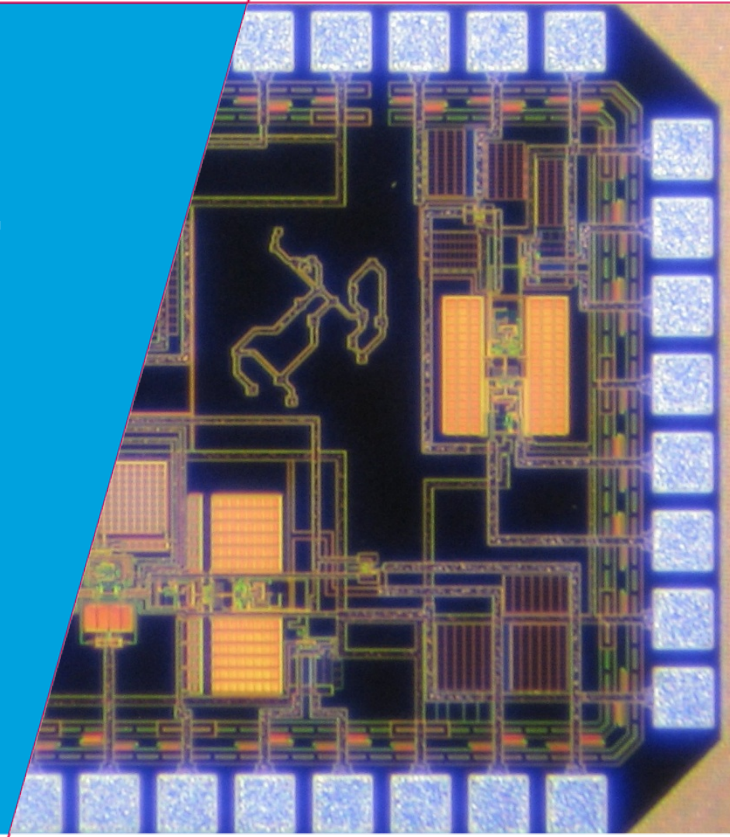
When to wake up?
Low power Wake-Up Receiver Design



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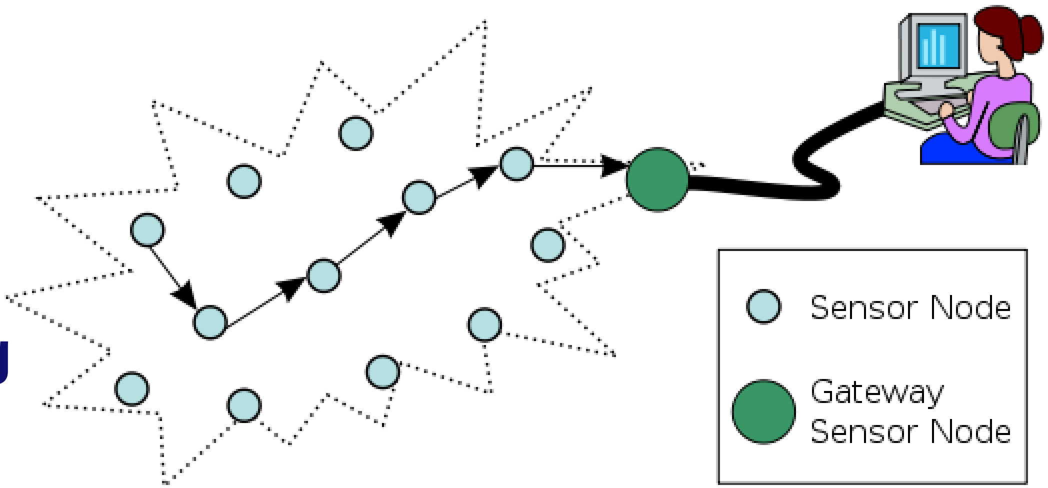
Where innovation starts

Outline

- Wireless Sensor Networks
- Network Synchronization
- Wake-up Receiver Design
- Results WURx Version 1
- WURx Version 2
- Conclusions

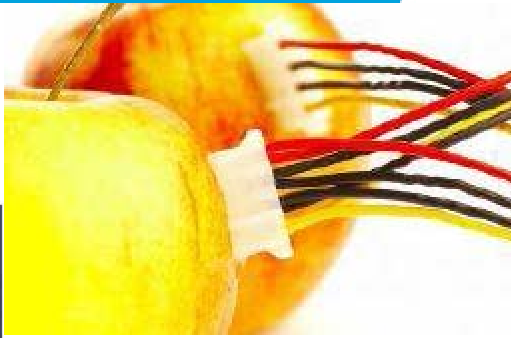
Wireless Sensor Networks

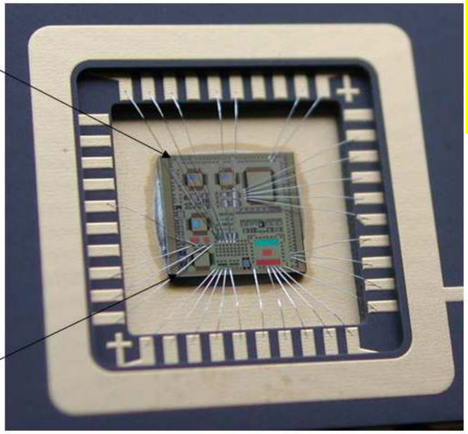
- A number of sensor nodes work together to collect and process information
- Biggest challenge → Power consumption
- Applications
  - Healthcare
  - Condition monitoring
  - Home automation
  - Military
  - …

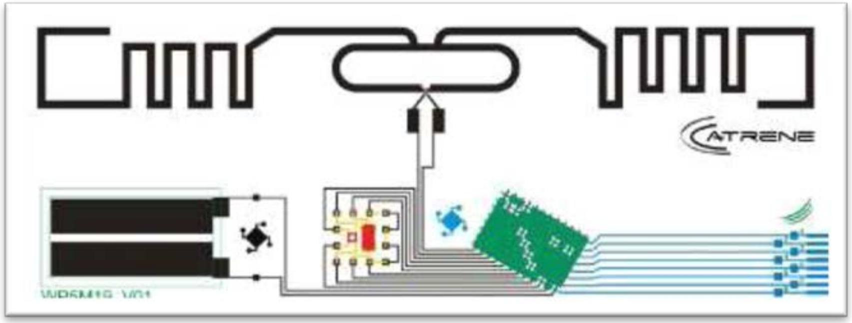


Sensor Network Example (Pasteur)

- **Supply chain monitoring of perishables**
- **Many companies/universities involved**
- **Wirelessly monitor**
  - **Temperature, Humidity, pH, O2, CO2, Ethylene**







