Wideband RF systems

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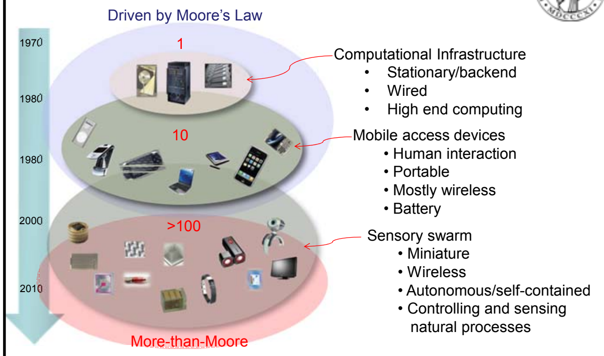
Technology trends



From few general systems → to many specialized systems

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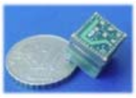
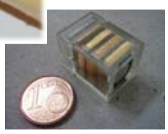
Sensory swarms

State-of-the-art WSN motes


UCB mm³ radio


IMEC e-cube


Dust networks M2600 mote


UCB Pico cube

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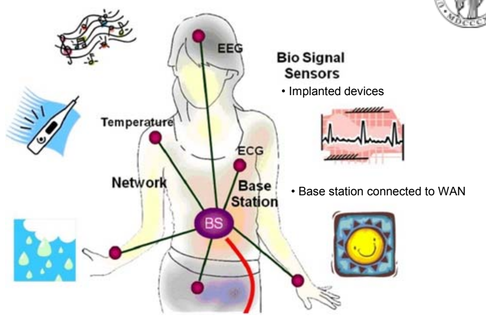
Wireless sensor networks



- Body-area network nodes (motes) are hard to make
- Implanted devices even harder

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WSN motes

- Computational speed not so important any more….
- Low power and minimal size more important
  - Computational efficiency rather than computational speed
    - Minimal power→ extended battery lifetime
    - Minimal size→ extended usage even inside body
    - Minimal cost→ increased availability
  - Autonomous
    - Independent operation without human interaction
    - Adaptable to changing environments
    - Robust
  - Wireless connectivity
    - Sensing and controlling functions
  - Sensing and control of physical (analog) processes
    - Temperature, pressure, light….
    - Blood pressure, Glucose level, vital signs….

Towards System-on-chip

- Single-chip CMOS solutions
  - Power efficiency
    - Power harvesting
  - Wireless
    - From physical layer to application
  - Analog interfacing
  - Integrated sensors/actuators
    - Electromagnetic
  - Robustness
  - Size – cost
- Use standard "digital" technology
  - Ways to design better systems (SoC)?
  - Same old ways and lean on technology scaling?

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PICOLab@ifi

- Three specialized labs
  - LowLab
    - Faraday chamber for low-noise/shielded measurements
    - RF probe station with laser
  - ProtoLab
    - Fast prototyping facilities
    - Laser PCB
  - MilliLab
    - Anechoic antenna chamber (1-100 GHz)
    - 3D positioner and 67GHz network analyzer

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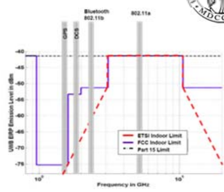
Why Ultra Wideband?



- Regulations
  - 3.1-10.6GHz
    - Largest unlicensed band ever released
  - Limited power
    - - 41.3 dBm/MHz
- New functionality
  - Higher bitrate?
    - After one decade: hard to make
  - RF ranging
    - Resolution increase with bandwidth
  - RF sensing
    - Short range radar
- UWB in CMOS
  - Hard to make: wideband much harder than narrowband
  - Inventive solutions required

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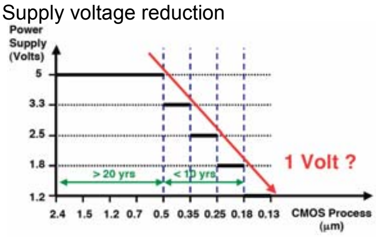
Wideband RF CMOS

- Supply voltage reduction



- Analog *value* with low supply voltage

$$SNR = \frac{\text{max amplitude}^2}{\text{noise amplitude}^2} = \frac{V_{PP}^2/2}{4kTR_N}C$$

  - Low SNR

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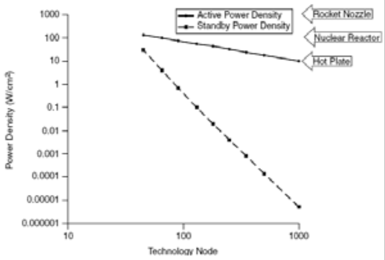
Power factors

- Poor switch
  - Not quite closed
    - Leaking current
  - Not quite open
    - Slow
- Standby current
  - Wasted power
- Gates not reliable
  - Leaky dioxide
- Velocity saturation



Designing with advanced technology is getting complicated
•Require awareness of low current level behavior → subthreshold
•Power awareness
•Leakage awareness
How do we improve computational efficiency?

