## EE 505

## Lecture 13

String DACs
Current Steering DACs

## What DAC Architectures are Actually Used?

Listing from Texas Instruments March 12023
String ..... 168
R-2R ..... 79
Current Source ..... 52
MDAC ..... 23
Current Sink ..... 17
SAR ..... 9
Pipeline ..... 7
Delta Sigma ..... 4
1-Steering ..... 3
Current Steering ..... 2

Support \& Community

TEXAS
InSTRUMENTS

## DAC8532 Dual Channel, 16-Bit, Low Power, Serial Input Digital-To-Analog Converter

## 1 Features

- 16-Bit Monotonic Over Temperature
- MicroPower Operation: $500 \mu \mathrm{~A}$ at 5 V
- Power-On Reset to Zero-Scale
- Power Supply: 2.7 V to 5.5 V
- Settling Time: $10 \mu \mathrm{~s}$ to $\pm 0.003 \%$ FSR
- Ultra-Low AC Crosstalk: -100 dB Typ
- Low-Power Serial Interface With Schmitt-Triggered Inputs
- On-Chip Output Buffer Amplifier With Rail-to-Rail Operation
- Double-Buffered Input Architecture
- Simultaneous or Sequential Output Update and Powerdown
- Available in a Tiny VSSOP-8 Package


## 2 Applications

- Portable Instrumentation
- Closed-Loop Servo Control
- Process Control
- Data Acquisition Systems
- Programmable Attenuation
- PC Peripherals


## 3 Description

The DAC8532 is a dual channel, 16 -bit digital-toanalog converter (DAC) offering low power operation and a flexible serial host interface. Each on-chip precision output amplifier allows rail-to-rail output swing to be achieved over the supply range of 2.7 V to 5.5 V . The device supports a standard 3 -wire serial interface capable of operating with input data clock frequencies up to 30 MHz for $\mathrm{V}_{\mathrm{DD}}=5 \mathrm{~V}$.

The DAC8532 requires an external reference voltage to set the output range of each DAC channel. The device incorporates a power-on reset circuit which ensures that the DAC outputs power up at zero-scale and remain there until a valid write takes place. The DAC8532 provides a flexible power-down feature, accessible over the serial interface, that reduces the current consumption of the device to 200 nA at 5 V .

The low-power consumption of the device in normal operation makes it ideally suited to portable batteryoperated equipment and other low-power applications. The power consumption is 2.5 mW at 5 V , reducing to $1 \mu \mathrm{~W}$ in power-down mode.

The DAC8532 is available in a VSSOP-8 package with a specified operating temperature range of $-40^{\circ} \mathrm{C}$ to $105^{\circ} \mathrm{C}$.

### 7.5 Electrical Characteristics

$\mathrm{V}_{\mathrm{DD}}=2.7 \mathrm{~V}$ to 5.5 V , all specifications $-40^{\circ} \mathrm{C}$ to $105^{\circ} \mathrm{C}$ (unless otherwise noted)

(1) Linearity calculated using a reduced code range of 485 to 64714 ; output unloaded.
(2) Ensured by design and characterization, not production tested.

Ironically INL not specified in datasheet but listed as 64 LSB in selection guide

