Ultra Low Power Radio

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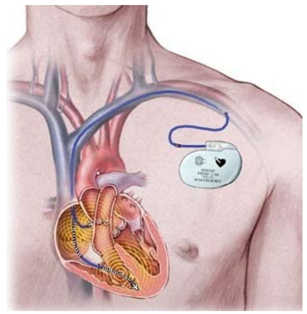
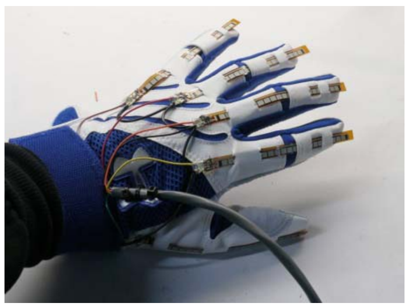
Applications

- Medical implants
- Hearing aids
- Pacemakers
- Watches
- Video game controls
- Active RFID tags
- Remote controls
- Keys
- Body area networks
- Sensor networks
- etc.





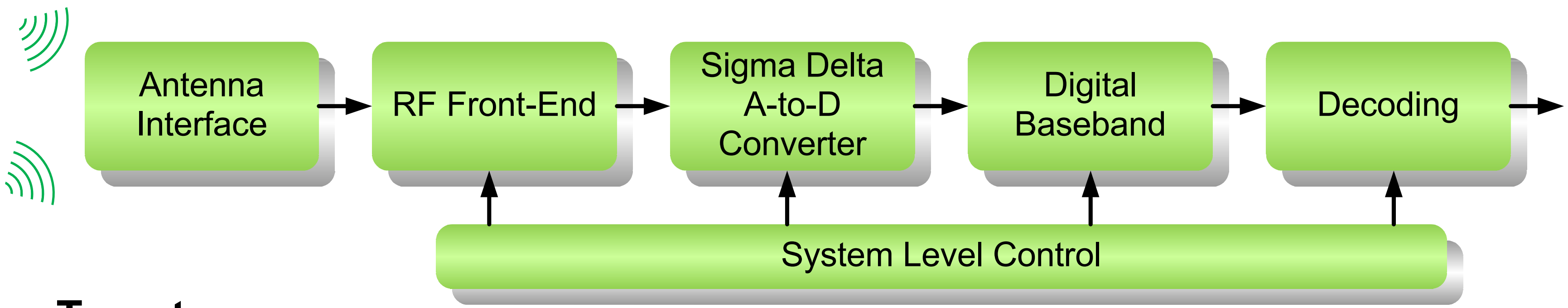
In some applications the battery must last the equipment lifetime!

Wireless Communication for Ultra Portable Devices

Swedish Foundation for Strategic Research

SSF Framework Program
- 5-year project, started 2008
- 6 PhD Students
- 9 Senior Researchers

Scope
- Receiver chain from antenna to decoder
- Medium Access Control (MAC)
- Propagation in bio-applications



Targets
- 1mW in active mode
- 1uW in standby
- 1mm^2 chip area in 65nm CMOS
- 250 kbit/s
- Final goal: Demonstration of antenna + chip in medical implant mock-up

System Parameters

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Sensitivity Calculation

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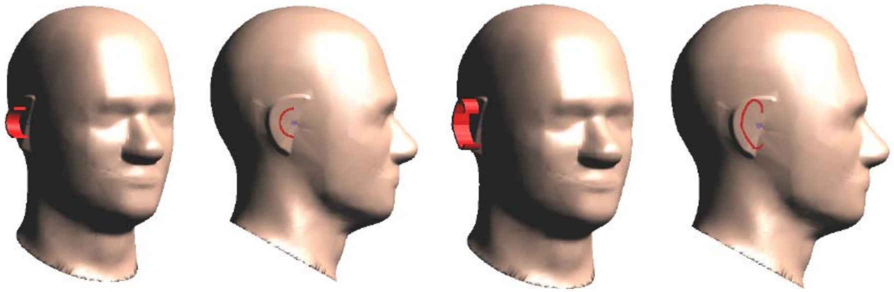
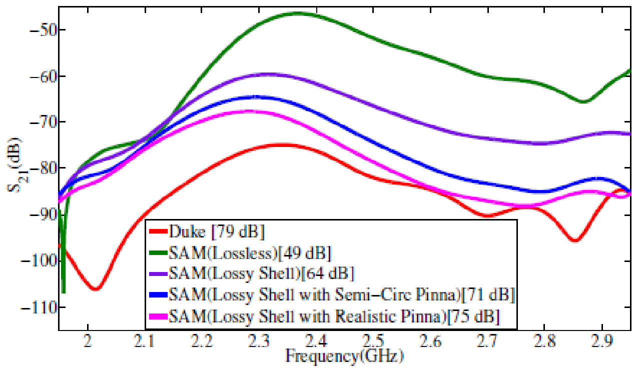
Rohit Chandra

Antennas and Propagation

Ear-to-Ear: Effect of Outer Ears and Lossy Skin





Lossy skin and outer ears must be included in the model
About 80dB total path loss worst case