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CTBV coding – for wideband CMOS

- Continuous Time – Binary Value
  - Joint work with Håkon A Hjortland

Time

Value		Discrete	Continuous
	Binary	Digital	CTBV Neuromorphic/spike
	Continuous	Analog sampled–data (switched–cap)	Analog

- No clock
  - Improving speed
  - Reduced power
    - Removing clock → removing clock power (≈1/3)
      - » Clock does not compute anything
  - Removing quantization noise
- Adapted for modern technology
  - Scaling: better technology → higher performance

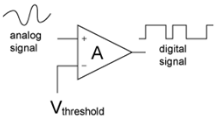
- *CTBV*
  - *- Only to states: '0' og '1'*
  - *- '>Infinite clock speed*
    - *Only limited by gate delays*
    - *→ Fastest possible*

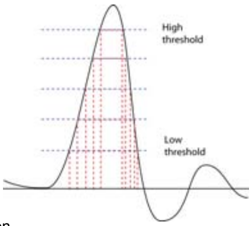
Related work

- CTDA Continuous-time discrete amplitude
  - Yannis Tsividis et al.
    - **Mixing domains in signal processing**
      Tsividis, Y., Circuits and Systems, 2004. ISCAS '04. Proceedings of the 2004 International Symposium on Page(s): I-157 - I-160 Vol.1
    - **Event-Driven Data Acquisition and Digital Signal Processing—A Tutorial**
      Tsividis, Y. Circuits and Systems II: Express Briefs, IEEE Transactions on Volume: 57 , *Issue*: 8, 2010 , Page(s): 577 – 581
    - MIXED-DOMAIN CIRCUITS AND SYSTEMS
      Tsividis, Y, ISCAS 2006 invited talk
- CTBV special case of CTDA
  - CTBV only binary value (0 and 1), not binary word
  - Bitstream
  - Pulse Width modulation?

Single-bit quantizer

- Comparator
  - High-gain differential amplifier

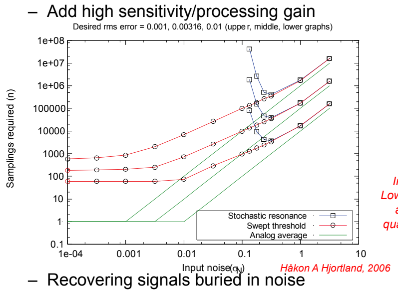




    - Thresholding – nonlinear operation
  - Repeated sampling and swept threshold
  - May reconstruct any signal
- Repeated, swept-threshold sampling
  - Interesting noise properties

Quantization ↔ noise

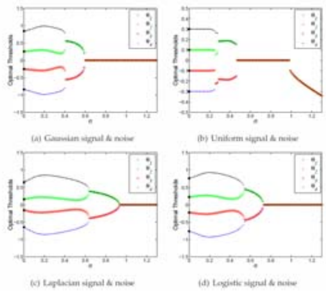
- Biological signal are weak and noisy
  - Hard to recover
  - Add high sensitivity/processing gain



In noisy environments Low resolution sampling is approaching an ideal quantizer in performance!

  - Recovering signals buried in noise

Optimal threshold levels ↔ noise

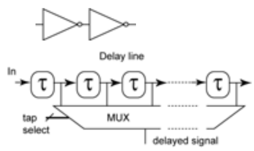


M. D. McDonnell, PhD thesis, 2006, chap 8, p. 301

- Binary coding optimal noisy signals

CTBV in silicon

- How to make CTBV processing systems?
  - No clock?
    - Use gate delays
    - Typical 10ps inverter delay
      - Potential high performance
    - Tapped delaylines



- Not quite sure, but have examples:
  - Impulse CTBV radar
    - Short-range sensor
    - Biomedical applications
      - Vital sign monitoring
      - EM body imaging
  - CTBV short range transceiver
    - Communication with localization
      - Wireless sensor networks

