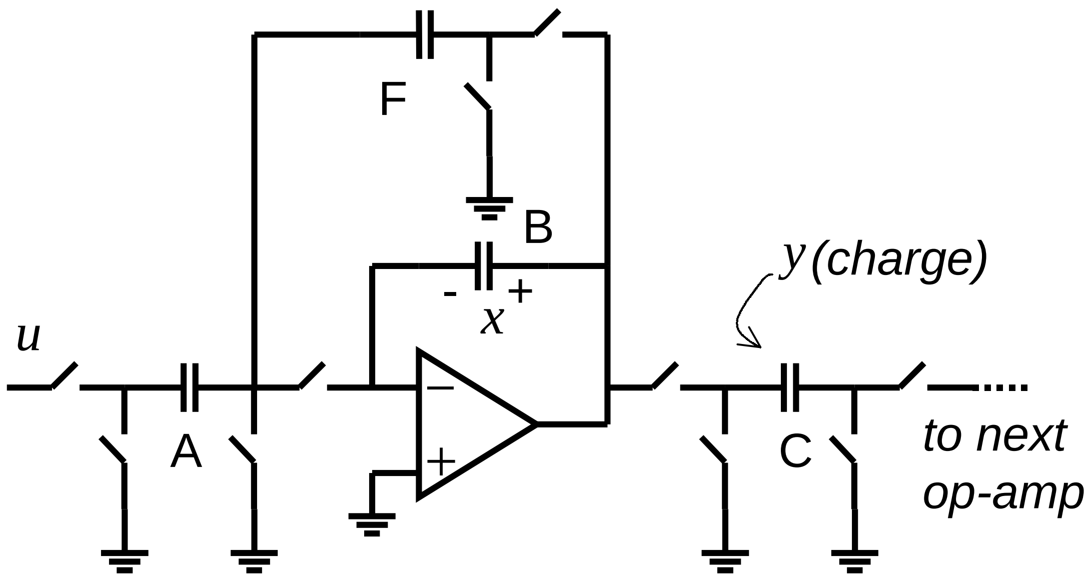
Companding



- Filters 1 & 2 have skewed operating ranges, identical dynamic range.
- Use filter-1 for large signals, filter-2 for small signals.
- Switch between filter-1 and filter-2 depending on the signal level, without changing the input-output behavior.
- DR increases by 20log(k) dB.

1. Gain switching at input and output

Linear first order SC accumulator prototype



u: input voltage

x: state variable

y: output (charge)

$$x[n+1]=\frac{B}{B+F}x[n]-\frac{A}{B+F}u[n+1]$$

$$y[n]=C\cdot x[n]$$

- input gain α A
- output gain α C

Gain switching at input and output

Define a new state variable w: $\boxed{w[n] = g[n] \cdot x[n]}$

$$w[n+1] = \frac{B}{B+F} w[n] - \frac{A}{B+F} g[n+1]\, u[n+1] + \frac{g[n+1]-g[n]}{g[n]} \frac{B}{B+F} w[n]$$