Antennas and Propagation

Ear-to-Ear: Meaurements

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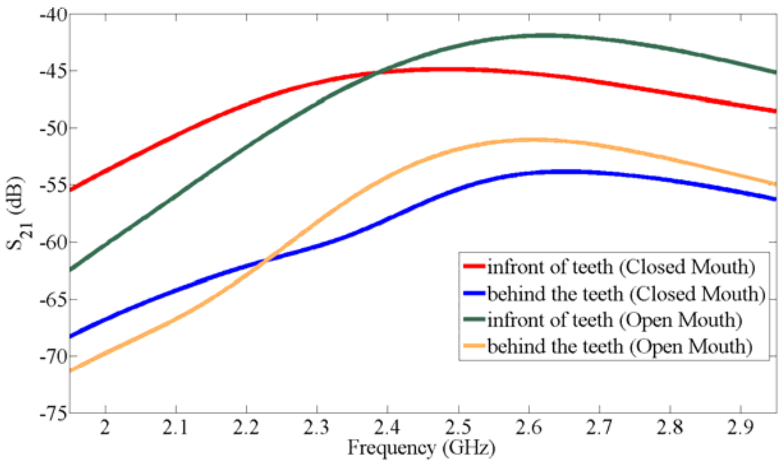
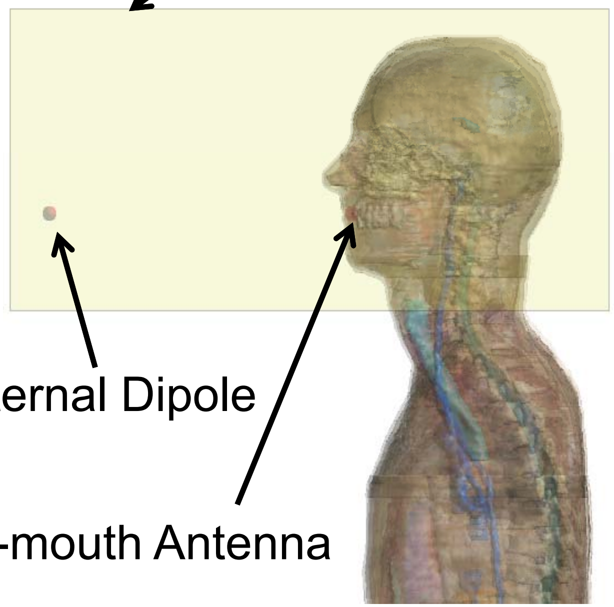
Antennas and Propagation

In-Mouth Antenna



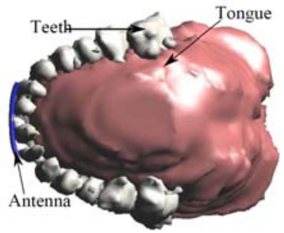
About 60dB path loss worst case

Simulation Boundary



External Dipole

In-mouth Antenna



Distance centre of head to external antenna = 400 mm

In cooperation with Aalborg University

Carl Bryant

RF front-end

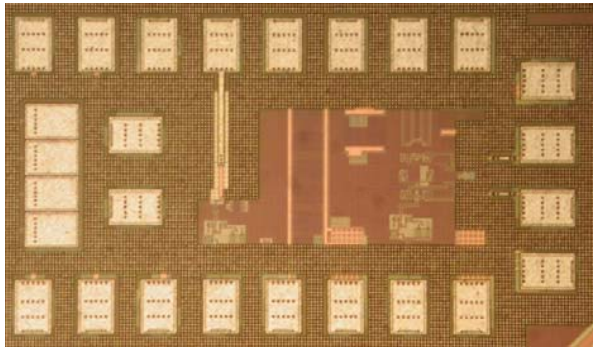
Minimize chip area => Inductorless design
Ultra low power => Weak inversion operation

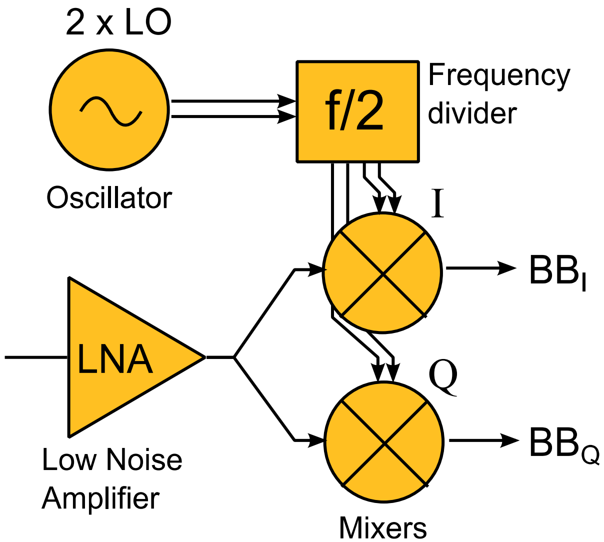
Inductorless Weak Inversion Front-End in 65nm CMOS
Performance?

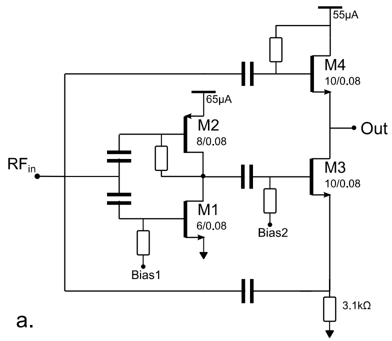
- Power
- Frequency
- Gain
- Noise figure
- Linearity
- Input impedance