## 16-bit TI String DACs

| DAC8775 | 16 | \$15.880 \| 1ku | String | 12 |
| :---: | :---: | :---: | :---: | :---: |
| DAC8551-Q1 | 16 | \$2.950 \| 1 ku | String | 16 |
| DAC8563T | 16 | \$4.066 \\| 1 ku | String | 12 |
| DAC8562T | 16 | \$4.066\|1 ku | String | 12 |
| DAC8563-Q1 | 16 | \$4.798\|1ku | String | 12 |
| DAC8750 | 16 | \$4.970 \| 1ku | String | 26 |
| DAC8760 | 16 | \$5.900 \| 1 ku | String | 52 |
| DAC8562-Q1 | 16 | \$4.798\| 1 ku | String | 12 |
| DAC8562 | 16 | \$4.066\|1ku | String | 12 |
| DAC8563 | 16 | \$3.860 \| 1 ku | String | 12 |
| DAC8718 | 16 | \$23.990\| 1ku | String | 4 |
| DAC8728 | 16 | \$23.990 \| 1ku | String | 4 |
| DAC8568 | 16 | \$10.600 \| 1 ku | String | 12 |
| DAC8411 | 16 | \$2.420 \| 1 ku | String | 8 |
| DAC8564 | 16 | \$6.282 \| 1 ku | String | 8 |
| DAC8565 | 16 | \$6.785\|1ku | String | 8 |
| DAC8560 | 16 | \$2.890 \| 1ku | String | 8 |
| DAC8552 | 16 | \$3.800\|1 ku | String | 12 |
| DAC8550 | 16 | \$3.000\|1ku | String | 8 |
| DAC8555 | 16 | \$6.070 \| 1ku | String | 12 |
| DAC8554 | 16 | \$6.490\|1ku | String | 12 |
| DAC8551 | 16 | \$2.500 \| 1 ku | String | 12 |
| DAC8544 | 16 | \$13.000\| 1 ku | String | 65 |
| DAC8571 | 16 | \$2.420 \| 1 ku | String | 65 |
| DAC8574 | 16 | \$7.647 \| 1ku | String | 64 |
| DAC8534 | 16 | \$9.605 \| 1ku | String | 64 |
| DAC8532 | 16 | \$5.785 \| 1ku | String | 65 |
| DAC8541 | 16 | \$2.904 \| 1 ku | String | 65 |
| DAC8501 | 16 | \$3.263\|1ku | String | 64 |
| DAC8531 | 16 | \$3.245 \| 1 ku | String | 64 |

## >16-bit TI R-2R DACs

| DAC11001B | 20 | \$59.000\|1 ku | R-2R | 1 |
| :---: | :---: | :---: | :---: | :---: |
| DAC11001A | 20 | \$35.778 \| 1ku | R-2R | 4 |
| DAC91001 | 18 | \$27.489 \\| 1ku | R-2R | 1 |
| DAC9881 | 18 | \$16.359 \| 1 ku | R-2R | 2 |
| DAC82002 | 16 | \$14.000 \| 1 ku | R-2R | 2 |
| DAC81402 | 16 | \$8.900\| 1ku | R-2R | 1 |
| DAC81404 | 16 | \$15.990 \| 1ku | R-2R | 1 |
| DAC81001 | 16 | \$17.589 \| 1 ku | R-2R | 1 |
| DAC80502 | 16 | \$3.949 \| 1ku | R-2R | 1 |
| DAC80501 | 16 | \$2.750\|1ku | R-2R | 1 |
| DAC81408 | 16 | \$23.990 \| 1ku | R-2R | 1 |
| DAC81416 | 16 | \$32.990 \| 1ku | R-2R | 1 |
| DAC80504 | 16 | \$8.702 \| 1ku | R-2R | 1 |
| DAC80508 | 16 | \$9.240 \| 1ku | R-2R | 1 |
| DAC80004 | 16 | \$7.734 \| 1ku | R-2R | 1 |
| DAC161S055 | 16 | \$4.840 \| 1ku | R-2R | 3 |
| DAC8734 | 16 | \$19.990\|1ku | R-2R | 1 |
| DAC8881 | 16 | \$8.906\|1ku | R-2R | 1 |
| DAC8871 | 16 | \$25.000 \| 1 ku | R-2R | 1 |
| DAC8831-EP | 16 | \$12.013 \| 1 ku | R-2R | 1 |
| DAC8830-EP | 16 | \$11.664\|1ku | R-2R | 1 |
| DAC8832 | 16 | \$5.760 \| 1 ku | R-2R | 1 |
| DAC8831 | 16 | \$6.242 \| 1ku | R-2R | 1 |
| DAC8830 | 16 | \$5.910\| 1 ku | R-2R | 1 |
| DAC7664 | 16 | \$26.378\| 1 ku | R-2R | 3 |
| DAC7654 | 16 | \$38.165 \| 1 ku | R-2R | 3 |
| DAC7742 | 16 | \$13.665 \| 1 ku | R-2R | 3 |
| DAC7632 | 16 | \$10.116\|1ku | R-2R | 3 |
| DAC7642 | 16 | \$14.741\|1ku | R-2R | 3 |
| DAC7741 | 16 | \$9.244 \| 1ku | R-2R | 3 |
| DAC7731 | 16 | \$8.335 \| 1ku | R-2R | 3 |
| DAC7631 | 16 | \$7.209 \| 1ku | R-2R | 3 |
| DAC7641 | 16 | \$8.334 \| 1 ku | R-2R | 3 |
| DAC7734 | 16 | \$37.464 \| 1ku | R-2R | 2 |
| DAC7634 | 16 | \$24.576 \| 1 ku | R-2R | 3 |
| DAC7744 | 16 | \$38.643 \| 1 ku | R-2R | 2 |
| DAC7644 | 16 | \$21.282 \| 1 ku | R-2R | 3 |
| DAC716 | 16 | \$23.642 \| 1 ku | R-2R | 2 |
| DAC715 | 16 | \$25.556 \| 1 ku | R-2R | 2 |
| DAC714 | 16 | \$20.350 \| 1ku | R-2R |  |

