A Switched-Capacitor Controlled Digital-Current Modulated Class-E EER Transmitter

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Digital Frontends: Flexibility

- Digital Transmitters – Leverage CMOS strengths
  - Low on-resistance, fast switch → switching “amplifiers”
  - Interface RF directly with DSP → bits in to RF out
- Embed DAC functionality in PA/Transmitter

Software Defined Radio: Dream

Digital Polar PAs using Switched Capacitor Circuits

Kahn EER Technique (1952)

Original Kahn
- Polar conversion: analog
- Need: envelope detector and limiter

Modern Kahn
- Polar conversion: DSP
- Need: DAC, Supply modulator and limiter
- Digital “Friendly” Analog

[Kahn, Proc. IRE 1952]
Outline

- Motivation and Background
- Digital PA (SCPA) Introduction
- SC-DAC Controlled, Current-Modulated EER PA
- Implementation and Measurements
- Conclusions
Class-D PA with capacitive voltage divider

- Very linear $\rightarrow$ precision capacitors and low-loss switches
- **OOB Noise** $\rightarrow$ Limited by quantization!
DPA Signal Quantization: White Noise

- 4b for close in spectral mask and EVM
- Quantization is AWGN → OOB Noise

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SC-DAC controls an open-loop $g_m$ cell
- $G_m$ modulates current into Class-E PA
- Digital Pre-Distortion (DPD) corrects for $g_m$ non-linearity
Interleaved Pipeline SC-DAC

- Good Matching: Identical Capacitors
- Less power than current steering DAC
- 10b resolution → allow for DPD
Interleaved Pipeline SC-DAC

- Class-E → High Voltage Swing
- Cascode → Distribute Voltage Stress
- Use Finite Drain Inductance → Reduce Peak Voltage Swing
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Chip Microphotograph

- 130nm RF CMOS – UTM/MiM
- PA/Current Modulator/DAC → On-chip
- Phase modulator → Off-chip
- DPD loop → on instrument
Measurements at 2.25 GHz
- Peak $P_{out} = 22.5\text{dBm}$
- Peak PAE = 23.6%
- PAE Bandwidth > 500 MHz
DPD – Memoryless LUT Training
Dynamic Measurements: LTE I

- **Traces:** 1, 2, 3, 4
- **Type:** A, S
- **Det:** S
- **Ref Lvl:** 23.90 dBm
- **Atten:** 39.9 dB
- **Ref Ck:** Onboard Ck

**Measurement: Adjacent Channel Power**
- **Center Freq:** 2.250000000 GHz
- **Bandwidth:** 9.000000 MHz
- **Pwr in Ref Ch:** 18.02 dBm
- **Noise Correction:** Enabled
- **Pwr in Left Ch:**
  - # Offset: 10.000000 MHz, 9.000000 MHz
  - Pwr: -12.55 dBm (-30.58 dBc), -12.29 dBm (-30.31 dBc)

- **Pwr in Right Ch:**
  - # Offset: 20.000000 MHz, 9.000000 MHz
  - Pwr: -14.44 dBm (-32.47 dBc), -14.60 dBm (-32.63 dBc)

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- EVM improved from 11% to 2.5% with DPD
- $P_{\text{out}} = 18\text{dBm@}11\%\text{PAE}$
PA Resolution 10b

Additional filtering reduces far OOB noise compared to other DPAs

Close-in noise still dominated by EER (timing mismatch/finite bandwidth)
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Digital PAs and Transmitters offer flexibility but:

- OOB noise is problematic!

Current Mode DAC based PA offers same DPA flexibility while offering additional filtering!

We demonstrate the first current modulated EER PA/Transmitter
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