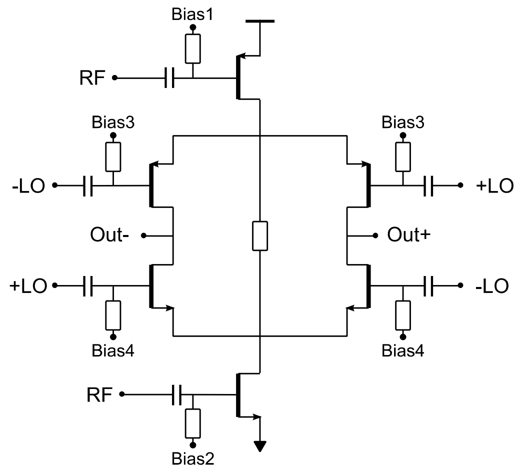
RF front-end

- Inductorless design
- Feedback LNA
- Current reuse active mixers





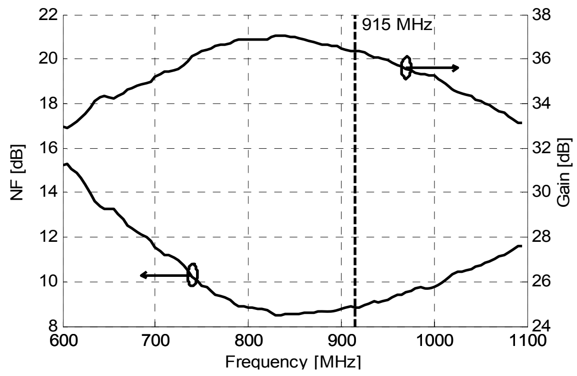


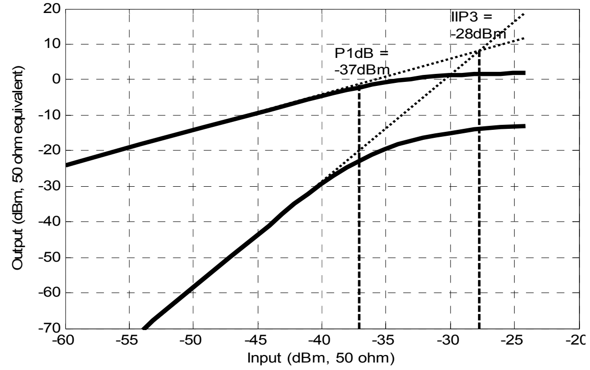


RF front-end

Measurement Results

- LNA + Frequency divider + Quadrature mixer
- Ultra low power: **280 µW**
- Active area: 0.016mm^2 in 65nm CMOS
- Measurements:
  915 MHz (limited by frequency divider)
  200Ω input impedance
  30dB voltage gain
  9dB NF
  100kHz 1/f noise corner
  -37 dBm CP_{1dB}
  -28 dBm IIP3
  < -95dBm LO to RF leakage
  > -5dBm IIP2
- ESSCIRC 2011





RF front-end

Quadrature LO Generation

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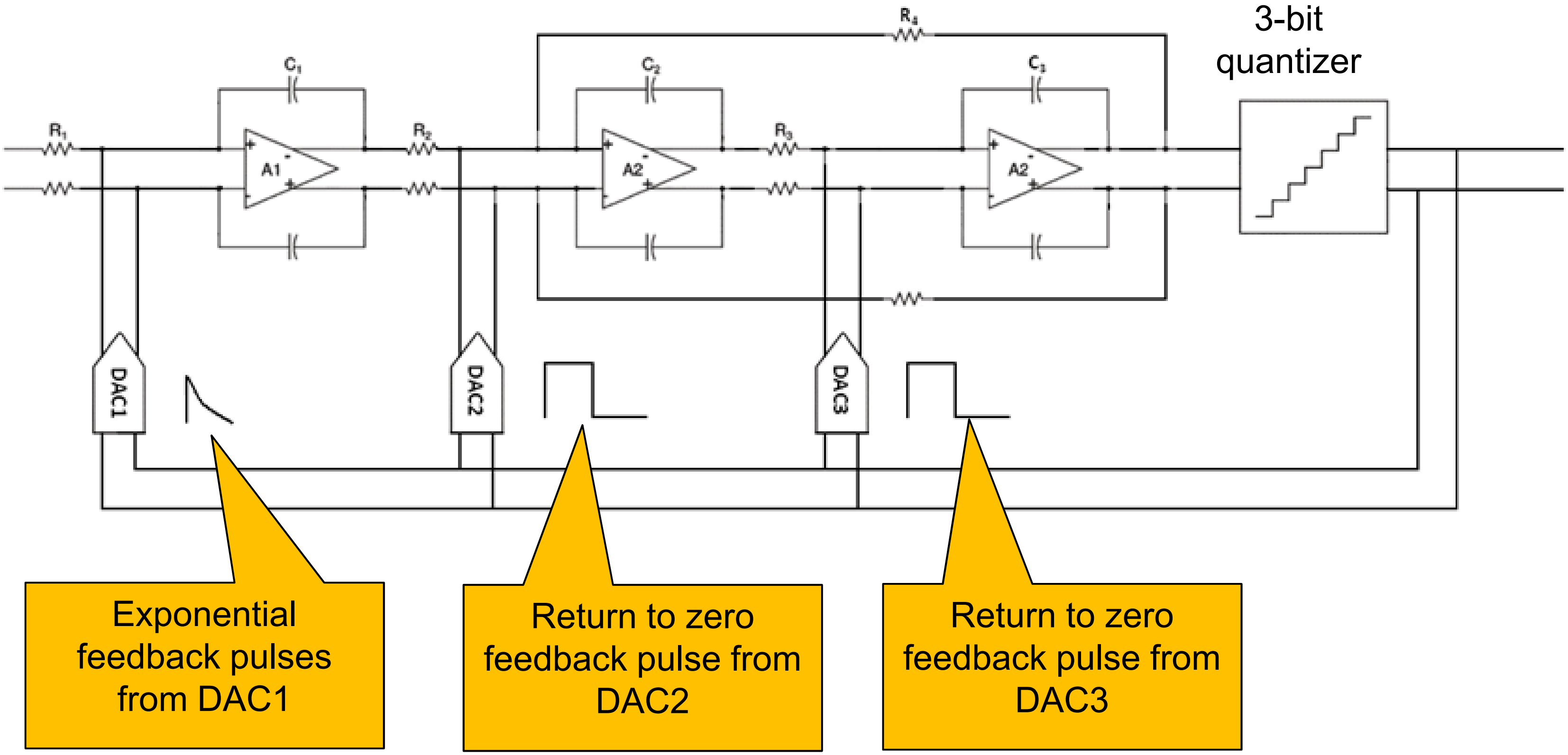
Dejan Radjen