- **<u>Challenge:</u>**
  - **Passive RFID -> Range**
  - **Could we do active RFID?**

http://pasteur-project.info

Wireless Sensor Networks

Many types of sensor networks

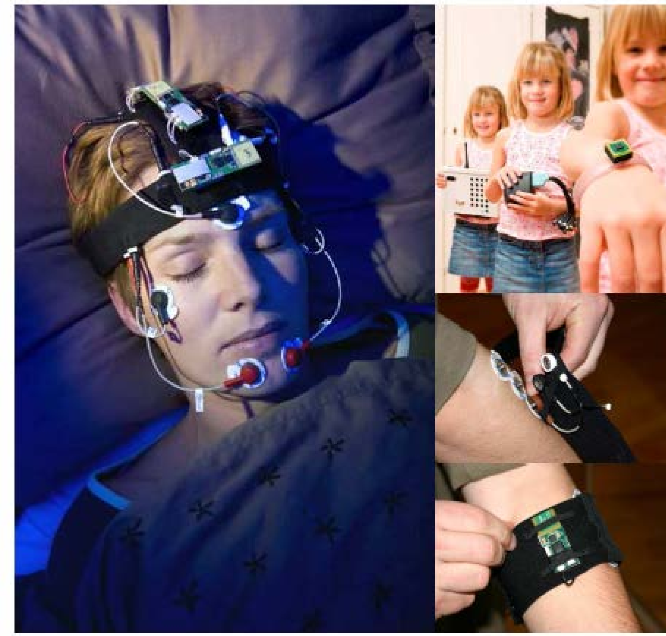
- Short distance / Long distance
  - Long distance: Multi-hop
- Symmetric / Asymmetric
  - Are all the nodes equal? Is there a master node with more power and processing?
- Packet rate and latency

One solution is not optimal for every situation

- Choose application type

Wireless Body Area Network

- **New application of WSNs**
  - **Wearable sensors**
  - **Implantable medical devices**
  - **Swallowable sensors**
  - **Implantable sensors**
  - **Wellness / Fitness sensors**
  - **Baby care**
  - **…**



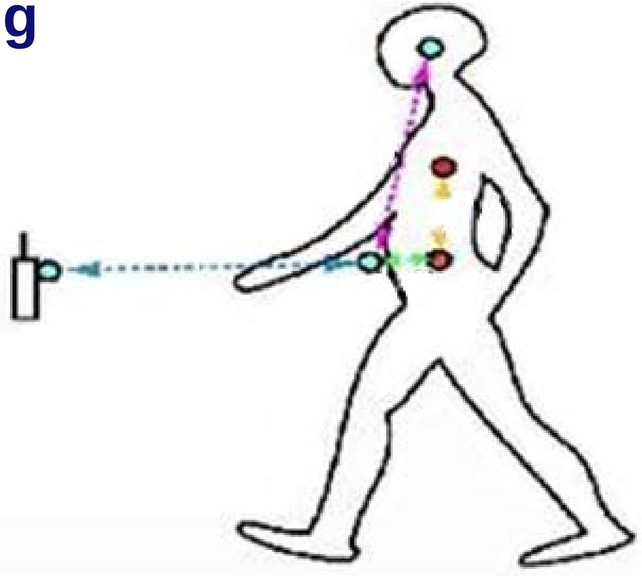
Wireless EEG, ECG, EMG and EOG monitoring

Wireless ECG patch

Wireless ECG, respiration, Skin Temperature and Skin conductance monitoring

Wireless Body Area Networks

- Short distance < 10m
- Asymmetric network
  - Master node: high power, synchronisation
  - Sensor node: low power, less processing
- We will focus on the receiver
  - Node knows when to transmit
    - transmitter only on when needed
  - When does the node need to wake up?



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Network synchronisation

- Sensor node in deep sleep to save energy
- Synchronized before transmission
- Synchronous network:
  - Node “knows” when to wake up
- Asynchronous network:
  - Node wakes up often to listen for wake-up call
  - Only synchronize before transmission

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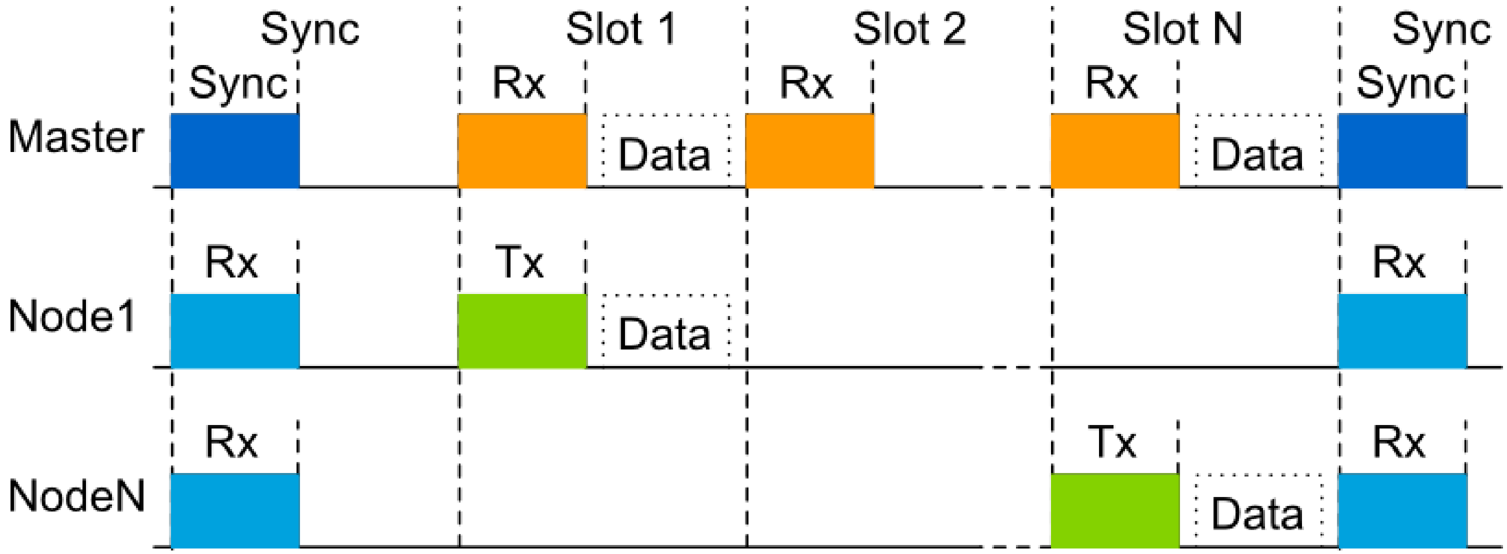
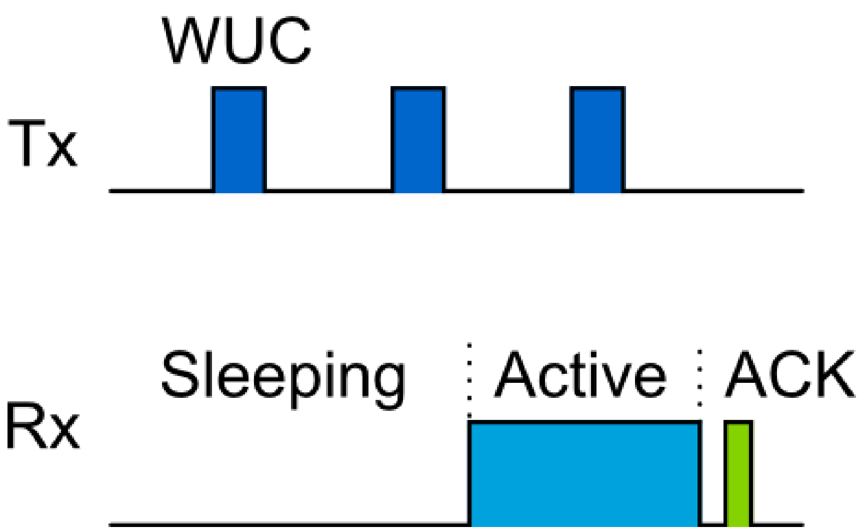
Synchronous network (TDMA)

