IMEKO2024 XXIV World Congress
26 – 29 August 2024 | Hamburg, Germany

IMPROVING THE ACCURACY OF DIGITAL-TO-ANALOGUE CONVERTERS

Jonathan Sæthre Ege

NTNU | Norwegian University of Science and Technology

Introduction of speaker

Jonathan Sæthre Ege

- PhD Candidate at NTNU
  - Faculty of Information Technology and Electrical Engineering (IE)
  - Department of Electronic Systems (IES)
  - Research group: Circuit and Radio Systems (KR)
  - Researching DAC IC design
    - DAC with >=18 ENOB @ 100 kHz BW
    - Collaborating with:
      - The research group Precision Instrumentation & Control Lab (PINACL) at University of Stavanger (UiS)
      - Aalborg University in Denmark
      - Justervesenet (Norwegian Metrology Service)

https://www.ntnu.edu/employees/jonathan.s.ege
https://pinacl.ux.uis.no/

What, why, and how?

- **What**
  - Evaluate five linearisation / error mitigating methods
  - In-house designed DACs
- **Why**
  - State-of-the-art semiconductor-based DAC 17 ENOB @ 10 kHz BW [1]
  - Principally limited by static errors [1]
  - Mainly slew rate limited at higher BW [2]
  - Wide range of applications
  - Off-the-shelf DACs

Applications
- Metrology
- Mechatronics
- Lithography
- Optics

Digital-to-analogue converter (DAC)
Effective number of bits (ENOB)
Integrated circuit (IC)
Bandwidth (BW)

[1] A. Eielsen and A. J. Fleming, "Existing methods for improving the accuracy of digital-to-analog converters," Review of Scientific Instruments, vol. 88, no. 9, p. 094702, 2017.
[2] M. J. Pelgrom, Analog-to-Digital Conversion. Springer, 2013

What, why, and how?

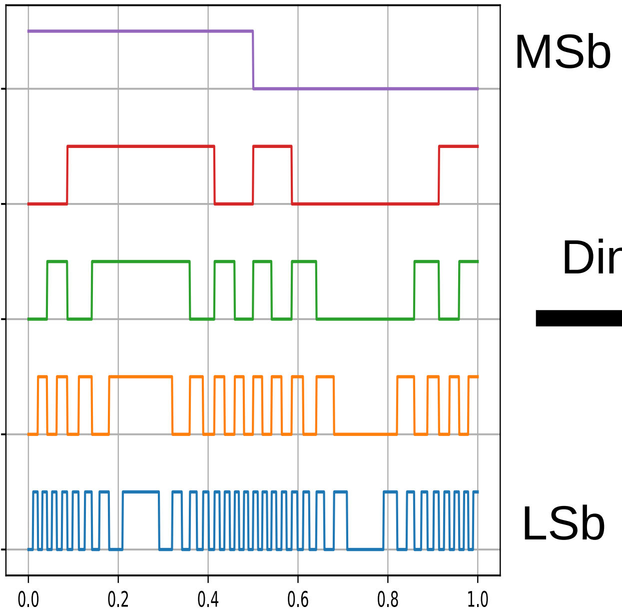
- **How**
  - DAC IC design
  - Static and dynamic models

Applications
- Metrology
- Mechatronics
- Lithography
- Optics

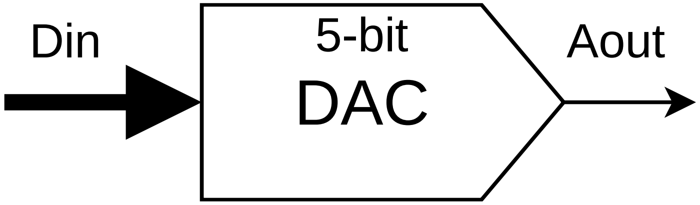
Digital-to-analogue converter (DAC)
Effective number of bits (ENOB)
Integrated circuit (IC)
Bandwidth (BW)