Analog to Digital Converter

- Continuous-Time (CT) ΔΣ-ADC eliminates analog channel select filter
- 3rd order modulator with 3 bit quantizer



Analog to Digital Converter

Measurement Results

Unpublished Material Removed

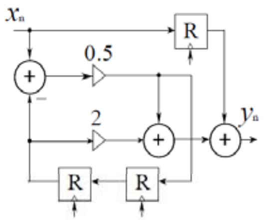
Yasser Sherazi

Digital Baseband

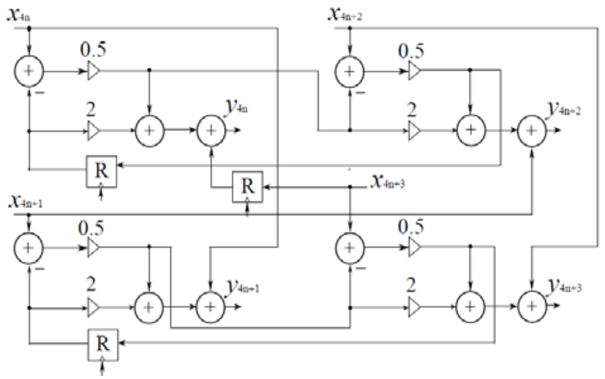
- Combined Decimation and Channel Select Filter
- Sharp filtering in digital domain
- Challenge: Weak inversion design with high throughput
- Chain of half-band filters & decimate by 2

Digital Baseband

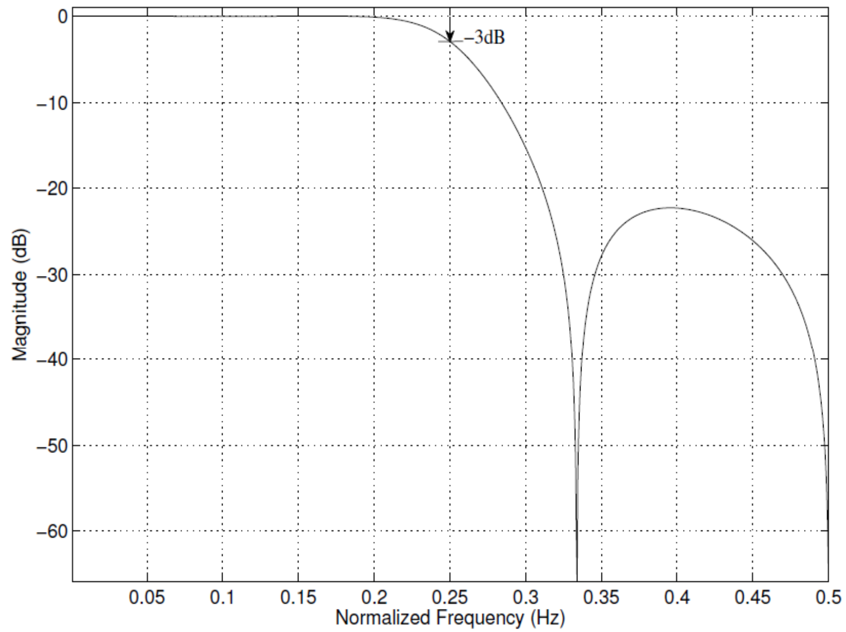
Half-band filters



Original (ORG)



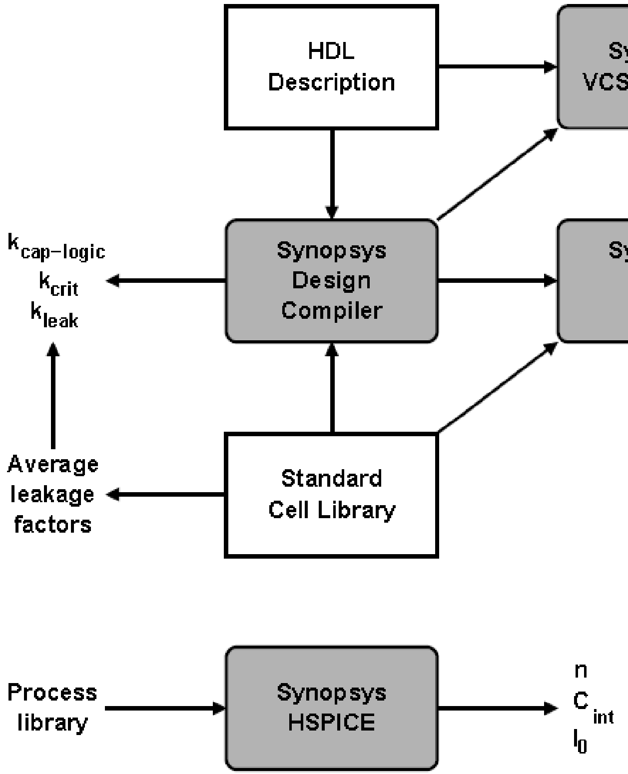
Unfolded by 4 (UF4)



$$H_z = \frac{1 + 2z^{-1} + 2z^{-2} + z^{-3}}{2 + z^{-2}}$$

Digital Baseband

High-Level Sub-V_T Energy Model



$$E_T = \underbrace{\alpha C_{tot} V_{DD}^2}_{E_{dyn}} + \underbrace{I_{leak} V_{DD} T_{clk}}_{E_{leak}} + \underbrace{I_{peak} t_{sc} V_{DD}}_{E_{sc}}$$