update w

accumulation

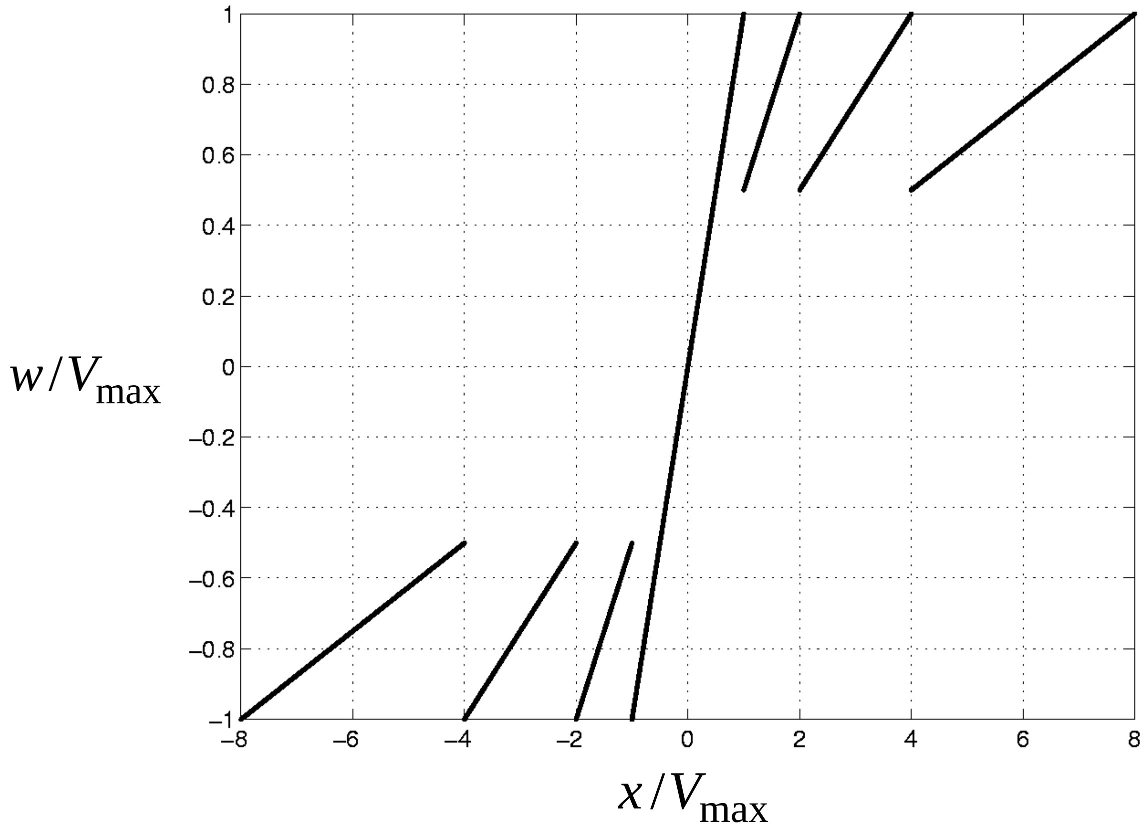
input gain

$$y[n] = \frac{C}{g[n]} w[n]$$

output gain

- Realizes a linear accumulator, identical to the prototype.
- g can be selected to achieve companding.
- One of the possibilities: “Analog floating point technique” (Blumenkrantz ‘95).

Mapping between x and w (four values of g)



- g decreases by a factor of 2 whenever w increases beyond a predetermined level, and vice versa. (Blumenkrantz '95)
- monotonically increasing x, but a limited value of w.

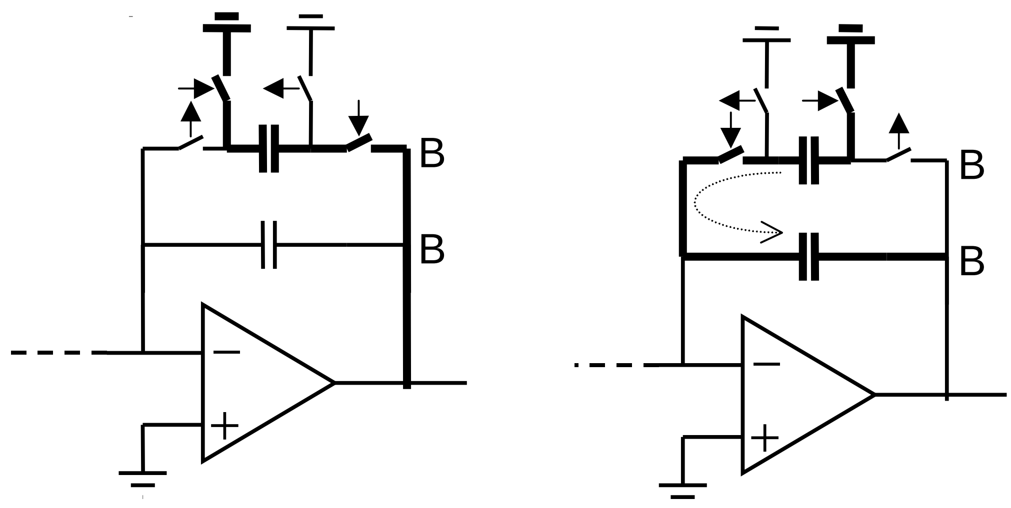
Switched-capacitor implementation

- When g doesn't change, same as a conventional accumulator.
- A set of comparators are used to detect overflow ($>V_{max}$) or underflow ($< 0.5 \cdot V_{max}$) of the state variable.
- A state machine used to "remember" the current value of g .
- An array of capacitors used at the input and the output to alter the gains as desired.