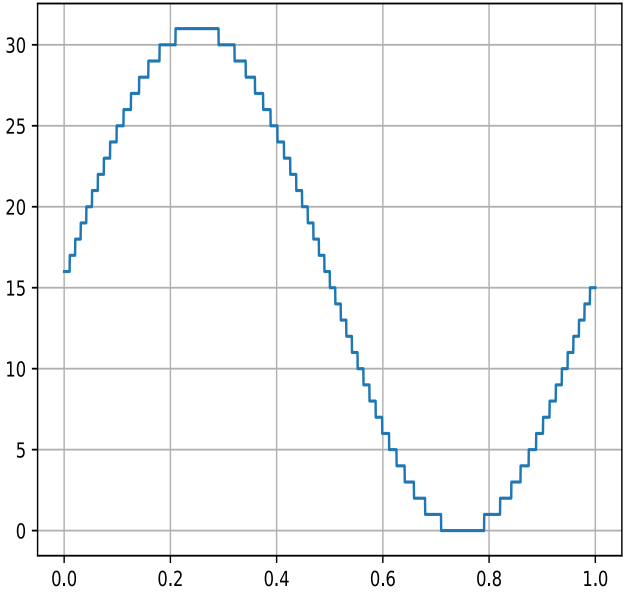
[1] A. Eielsen and A. J. Fleming, “Existing methods for improving the accuracy of digital-to-analog converters,” Review of Scientific Instruments, vol. 88, no. 9, p. 094702, 2017.
[2] M. J. Pelgrom, Analog-to-Digital Conversion. Springer, 2013

Digital-to-analogue converters (DACs)



$$\text{ENOB} = \frac{\text{SINAD} - 1.76}{6.02}$$





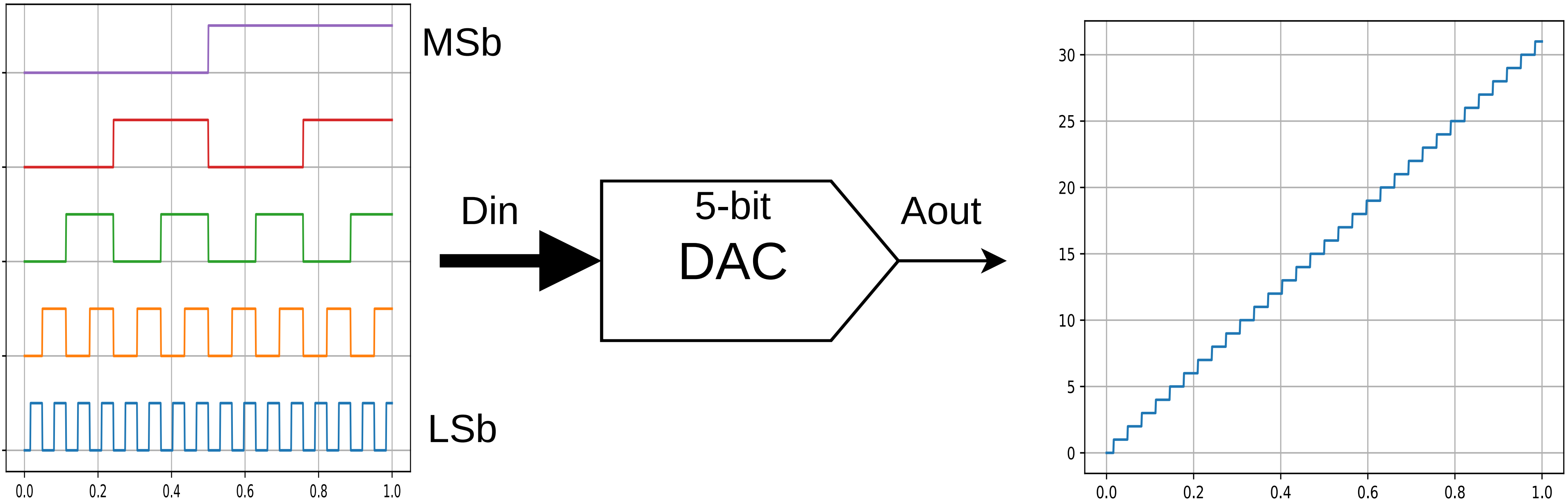
Digital-to-analogue converter (DAC)
Effective number of bits (ENOB)
Most significant bit (MSb)