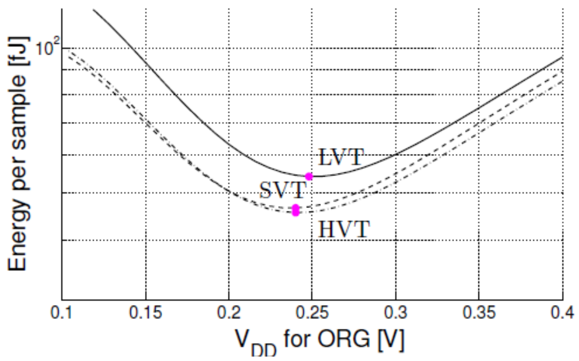
$$E_T = \mu_e C_{inv} k_{cap} V_{DD}^2 + k_{leak} I_0 V_{DD} T_{clk}$$

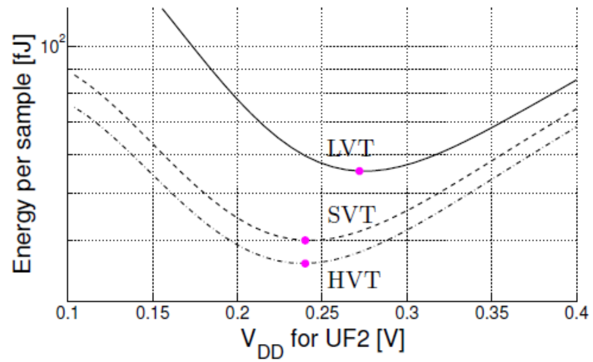
$$E_T = C_{inv} V_{DD}^2 \left[\mu_e k_{cap} + k_{crit} k_{leak} e^{-V_{DD}/(nU_t)} \right]$$