Switched-capacitor implementation

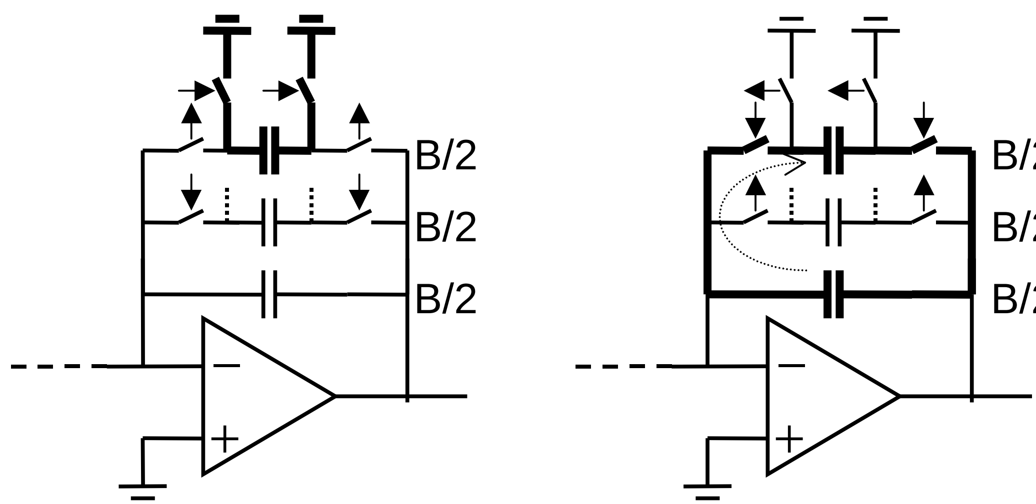
g increases:

double w using a precharged capacitor.



g decreases:

halve w using a pre-discharged capacitor.