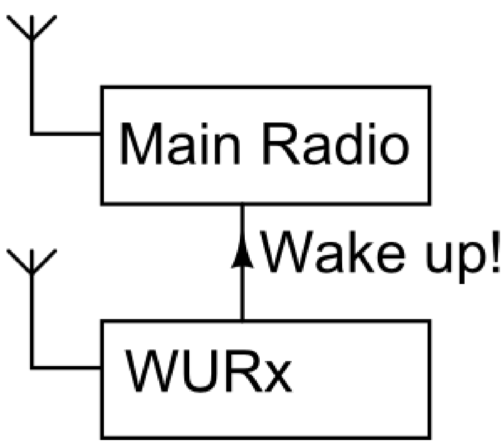
- Master transmits synchronization beacons
- Network is always synchronized (overhead)
- Receiver "knows" when to listen to beacon



Asynchronous network (X-MAC)

- **Master transmits wake-up calls until receiver sends an acknowledge**
- **Only synchronized when transmitting data**
- **Receiver is duty-cycled & low power**
  - **Wake-up Receiver (WURx)**





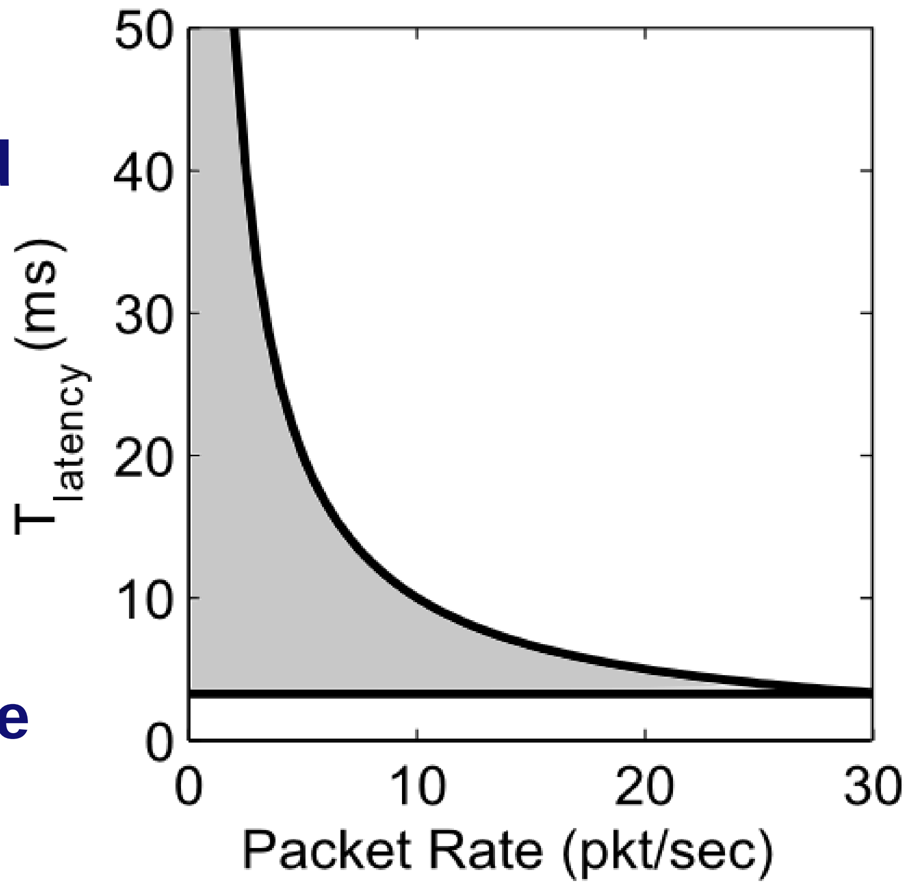
Synchronization overhead

Packet rate:

- Low: large sync. overhead
- High: node never sleeps

Low Latency:

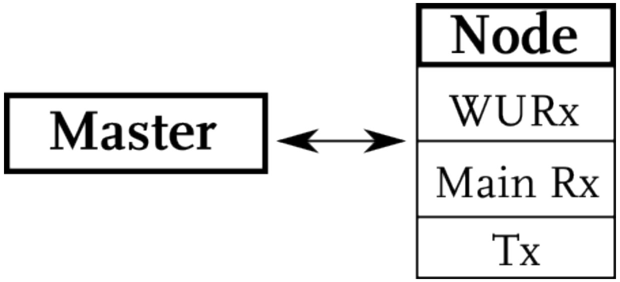
- Node has to react very quickly
- Can not use low duty cycle



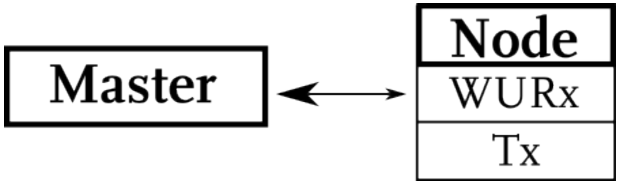
WURx: low latency / low packet rate

WURx Scenarios

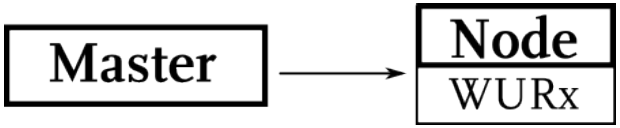
- <u>Multimedia, ECG, etc.</u>
- WURx can't handle bit rate
- Main Rx needed