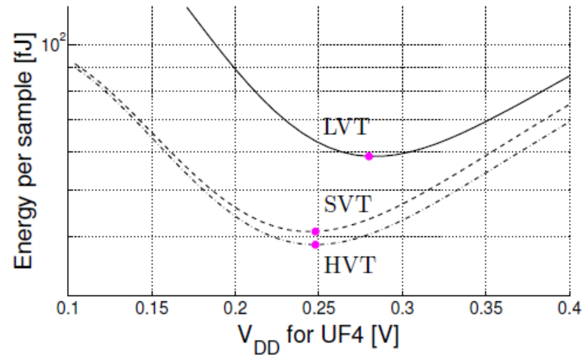
In cooperation with EPFL

Digital Baseband

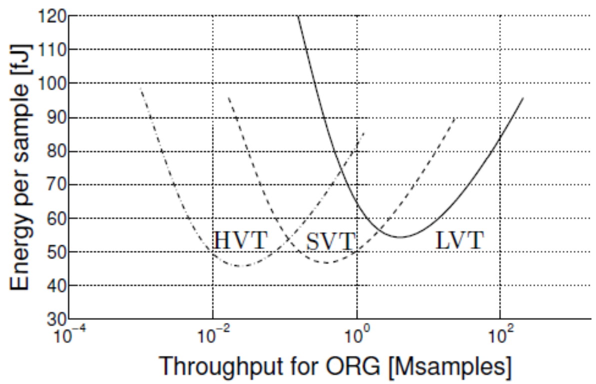
Energy vs V_{DD}

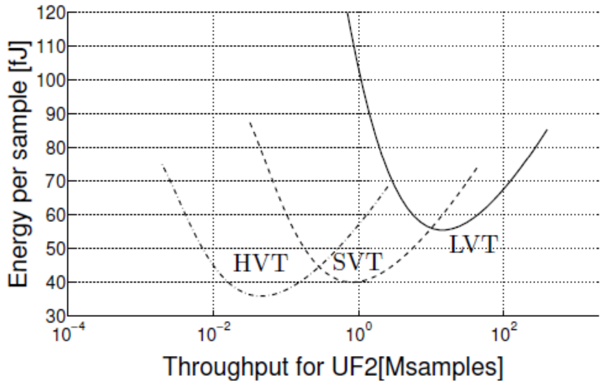


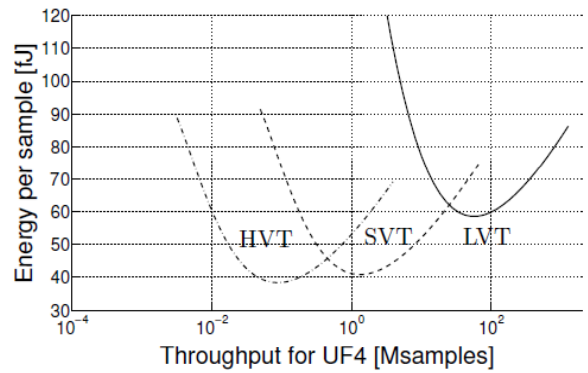




Energy vs Throughput

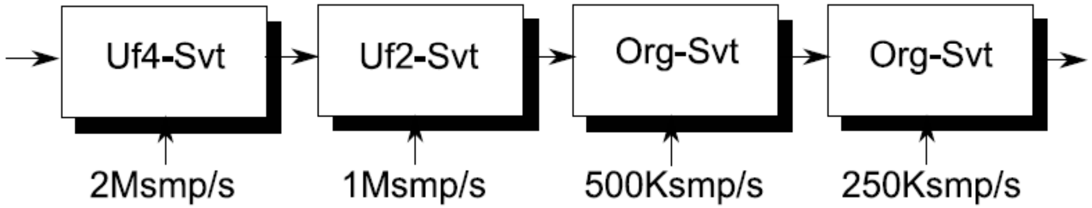


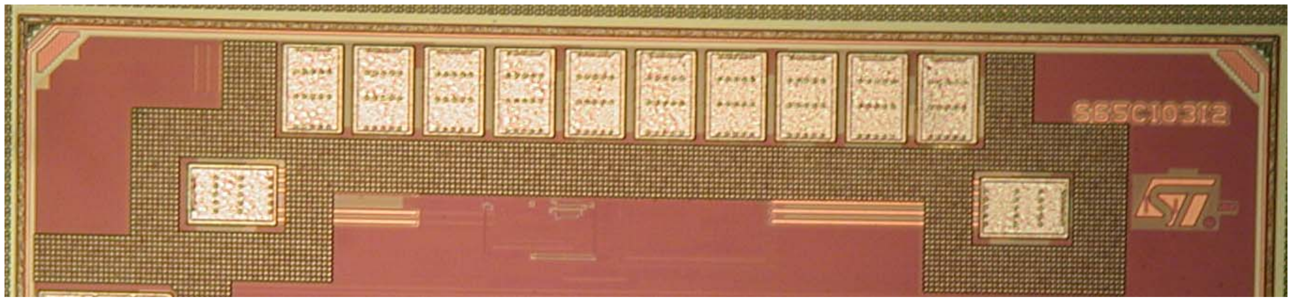




Digital Baseband

First chip ready measurements to start





Digital Baseband

Next tape-out: Modified Filter Chain + demodulation
Suppression of ΔΣ noise & sharp channel filtering

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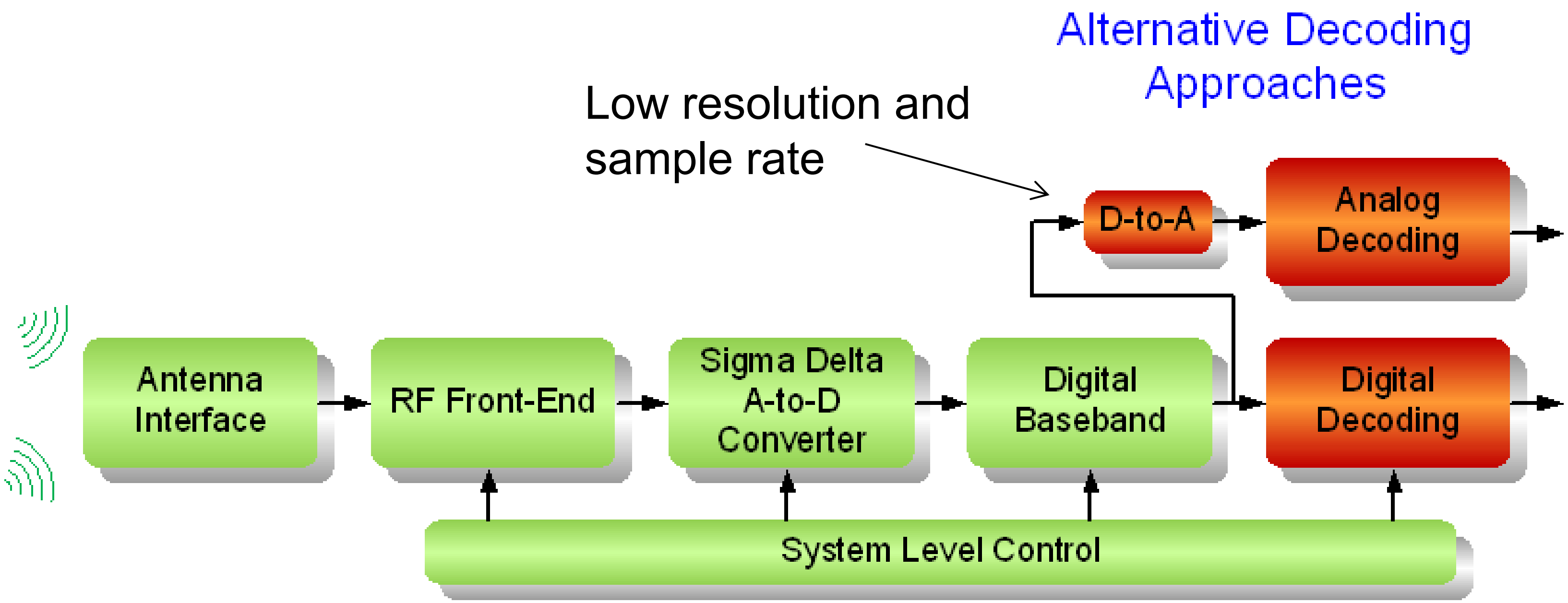
Reza Meraji

Analog Decoder



Key advantage of analog decoder: Ultra low power consumption

Analog Decoder

Advantages and Challenges

+ Fewer transistors than digital implementation
+ Computations performed in continuous time
+ High throughput by parallel computations
+ Power efficiency improvements up to two orders of magnitude have been reported

- Weak inversion operation => sensitive to V_{Th} mismatch
- Increased transistor sizes needed
- Complex analog circuit => Long simulation
- Stacked transistors in multipliers => Hard to reduce supply

Investigated Analog Decoders with digital I/O

Hamming decoder

- Transistor level simulations
- Consumes 20 μW at 250 kb/s
- Coding gain:1.5 dB at BER 10^{-3}