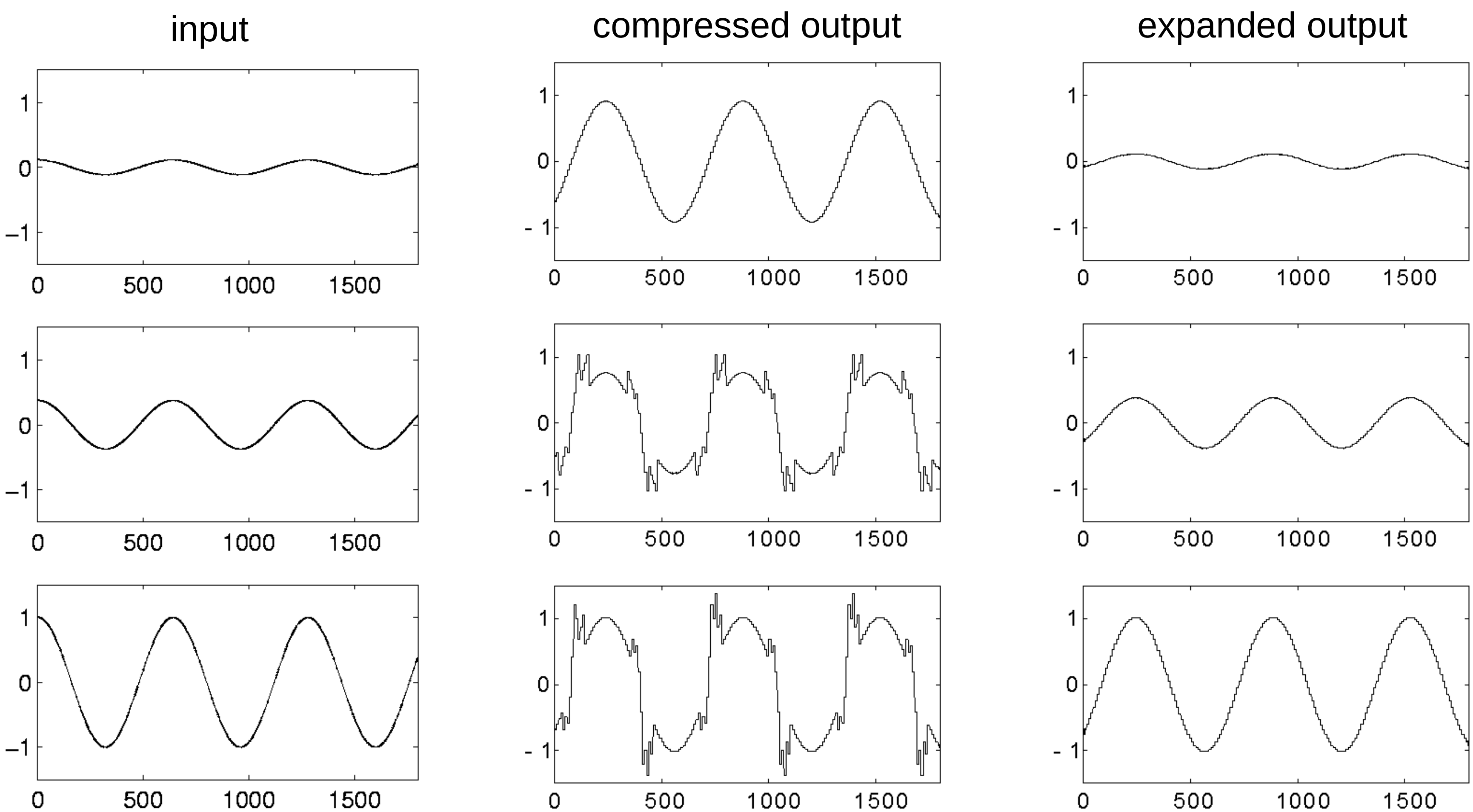


comparison phase *update phase*

Remarks

- As the number of segments increases:
  - Larger signals can be handled.
  - Input / output capacitor spread increases.
  - Practical limit ~ 3-4 values of g.
- With 4 segments:
  - Can handle a 8 X larger signal than a linear filter without distortion.
  - Output noise: same as in the linear case (reduces to a conventional filter for small signals).
  - Has 64 X larger dynamic range (= P_{max}/ P_{min}) than the linear filter.
  - Uses ~ 8 X larger bias current (op-amp loading) in the worst case $\Rightarrow$ 8 X larger power drawn from the supply.
  - A conventional filter would use 64 X larger bias current and 64 X larger capacitor.

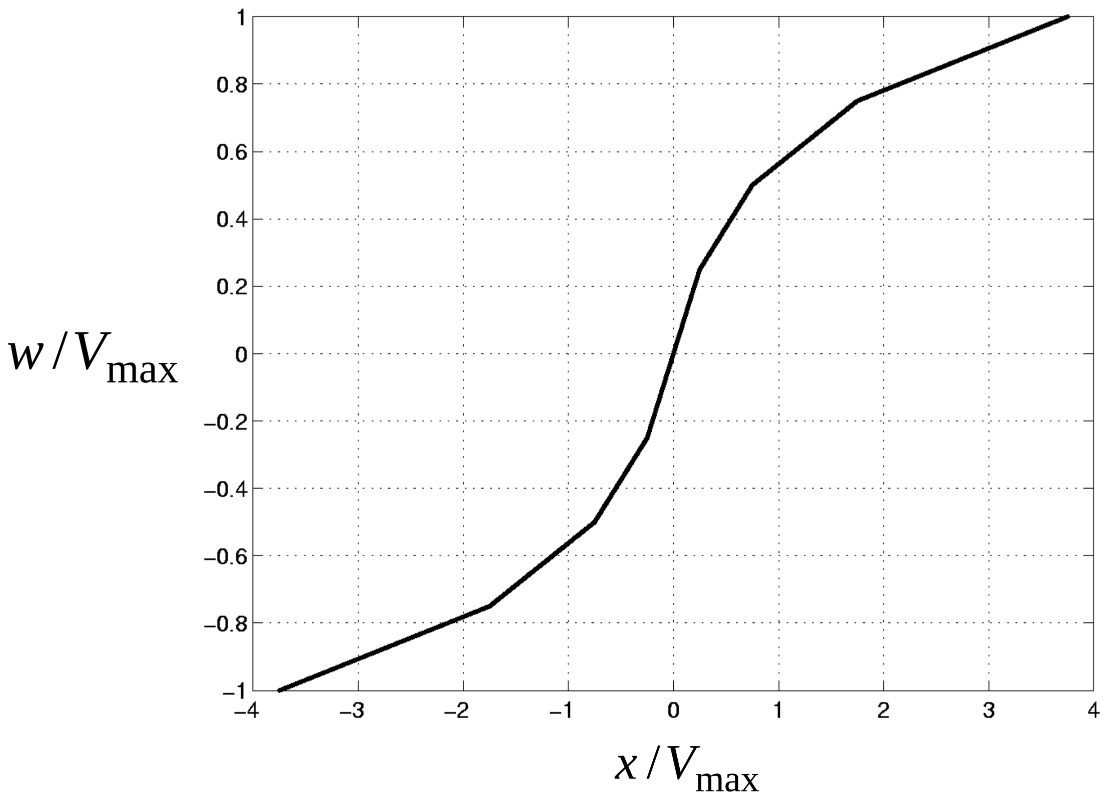
Simulation: 6th order low-pass filter



Stays away from the noise-prone low-voltage regions.