- <u>Active RFID</u>
- Low bit rate
- WURx receives payload

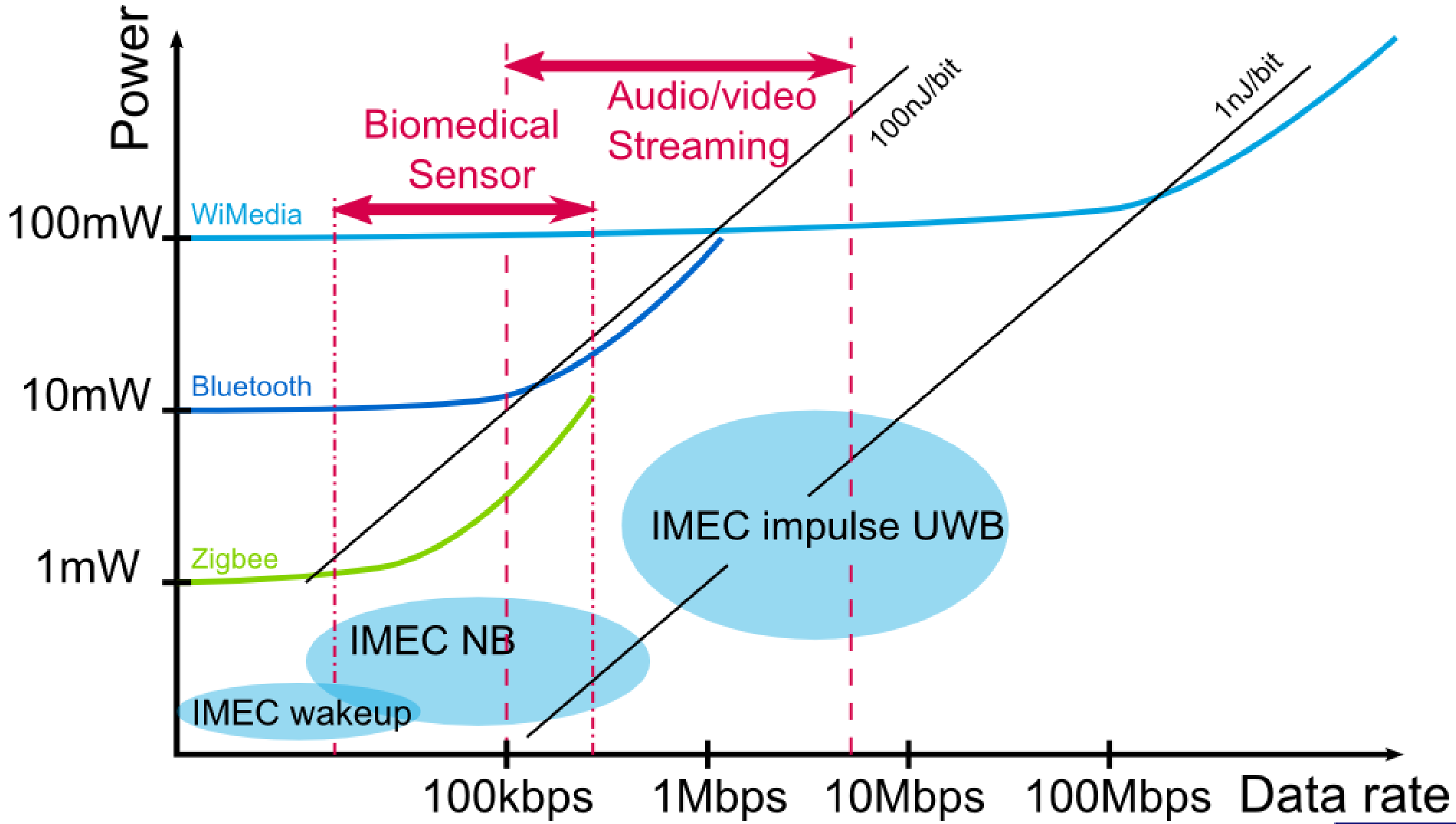


- <u>Remote control</u>
- One-way communication



WURx Power Consumption

- **Asymmetric / Asynchronous network**
- **Wake-up Receiver takes care of the wake-up**



WURx specifications

- Low power consumption
  - 100 – 200 uW

- Small distance < 10m
  - Low path loss
- Asymmetric
  - Large transmit power

} Low sensitivity -70dBm

- Low bit rate (only receive wake-up call)
  - Rb < 50kbps

Receiver Design - Modulation

- Often listen without data present
  - Average power is important
  - nJ/bit less important

- Low complexity modulation: OOK / FSK
- OOK
  - Can use low power envelope detector
  - Sensitive to fading and interferers
- FSK
  - No information in amplitude, use limiter
  - Less sensitive to fading

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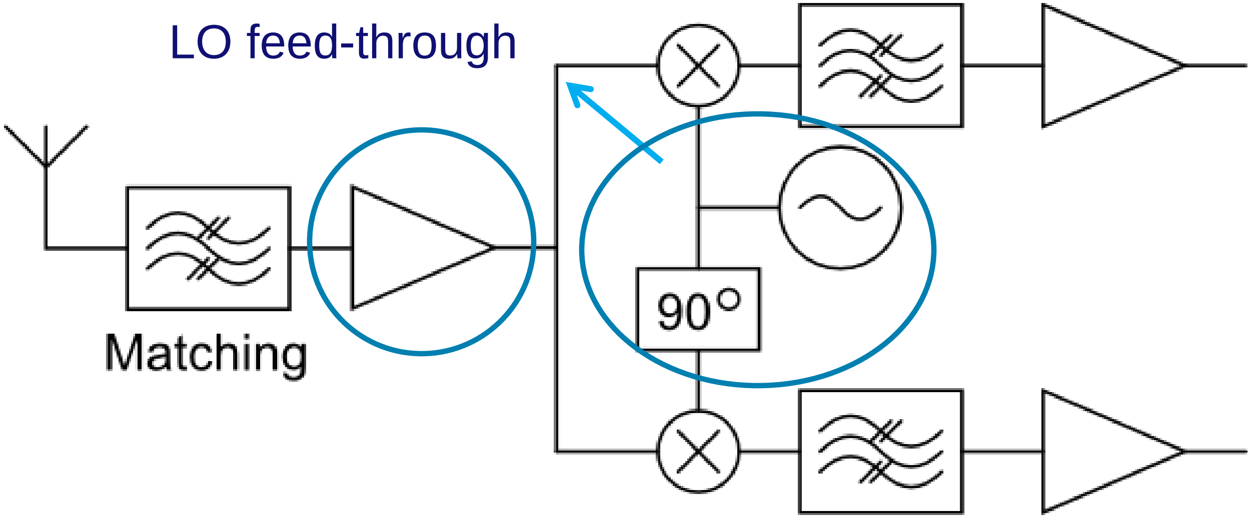
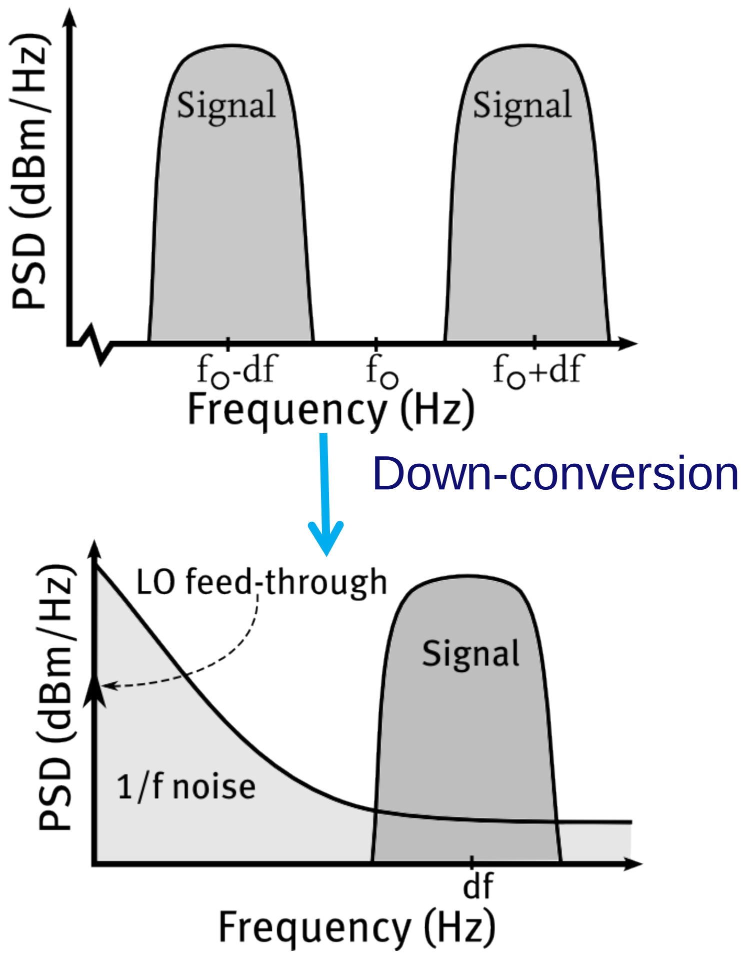
Zero-IF architecture