Least significant bit (LSb)
Signal-to-noise and distortion ratio (SINAD)
Integral Non-linearity (INL)

Faculty of Information Technology and Electrical Engineering (IE)
Department of Electronic Systems (IES)
Research group: Circuit and Radio Systems (KR)

NTNU

Digital-to-analogue converters (DACs)

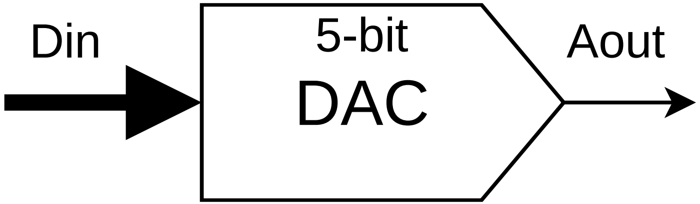


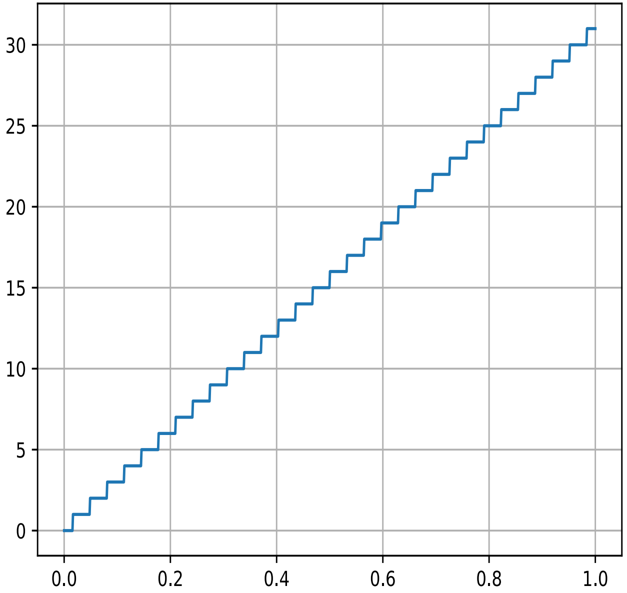
Digital-to-analogue converter (DAC)
Effective number of bits (ENOB)
Most significant bit (MSb)

Least significant bit (LSb)
Signal-to-noise and distortion ratio (SINAD)
Integral Non-linearity (INL)

Digital-to-analogue converters (DACs)

- **Deviations**
  - Static
    - Mismatch
  - Dynamic
    - Slew rate
    - Glitch





Digital-to-analogue converter (DAC)
Effective number of bits (ENOB)
Most significant bit (MSb)
Least significant bit (LSb)
Signal-to-noise and distortion ratio (SINAD)
Integral Non-linearity (INL)

Faculty of Information Technology and Electrical Engineering (IE)
Department of Electronic Systems (IES)
Research group: Circuit and Radio Systems (KR)

DAC IC design

- 130 nm technologies
  - Open-source, SkyWater SKY130
  - Proprietary
- 6-bit and 16-bit DAC
- Current-steering (CS) topology

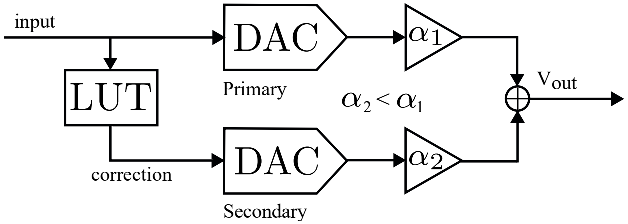
Integral Non-linearity (INL)		
Tech \ DAC	**6 bit**	**16 bit**
SKY130	$\pm$0.8 LSb	$\pm$42 LSb
Proprietary	$\pm$1.7 LSb	$\pm$700 LSb

Least significant bit (LSb)
Integral Non-linearity (INL)