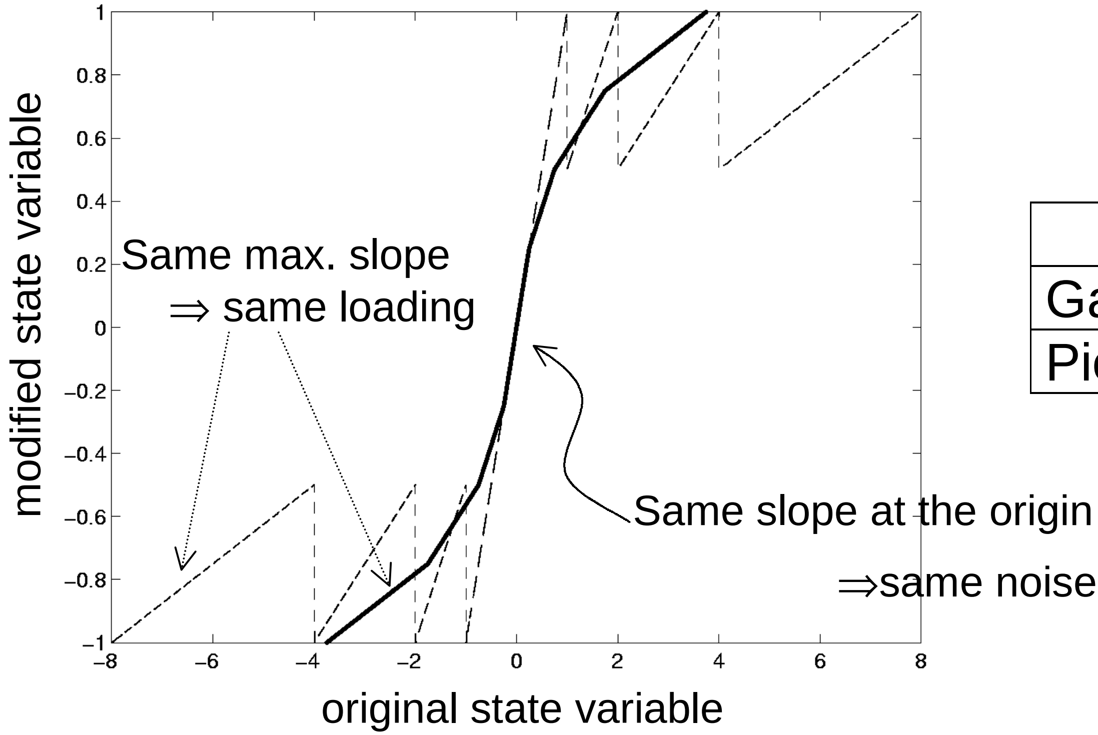
2. Use a piecewise linear compression

Mapping between x and w



- The slope decreases by a factor of 2 in successive segments, but the mapping is continuous.
- input, output blocks similar to the previous case.

Comparison



Compression	
Gain switching	8: 1
Piecewise linear	3.75: 1

gain switching	piecewise linear
+ larger improvement in dynamic range.	– smaller improvement in dynamic range.
– large “jumps” in the o / p.	+ no “jumps” in the o / p.
+ # comparators: fixed	– # comparators α # segments

Conclusions

- Two possible techniques for implementing switched-capacitor companding filters are discussed.
- The increase in the dynamic range for a given power consumption is estimated.
- Companding can overcome the tradeoff between the dynamic-range and the power consumption that is present in linear switched capacitor filters.

Switched-capacitor implementation

- Input / output gain values: switch capacitors in/out
- updating term:
  - $g[n] = g[n\text{-}1]$