- Power consumption
  - High frequency gain (LNA)
  - Local Oscillator
- Challenges
  - LO feed-through
  - 1/f Noise



Wide-band FSK

- **Wideband: df >> R_b (bit rate)**
- **Not bandwidth efficient**
- **Signal <u>mostly</u> around f_0±df**
- **Signal at df not round DC**
  - **Filter 1/f noise**
  - **Remove LO feed-through**



LNA Less Receiver

- Short distance + Large transmit power
  - Low sensitivity / high noise figure
- Remove LNA
- Create gain at low frequency
  - Lower power consumption
- Match antenna to the mixer

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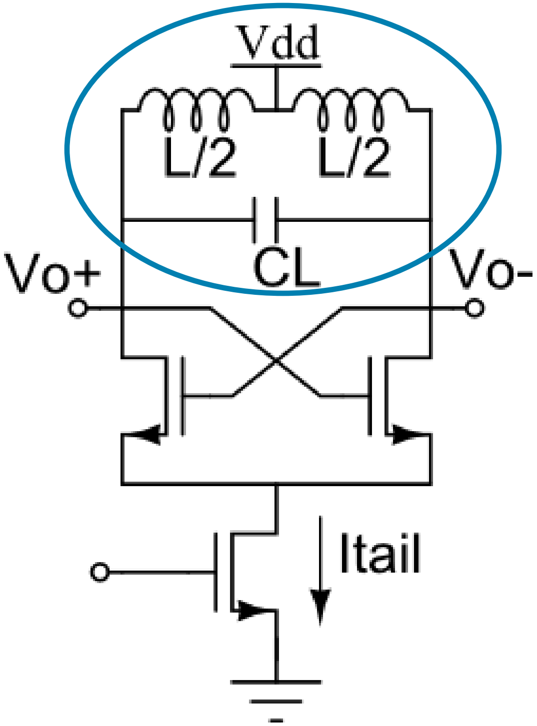
Low Power Oscillator

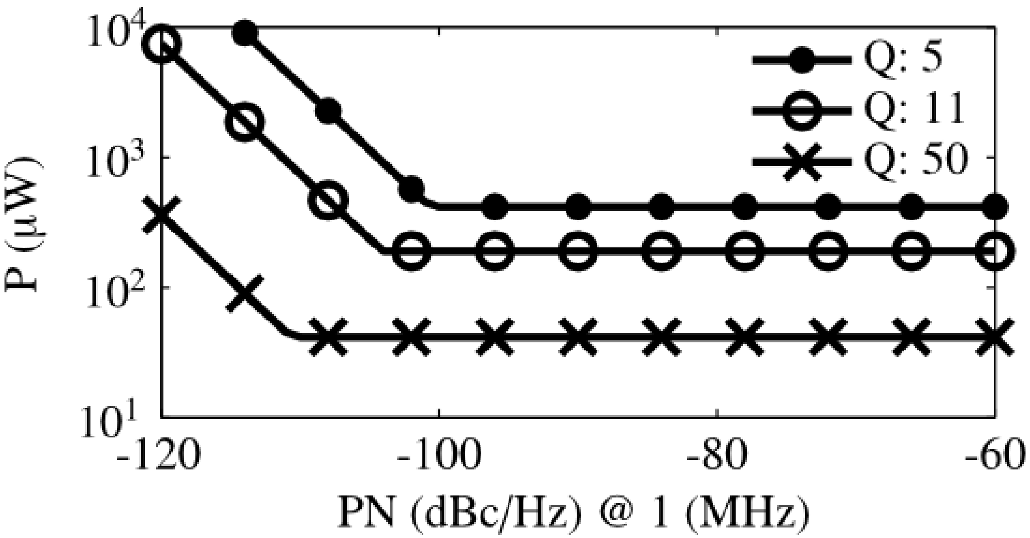
- **Phase noise is an important design constraint**
- **Leeson:** $$\mathcal{L}(\Delta\omega) = \frac{F}{P_{sig}}\left(\frac{\omega_0}{2Q\Delta\omega}\right)^2$$
- **Trade-off between power and phase noise**
  - **Decrease power -> increase phase noise**

- **Different oscillator types**
  - **LC oscillator**
  - **Ring oscillator**

Low Power Oscillator - LC

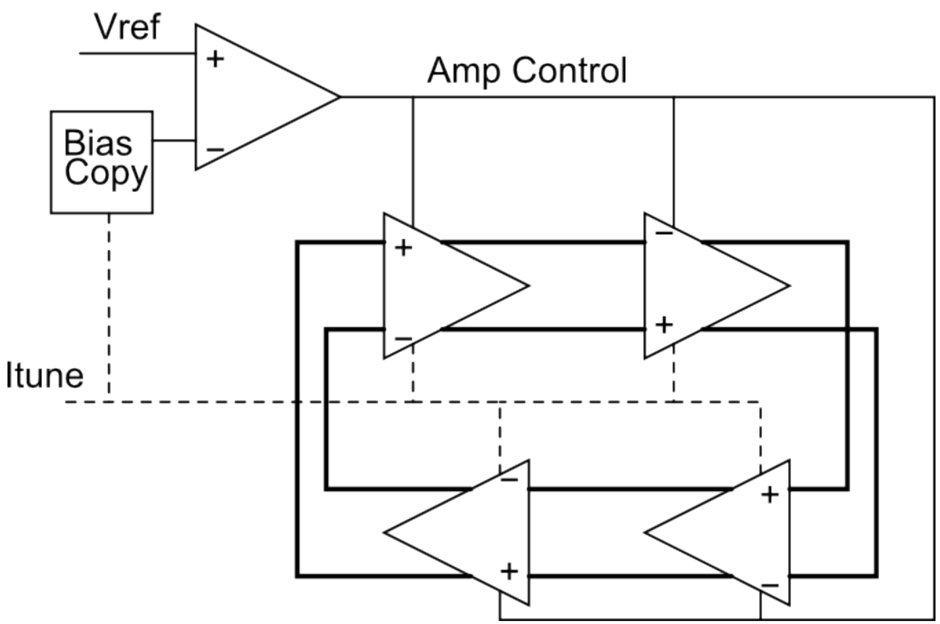
- **Tuned tank**
- **Power needed to compensate tank losses**
- **Power limited by maximal Q (loss) & L**