Impulse Radar History

- H. Hertz spark generator (1893)
  - Impulse Radio
- Impulse radar
  - Old technology
  - Hülsmeyer patent


N° 13,170 A.D. 1904

Date of Application, 10th June, 1904—Accepted, 22nd Sept., 1904

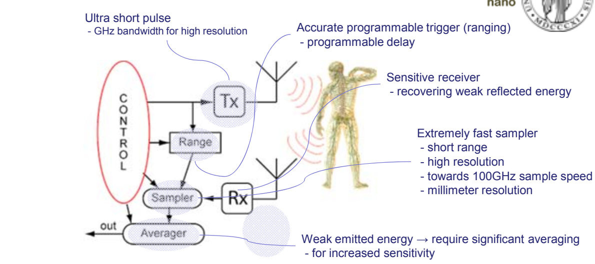
COMPLETE SPECIFICATION.

"Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as a Ship or a Train, in the Line of Projection of such Waves".—

- World War II radar
  - USA, Russia, Germany, UK
- Ground Penetrating Radar
  - Recent Defense development
    - High energy pulses or chirps

- Micropower Impulse Radar (MIR)
  - McEwan (LLNL)
- UiO/Novelda single-chip radar

Impulse Radar Implementation Challenges

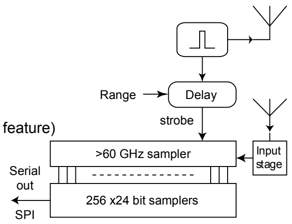


- Standard radar implementations (LLNL)
  - ➢ High speed analog front-end
  - ➢ High supply voltage >15V
    Improved noise performance
  - ➢ Analog sampler (SRD diodes…)

Not implementable in standard digital CMOS technology

CTBV Impulse Radar

- Single chip CMOS impulse radar – 1mm^2 silicon
  - High speed sampler
    - Millimeters resolution
  - Single pulse → multiple depth
    - 512 parallel digital samplers
    - Covering ≈ 60 cm depth
      - Multiple "radars" (unique feature)
  - Power efficient – no clock
    - 1V supply
    - Low speed SPI readout
  - First version in 2006
    - Håkon A. Hjortland, MS thesis

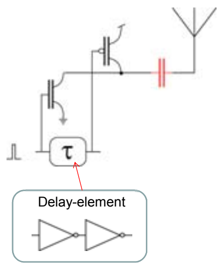


Håkons's first radar (2006)

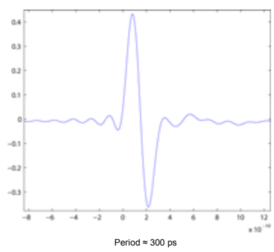
Hjortland, H.A., and Lande, T.S.,
"CTBV Integrated Impuls Radio Design for Biomedical Applications", Biomedical Circuits and Systems, IEEE Transactions on, April 2009, Volume: 3, Issue: 2, pp. 79-88.

CTBV pulse transmitter

- Dual slope generator
  - Delayline



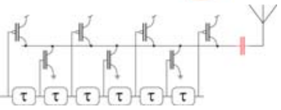
Measured dual slope

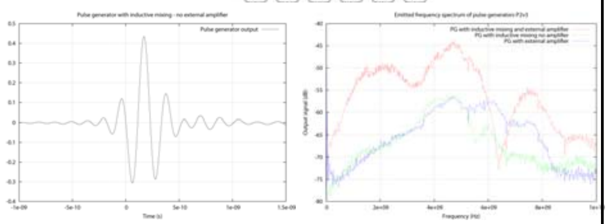


90nm STMicroelectronics process
50 Ω load with cable to scope

Higher order Gaussian

- Longer cascade
  - Scaling sizes



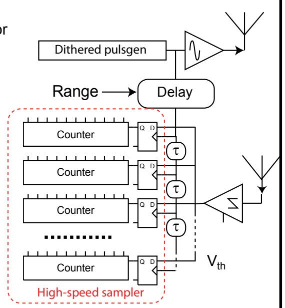


- No oscillator
- No stand-by power

- Works in digital CMOS
- Limited signal swing

CTBV Impulse Radar

- CMOS implementation
  - Dithered (staggered) pulse generator
    - Increased PRF
  - Tunable ranging delay
    - Moving window → 60 meters
  - Swept Threshold Sampling
    - DAC controlled
  - Fast sampler using delayline
    - Inverters
    - >40 GHz equivalent sampling rate!
  - D flip-flop samplers
  - Lossless integrators
    - "Incrementer"
    - Counters
    - 512 in parallel
- First single-chip CMOS radar