$$\boxed{(B+F)\cdot w[n+1] = B\cdot w[n] - A\cdot g[n+1]u[n+1]}$$

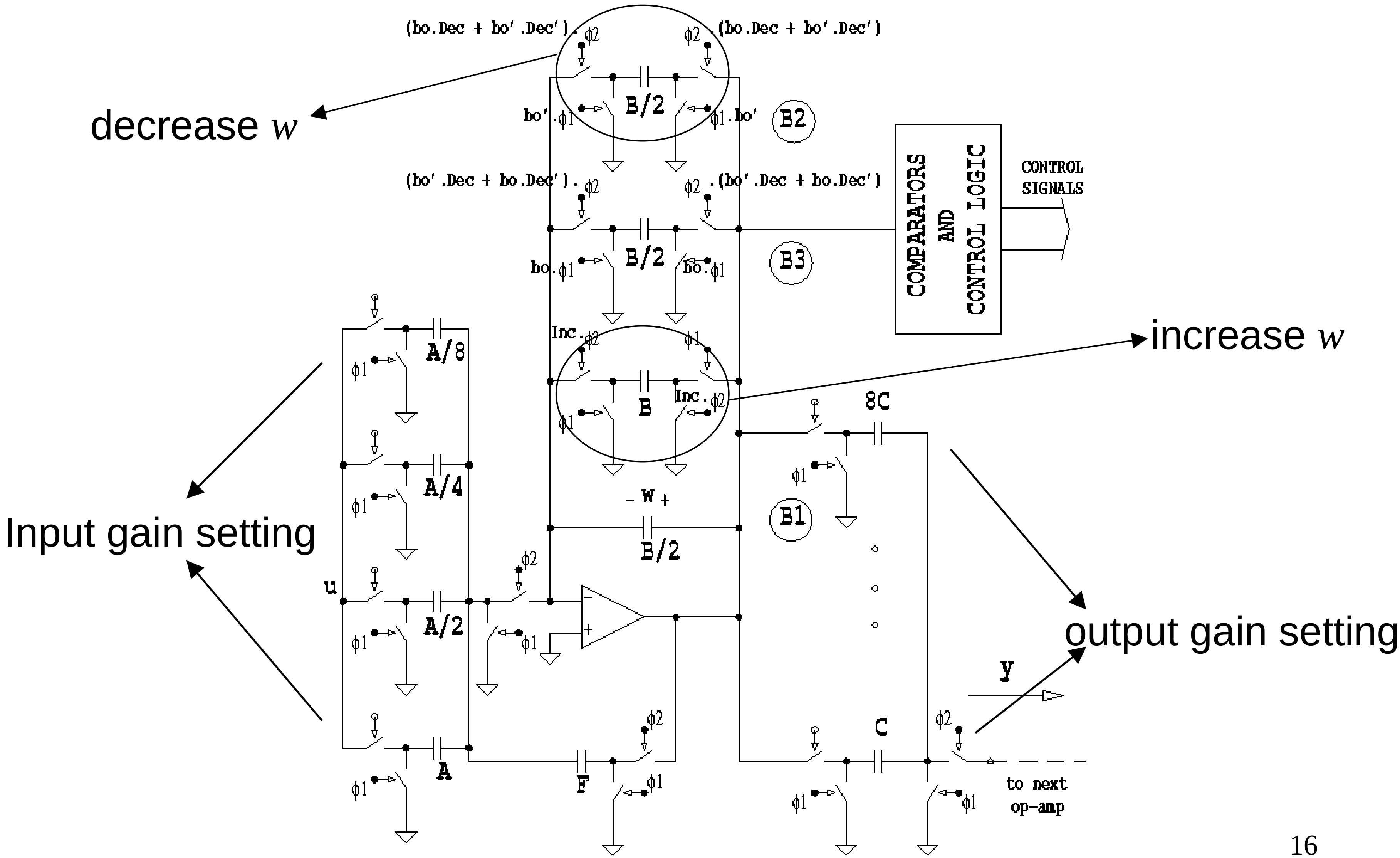
  - $g[n] = 2g[n\text{-}1]$

$$\boxed{(B+F)\cdot w[n+1] = 2B\cdot w[n] - A\cdot g[n+1]u[n+1]}$$

  - $g[n] = 0.5g[n\text{-}1]$

$$\boxed{(B+F)\cdot w[n+1] = \frac{B}{2}\cdot w[n] - A\cdot g[n+1]u[n+1]}$$

Switched-capacitor implementation



Result

conventional

- output maximum = V_{max}
- output minimum = N_{out}
- load = C + (B+F)||A
- capacitance:
  A + B + C + F
- power = P
- dynamic Range: DR
- (DR / P)

companding

- output maximum = $8V_{max}$
- output minimum = N_{out}
- load : C/g[n] + B +
  (B+F)||A
- capacitance:
  15A + 3B + 15C+F
- power $\approx 8 \cdot P$
- dynamic Range: $64 \cdot DR$
- $8 \cdot (DR / P)$

Gain switching - cont'd...

- Output rises to $8V_{max}$!
  - Incorporate an 8x attenuator in the expandor ($1/g[n]$)
- Input should also be limited to V_{max}
  - Apply 8x smaller input, increase the input capacitors 8x

$$\boxed{\text{This does not alter the dynamic range}}$$