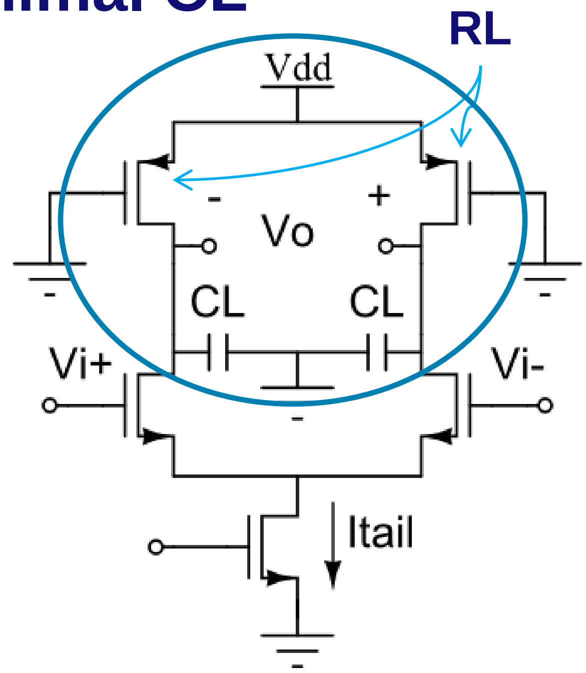




Low Power Oscillator - Ring

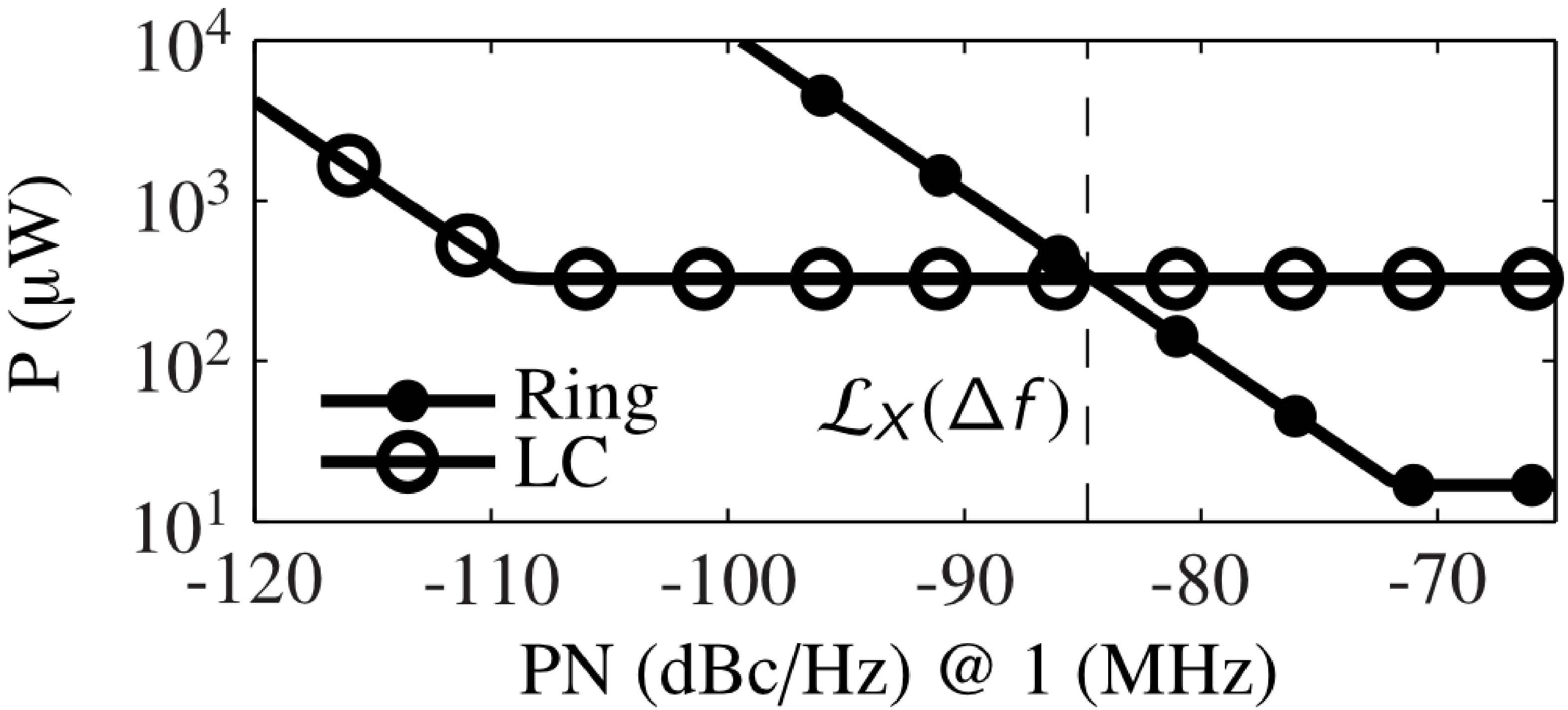
- **Series (ring) of amplifiers, gain ~ RL**
- **Frequency sensitive to Vdd, Temp, …**
- **Power limited by maximal RL / minimal CL**