Faculty of Information Technology and Electrical Engineering (IE)
Department of Electronic Systems (IES)
Research group: Circuit and Radio Systems (KR)

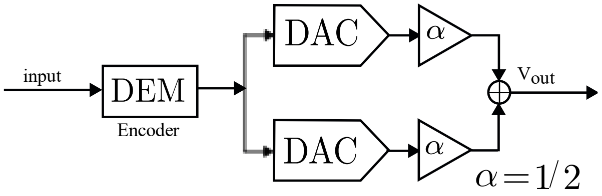
Linearisation methods

- Physical level calibration (PHYSCAL)
- Noise shaping with digital calibration (NSDCAL)
- Dynamic element matching (DEM)
- Periodic high-frequency dithering (PHFD)
- Stochastic high-pass dithering (SHPD)

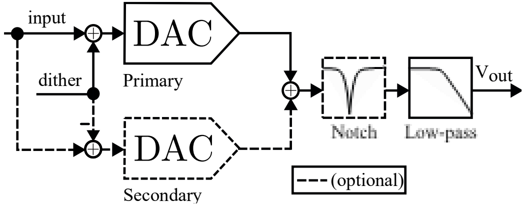


PHYSCAL

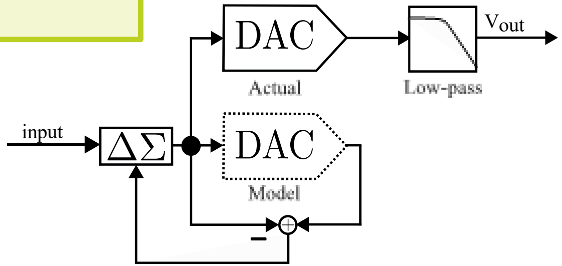
Reconstruction filter
3. order Butterworth LPF
Fc = 100 kHz



DEM



PHFD and SHPD



NSDCAL

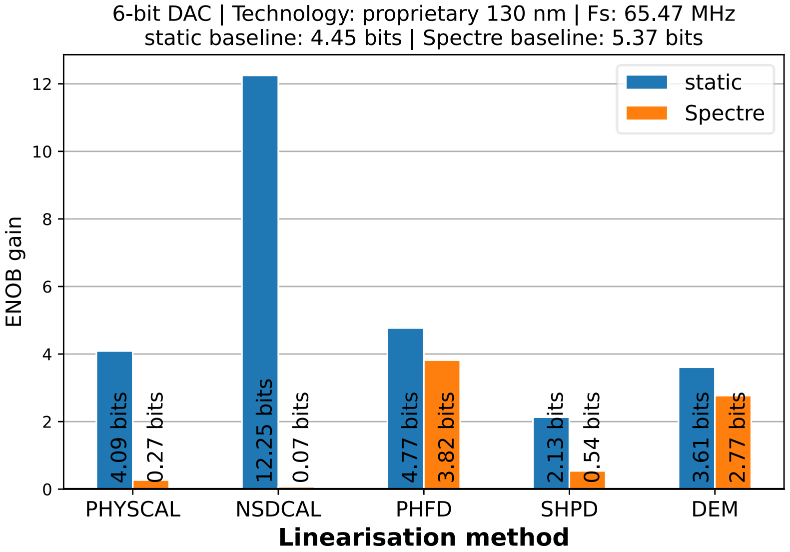
Low-pass filter (LPF)