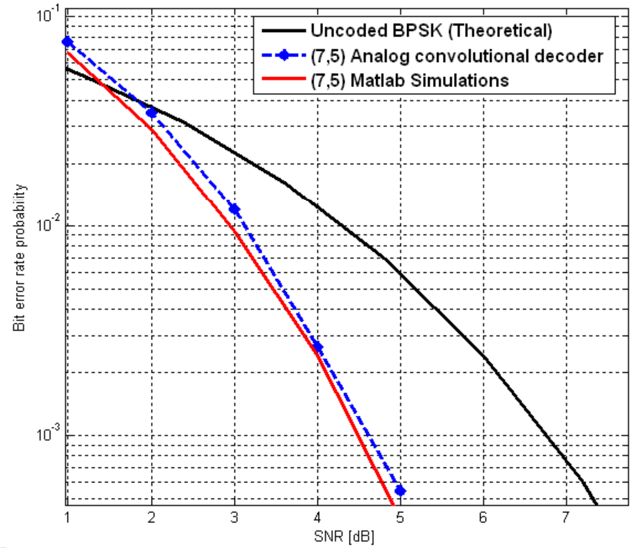
(7,5) Convolutional decoder

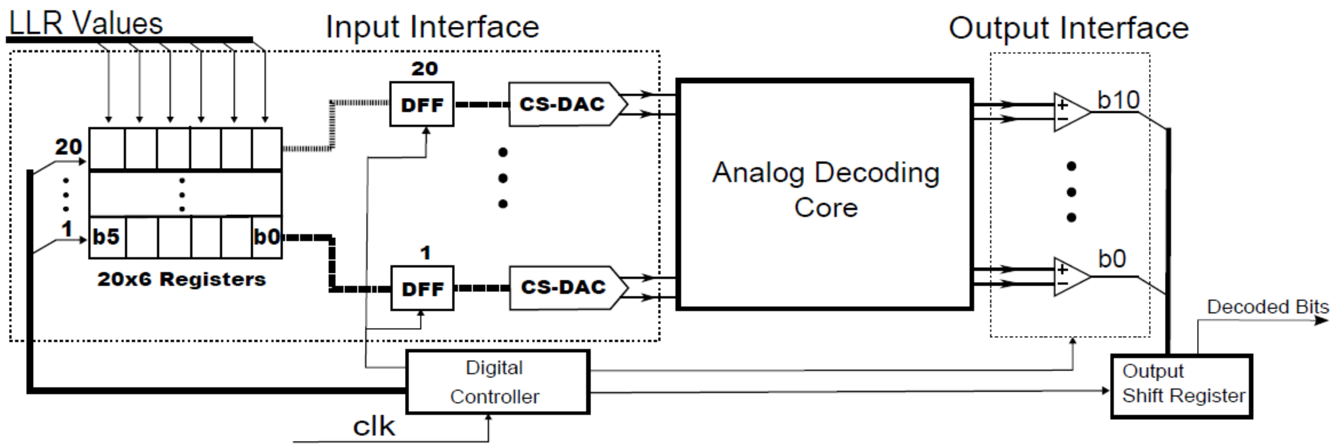
- Post layout simulations
- Consumes 50 μW at 250 kb/s
- Coding gain: 2.1 dB at BER 10^{-3}

Analog Decoder

(7,5) Convolutional tailbiting decoder

- Digital I/O (not optimized resolution/power)
- 47uW total at 250kbit/s
- 15uW in analog decoder core





Medium Access Control (MAC)

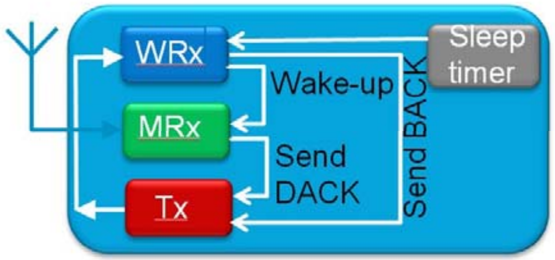
- Focus on low-traffic conditions
- Minimize energy waste
- Provide sufficient quality of service
- Sources of energy waste
  - Idle listening
  - Overhearing
  - Data overhead
  - Collision

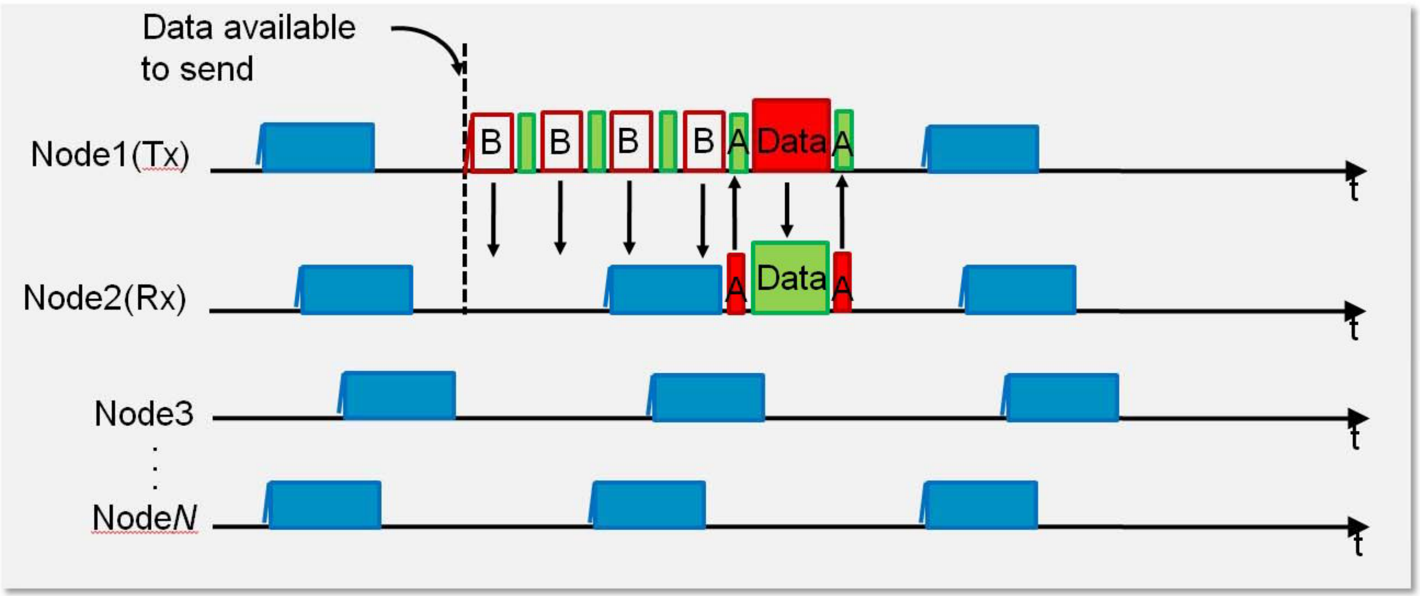
Duty-cycled MAC protocols are a *common approach* to reduce *idle listening*