Low Power Oscillator

- **Higher Phase Noise – Less Power**
- **Technology limits lower power limit**



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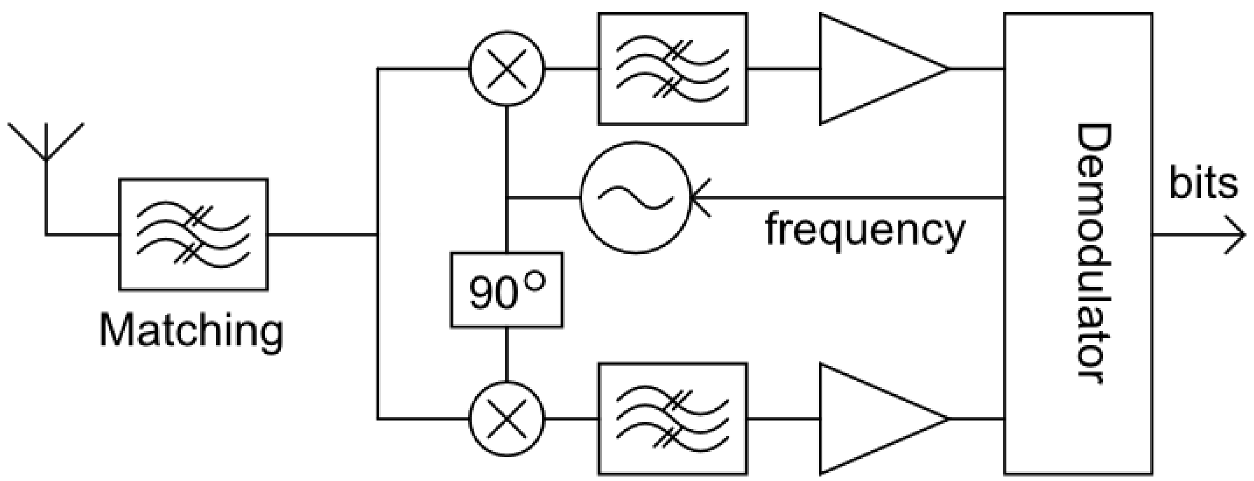
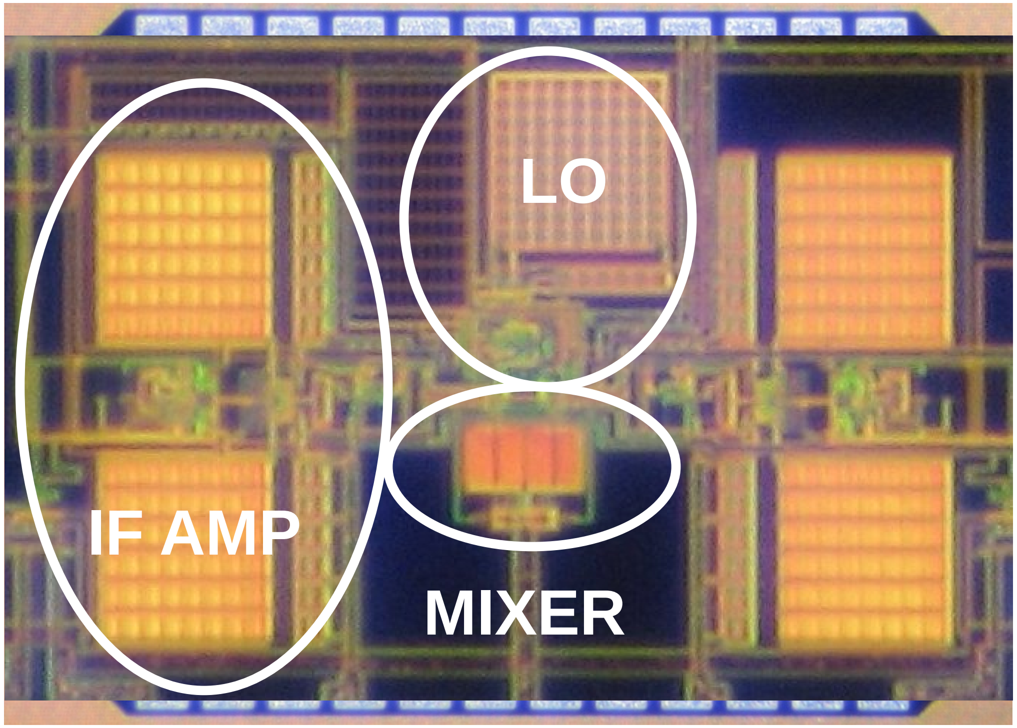
Frequency instability

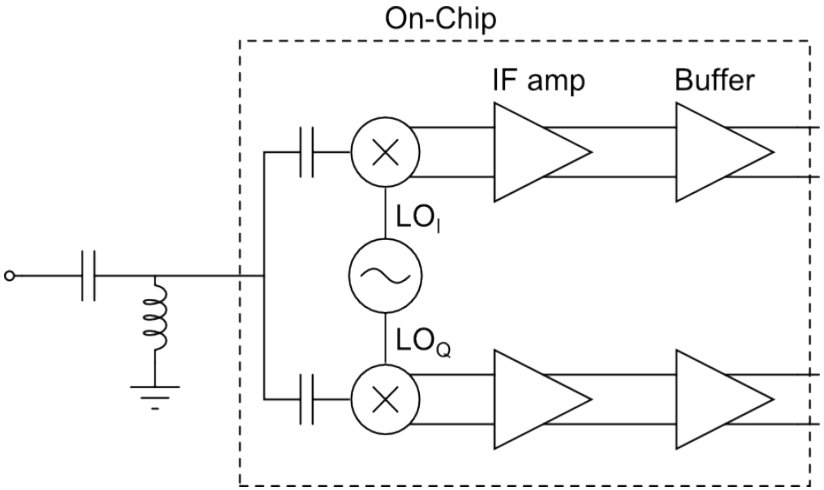
- Frequency of ring oscillator is sensitive
  - Supply voltage
  - Temperature
- Frequency offset at output of demodulator
- Use frequency feedback



Measurement Results (Version 1)

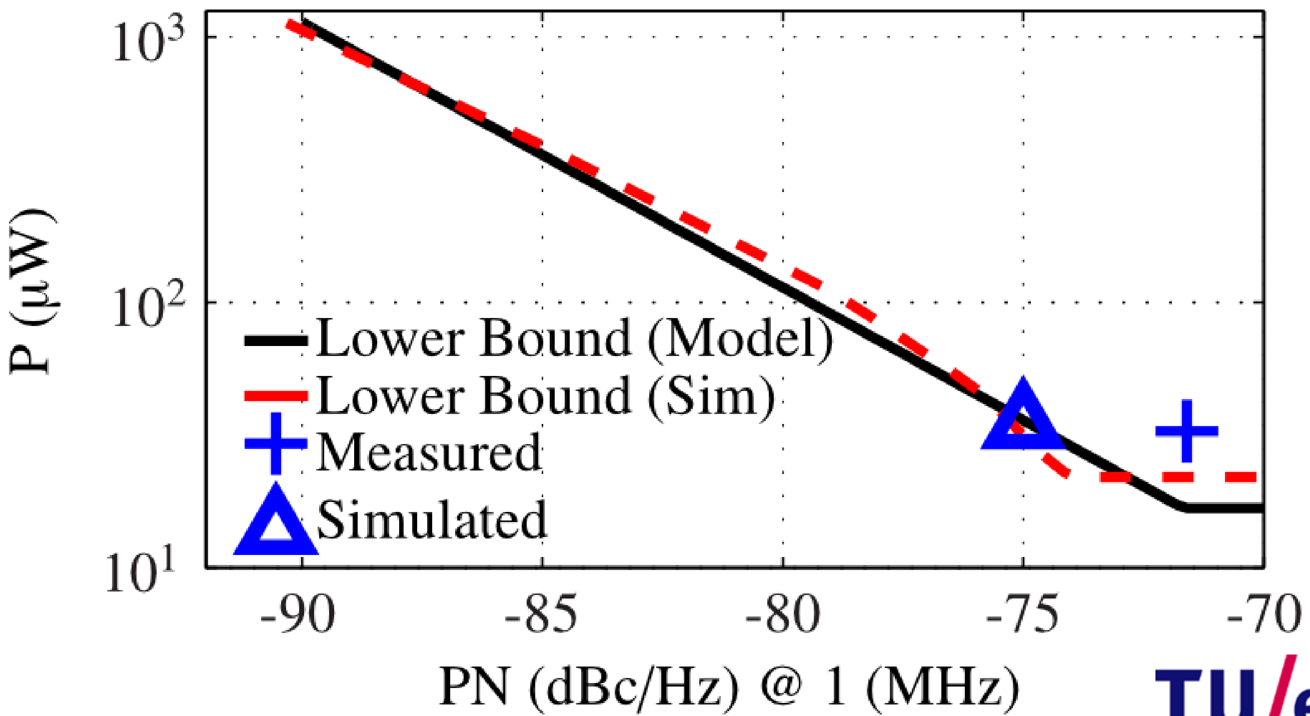
- Taped-out mixer first design in 90nm CMOS
- Demonstrate mixer-first approach