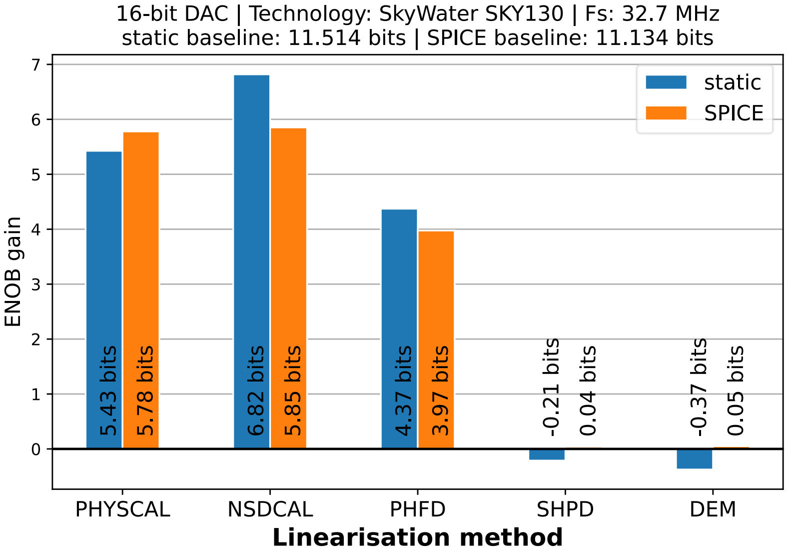
Faculty of Information Technology and Electrical Engineering (IE)
Department of Electronic Systems (IES)
Research group: Circuit and Radio Systems (KR)

Results

- Relative to baseline results
- Static modelling and dynamic modelling

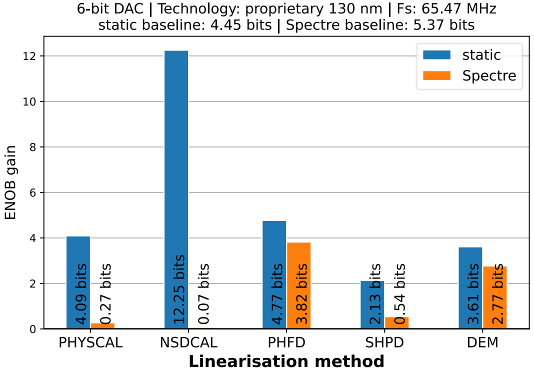
$$\text{ENOB} = \frac{\text{SINAD} - 1.76}{6.02}$$

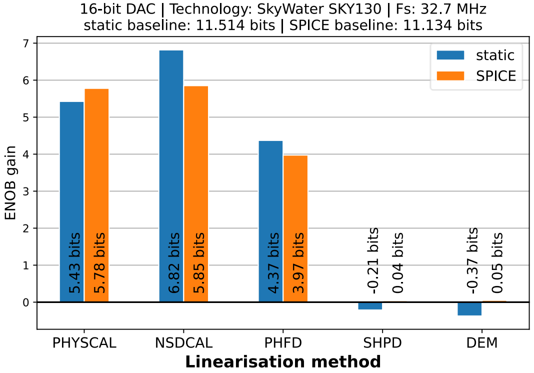




Signal-to-noise and distortion ratio (SINAD)
Sampling frequency (Fs)

Conclusion





Effective number of bits (ENOB)

Strong correlation between the static modelling and the dynamic modelling (Mainly for SKY130)

Performance improvements

- Physical level calibration (PHYSCAL)
- Noise shaping with digital calibration (NSDCAL)
  - 18 ENOB @ 100 kHz BW using static models and assuming accurate INL measurements
- Periodic high-frequency dithering (PHFD)

Small or no performance improvements

- Dynamic element matching (DEM)
- Stochastic high-pass dithering (SHPD)

Faculty of Information Technology and Electrical Engineering (IE)
Department of Electronic Systems (IES)
Research group: Circuit and Radio Systems (KR)

IMEKO2024 XXIV World Congress

26 – 29 August 2024 | Hamburg, Germany

Discussion

IMPROVING THE ACCURACY OF DIGITAL-TO-ANALOGUE CONVERTERS

This work was supported by the Research Council of Norway, project FRIPRO 313716
https://prosjektbanken.forskningsradet.no/en/project/FORISS/313716

NTNU | Norwegian University of Science and Technology

Thank you

IMPROVING THE ACCURACY OF DIGITAL-TO-ANALOGUE CONVERTERS

This work was supported by the Research Council of Norway, project FRIPRO 313716
https://prosjektbanken.forskningsradet.no/en/project/FORISS/313716

NTNU | Norwegian University of Science and Technology