Medium Access Control (MAC)

DCW-MAC scheme

Combines ultra low-power WRxs and duty-cycled listening.

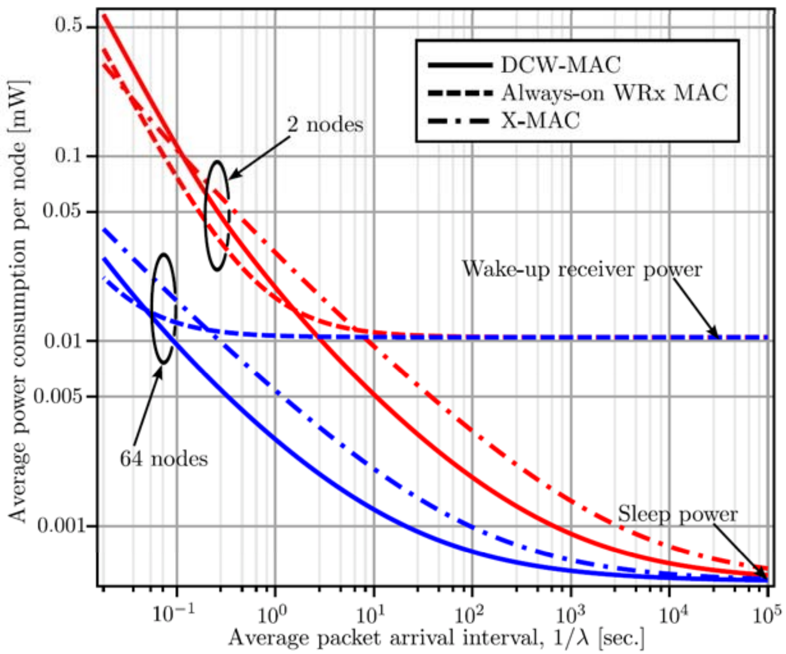




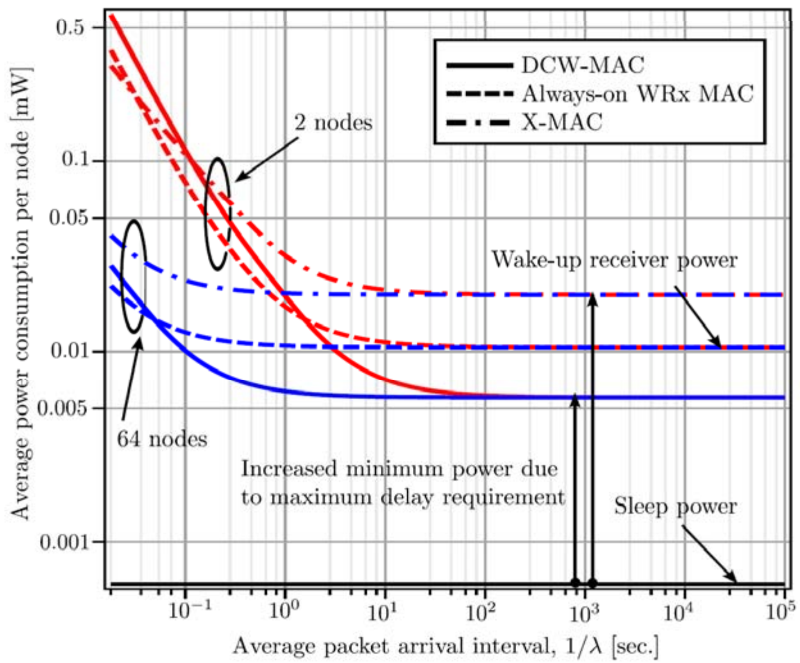
Medium Access Control (MAC)

Numerical results, perfect beacon detection

a) No delay requirement



b) With delay requirement



Excellent performance in low traffic with maximum delay requirement

Medium Access Control (MAC)

Effect of imperfect beacon detection

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Future Plans

- Measure digital filter and analog decoder
- 50Ω RF sent for fabrication
- More system simulations & investigations
- Wake-up receiver
- New application: Mouth keyboard
- Co-design of RF+ADC
- Baseband including time synchronization

- … Demo of complete receiver chip + antenna

Research Team

Senior Researchers:
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Peter Nilsson
Joachim Rodrigues
Markus Törmänen
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Dejan Radjen
Yasser Sherazi
Reza Meraji
Nafiseh Mazloum

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&
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Questions?