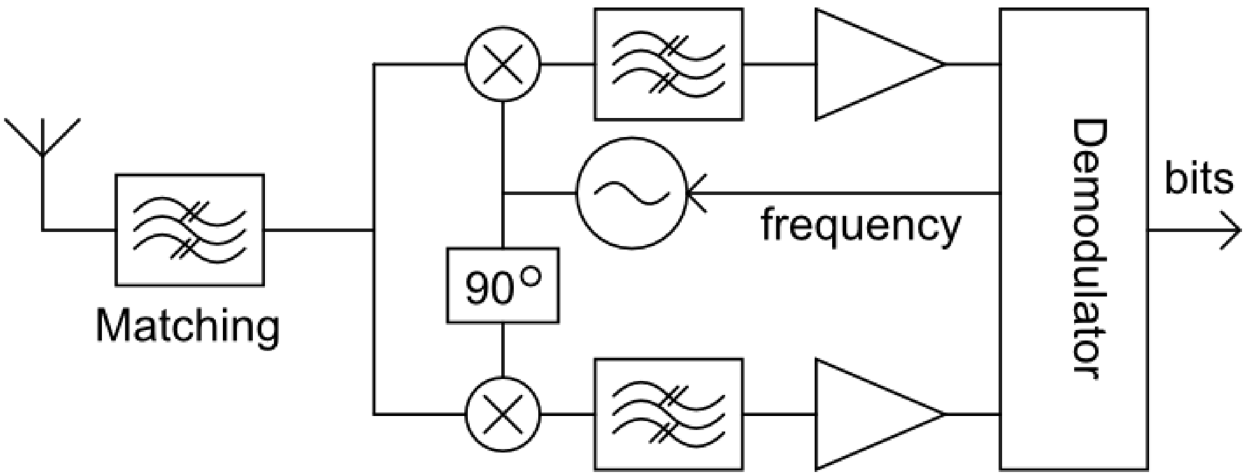
Oscillator (Version 1)

- **Phase Noise higher than expected**
  - **Limits BER to 0.1%**
- **Low power oscillator: 40uW**



WURx Version 2

- **Goal:**
  - **Close the frequency feedback loop**
  - **Track frequency drift**
  - **Demonstrate low power stable local oscillator**



Comparison

	Zigbee	WURx V1	WURx V2 (SIM)
Power (uW)	**±50.000**	**132**	**230**
Bit Rate (kbps)	250	<50	<50
PN (dBc/Hz @ 1MHz)	< -88	-72	< -80.2
Tuning (MHz)	868-915-2400	350 - 1100	868 - 915
IIP3 (Linearity)	> -40 dBm	-21 dBm	-23.8 dBm
Sensitivity (dBm)	± -90	-65	< -75

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Conclusions

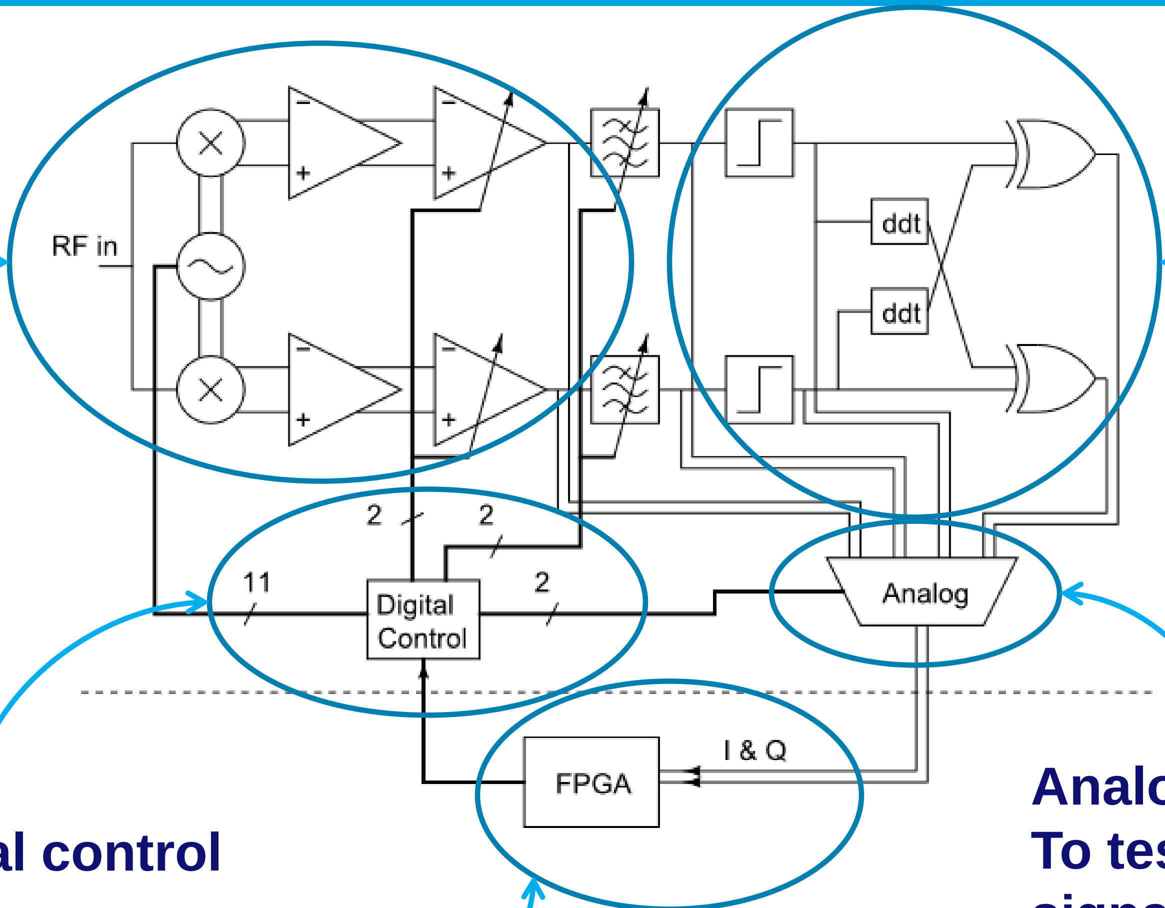
- One solution not optimal for every problem
  - Optimize power for application

- Small scale networks (like BAN)
  - Short distance
  - Asymmetric

- WURx
  - Low peak power - nJ/bit less important
  - Mixer–first is possible

WURx (Version 2)

Analog front-end



On-chip FSK demodulator

JTAG digital control

Analog MUX
To test internal signals

Off-chip frequency control loop

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WURx Version 2

- **Goal:**
  - **Close the frequency feedback loop**
  - **Demonstrate low power stable local oscillator**