## DAC Performance Issues and Concerns



## DAC Performance Issues and Concerns



Incomplete Nonlinear Settling

Complete with glitch
Incomplete with glitch

Incomplete with big glitch

## DAC Performance Issues and Concerns



Previous code dependent glitches
Previous code dependent settling

## DAC Performance Issues and Concerns

Linear settling of DAC outputs do not affect linearity if all have same settling times (for both sampled outputs and overall transient response

Incomplete settling introduces nonlinearities in transient response and usually in settled response

Previous code dependent outputs or settling almost always introduces nonlinearities

Glitches can be many LSB in magnitude and are often previous-code dependent

Glitches in output at transition points do not introduce nonlinearities in settled outputs but may introduce distortion in continuous-time outputs

## R-String DAC



Conceptual
$\square$ Simple structure
$\square$ Inherently monotone
$\square$ Very low DNL
Potential for being very fast
$\square$ Low Power Dissipation
$\square$ Widely Used Approach (with appropriate considerations)

## Challenges:

- Managing INL
- Matching (resistors, switches)
- Leakage currents
- Large number of devices for $n$ large ( $2^{n}$ or $2^{\mathrm{n}+1}$ lines)
- Decoder
- Routing thermometer/bubble clocks
- Transients during Boolean transitions
- Glitches
- Switch implementation
- Thevenin impedance facing $\mathrm{V}_{\text {OUT }}$ highly code dependent


## R-String DAC <br> (minor variant where $\mathrm{V}_{\text {out }}(0, \ldots 0) \neq 0$ )



Practical level shift

## Switch Implementation



- Large number required for large resolution
- Simple structure often used

- Good when switch terminals near gnd
- Will not turn on when terminals near $\mathrm{V}_{\mathrm{DD}}$
- Good when switch terminals near $V_{D D}$
- Will not turn on when terminals near gnd
- Use devices where cross-over occurs
- Good for both high and low term voltages
- Extra clock signal required
- Try to avoid this complexity

Other switch structures (such as bootstrapped switch) used but not for basic string DACs

## Switch Assignment



Challenges:

## Switch Impedances



## Switch Impedances


$R_{\text {SWIG }}$

$R_{\text {SWIG }}$



Switch impedance significantly both position and device size dependent

$$
\mathrm{V}_{\mathrm{Gp}}=0 \mathrm{~V}, \mathrm{~V}_{\mathrm{Gn}}=\mathrm{V}_{\mathrm{DD}}
$$



## Switch Parasitics



- $\mathrm{C}_{B D}$ and $\mathrm{C}_{\mathrm{BS}}$ can be significant and cause rise-fall times to be position dependent
- $\mathrm{C}_{G D O L}$ can cause "kickback" or feed-forward
- $\mathrm{C}_{G S}$ can slow turn-on and turn-off time of switch


## R-String DAC



## Additional Challenges:

- Capacitance on $\mathrm{V}_{\text {OUt }}$ can be large
- larger for p-channel devices
- even larger for TG switches
- Switch impedances position dependent
- Kickback from switches to R-string
- Capacitance on each node (though small) of Rstring from switch
- Thevenin impedance facing $\mathrm{V}_{\text {Out }}$ highly code dependent
- Gradient effects may cause nonlinearities since common-centroid layout may not be practical if $n$ is large


## R-String DAC



Additional Challenges

- Delay in Decoder may be significant
- Delay in Decoder may be previous code and current code dependent
- Intermediate undesired Boolean outputs may occur
- These may cause undesired opening and closing of switches
- Could momentarily short out taps on R-string
- Could introduce transients on all nodes of R-string that are code and previous code dependent