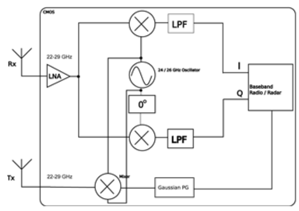
Novelda CTBV Radar

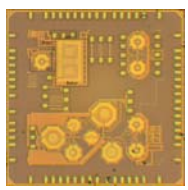
- Spin-off company www.novelda.no
  - Unlicensed UWB bands
    - -41.3dBm/MHz
    - USA: 3.1 – 10.6GHz
      - Low UWB: 3.1 – 5.1
    - Europe: 6 – 8.5 GHz
    - Asia: 7.2 – 10.2 GHz
    - 100MHz PRF
  - ≈ 30mW system
    - Should go down….
  - 1V supply
  - 512 samplers
    - 2 meters
- Novelda DEMO
  - SPI ↔ USB interface

Demo provided by Novelda A.S, Norway, www.novelda.no

Automotive pulsed radar

- Wideband CMOS radar 25-30GHz (Kristian)
    - Novelda funded project
  - Front-end to Novelda radar

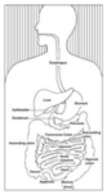




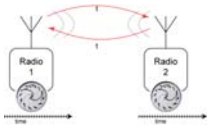
  - Working silicon in TSMC 90nm@28GHz

Localizing MOS transceiver

- Measuring distance with RF signals
  - Video Endoscope tracking



  - Time-of-flight (ToF) measurements
  - Hard to measure EM
    - → speed-of-light propagation
  - Clocked solution?
    - 10Ghz > 3cm resolution
  - Commercial short-range radio
    - RSSI ≈ 1m resolution!



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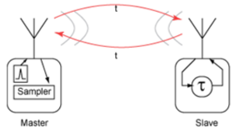
CTBV transceiver

- Active echo time-of-flight measurement
  - Øivind, Shanthi, Anh
  - Master: send symbol and start measuring
  - Slave: detect symbol and send back
  - Master: measure ToF by sampling
  - Provided:
    1. Constant processing time
       - Both master and slave
    2. High-resolution sampler
  - Actual time-of-flight only variable
    - Calibrate for constants to subtract



- Correlating CTBV pulsed radio transceiver
  - Complete continuous-time symbol transmission
  - Embedded ToF measurement
    - Radar sampler

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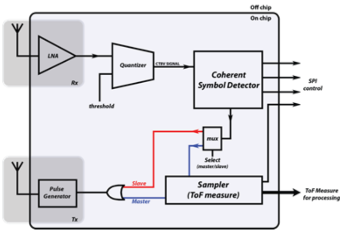
CTBV transceiver architecture

- RAKE pulse radio



- Running cross-correlator
  - Looking for received symbol
  - Time-domain for coherent symbol detection

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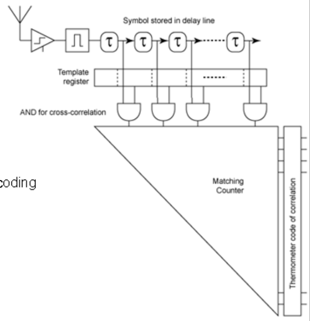
CTBV running cross-correlator

- Single-bit, high-gain quantizer
- Pulse extender
  - Ensuring sufficient detection time
- Delayline
  - Storing one symbol
  - Chip-size 10-20ns
- Template register
  - Storing expected symbol pattern
- Single-bit Cross-correlator
  - AND or XOR gates, depending on coding
- Compute symbol match
  - Counting '1' from AND gates
  - Thermometer coding
- Set symbol matching threshold
  - Measuring "temperature"



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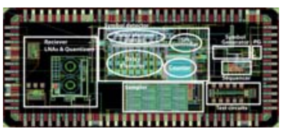
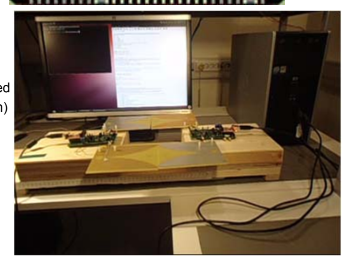
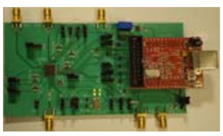
Single-chip CMOS transceiver