## R-String DAC



## R-String DAC



- Uses matrix decoder as analog MUX (don't synthesize decoder)
- Implements binary to decimal conversion with pass transistor analog logic
- Very structured layout
- Interconnection points are switches (combination of $n$-channel and $p$-channel)


## Challenges

- Still many signals to route
- Large capacitance on $\mathrm{V}_{\text {OUT }}$ (over $2^{\mathrm{n}+1}$ diff caps)
- Multiple previous code dependencies cause output transition time to be quite unpredictable
- Considerable transients introduced on R-string


## R-String DAC



Parasitic Capacitances in Matrix Decoder

## R-String DAC



Previous-Code Dependent Settling Assume all C's (except those on the R-string) initially with OV Red denotes $\mathrm{V}_{3}$, black denotes 0V, Purple some other voltage

## R-String DAC



## Previous-Code Dependent Settling

Assume all C's (except those on the R-string) were initially at 0V

## R-String DAC

Transition from <010> to <101> White boxes show capacitors dependent upon previous code <010>


## Previous-Code Dependent Settling

- Assume all C's (except those on the R -string) were initially at 0 V
- Red denotes $\mathrm{V}_{3}$, green denotes $\mathrm{V}_{6}$, black denotes 0 V , Purple some other voltage
- Some capacitors may retain values from a previous input for many clock cycles for some inputs resulting I previous-previous dependence of even longer


## R-String DAC



- Uses tree decoder as analog MUX
- Implements binary to decimal conversion with pass transistor analog logic
- Very structured layout
- Interconnection points are switches (combination of n-channel and p-channel)
- Dramatically reduces capacitance on output and switching capacitances
$V_{\text {out }}$ Challenges
- Still many signals to route
- Multiple previous code dependencies cause output transition time to be quite unpredictable


## R-String DAC



## Matrix-Decoder in Digital Domain

Single transistor used at each marked intersection for PTL AND gates
Dramatic reduction in capacitive loading at output
Do the resistors that form part of PTL dissipate any substantial power?
No because only one will be conducting for any DAC output
Will become more complicated if both p-channel and n -channel switches needed

## R-String DAC

## String DAC with Row-Column Decoder



- Dramatic reduction in decoder complexity
- Dramatic reduction of capacitive loading on output
- Changes decoder from a onedimensional to a two-dimensional solution (can be thought of as folding)
- Logic gates could be placed at each node to eliminate analog row decoder

Challenges (most were present in earlier structures too)

- Some previous code dependence
- INL large
- Difficult to cancel gradient effects in layout

Switching sequencing can help a lot

- Switch impedances code dependent
- Settling times code dependent


## R-String DAC

Can this concept be extended further?


- Dramatic reduction in decoder complexity
- Dramatic reduction of capacitive loading on output
- Changes decoder from a onedimensional to a m-dimensional solution (folding)
- Logic gates could be placed at each node to eliminate analog row decoder


## R-String DAC

What about this parallel R-string?


## R-String DAC

What about this parallel R-string?


## R-String DAC



## R-String DAC



A 10-b 50-MHz CMOS D/A converter with 75-w buffer
MJM Pelgrom - Solid-State Circuits, IEEE Journal of, 1990 - ieeexplore.ieee.org Abstracf-A 10-b $50-\mathrm{MHz}$ digital-to-analog (D/A) converter is pre-sented which is based on a
Note Dual Ladder is used! dual-ladder resistor string. This approach allows the linearity requirements to be met without the need for selection or trimming. The D/A decoding scheme reduces the glitch energy, ..

## R-String DAC <br> n $\downarrow$ <br> $\mathrm{n}=\mathrm{n}_{1}: \mathrm{n}_{2}$



A 10-b 50-MHz CMOS D/A converter with 75-w buffer

## Note Dual Ladder is used!

## : AND pixel sensor gate

 $32 \times 32$ MatrixMJM Pelgrom - Solid-State Circuits, IEEE Journal of, 1990 - ieeexplore.ieee.org Abstracf-A 10-b $50-\mathrm{MHz}$ digital-to-analog (D/A) converter is pre-sented which is based on a dual-ladder resistor string. This approach allows the linearity requirements to be met without the need for selection or trimming. The D/A decoding scheme reduces the glitch energy, ... Cited by 109 Related articles All 3 versions Cite Save


## Stay Safe and Stay Healthy !

## End of Lecture 13