- 462518 transistors
- 3.6 x 1.8mm
  - TSMC 90nm CMOS
- 32 bit Symbols
- SPI-control
- Extensive calibration
- ToF distance measurements
  - < 1 cm precision measured
  - May be improved (→ 3mm)

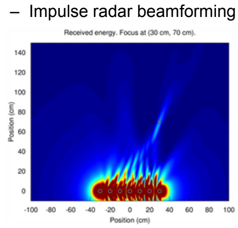






Imaging radar

- Fundamentals
  - Tx beamforming (phased arrays), constructive interference
  - Impulse radar beamforming ↔ frequency based



Modeled by H. A. Hjortland

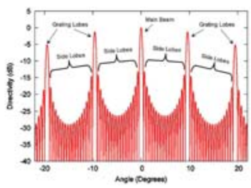


Figure from Wikipedia

  - No grating lobes
  - Impulse radar beamforming easier and much better

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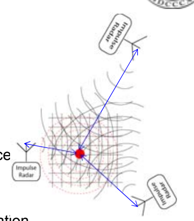
Imaging radar

- Fundamentals
  - Rx beamforming
  - Delay-and-sum beamforming
    - Look from several directions
      - MIMO
      - Multi-static
    - Reflector appears at radar specific distance
      - Seen from different angles
    - With known radar locations
      - Backscattered energy form same location may be accumulated
        - » Giving an Rx beamforming matrix
        - » Limited by depth resolution
  - Efficient with Novelda radar
    - Sensing backscattered energy in 512 depths



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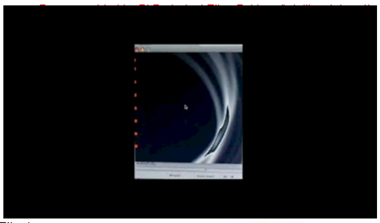
Beamforming research projects

- MISO radar Rx beamforming
  - 1 Tx + 8 Rx radars controlled with one ARM microcontroller



  - Landmine detection (Elias)
    - Novelda NVA6100 chip prepared for MIMO imaging
  - "Electromagnetic Camera" project (Malihe)
    - Improved calibration techniques
    - Own chip

16 radar modules

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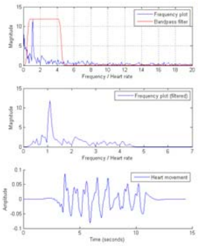
Medical radar

- Movement sensor with/ID
  - Home for elderly people
- Vital sign monitoring
  - hard!!!
  - Detached sensor
  - Sleep monitoring
  - Stress level of pilots
  - Sleeping alarm in cars
  - Surveillance
- EM picturing
  - Beamforming
  - EM do penetrate
    - Not as X-rays (ionization)
    - Better than ultrasound
    - Harmless non-ionization radiation



Measured heart movements at 1 meter distance

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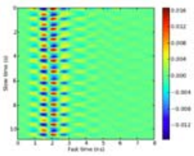
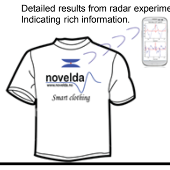
Vital sign radar

- Radar body coupling
  - Closer than 1/8λ → EM energy inward (coupling)
    - Øyvind Aardal/Svein-Erik Hamran, FFI
- Smart clothing (Robin)
  - Radar module + cloth-antennas + wireless (bluetooth, WIFI)
  - Smartphone app
    - Vital sign monitoring
      - Samsung Galaxy SII solution under development
- Coupled vital sign monitoring
  - In car-seat for sleep warning
  - In bed, chair, emergency….
- Remote vital sign monitoring is hard!
  - Probably only viable in stable body positions
    - In sleep?



Detailed results from radar experiments Indicating rich information.



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RFID tags

- Far-field RFID tags (Kody)
  - Pulsed radio RFID tag
    - CDMA coding with looong symbols
      - Large number of channels
    - Extremely power-efficient transmitter
  - Power harvesting
    - ISM band power beam (800-900MHz)
  - Correlating RAKE receiver (Melody)
    - Localization
  - Chips in testing

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CTBV technology in silicon

- Continuous-time binary-value (CTBV) signal processing
  - Changing representation → efficient computation
  - Useful engineering design approach
    - Beyond mimicking biology
  - Great for digital silicon technology
    - 10X speed with less power….
    - Scales to finer pitch
      - Getting even more speed or less power
  - Challenging to design
    - Scrapping clock → design complicated
    - No automation available
- Great potential for power-limited or speed limited systems
  - Good for single-chip radar (speed-limited)
  - Biomedical applications (power-limited)

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