Ultra-Low Power Wireless Design of Autonomous Sensor Networks

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Open Innovation by IMEC and TNO

TU/e

CWTe
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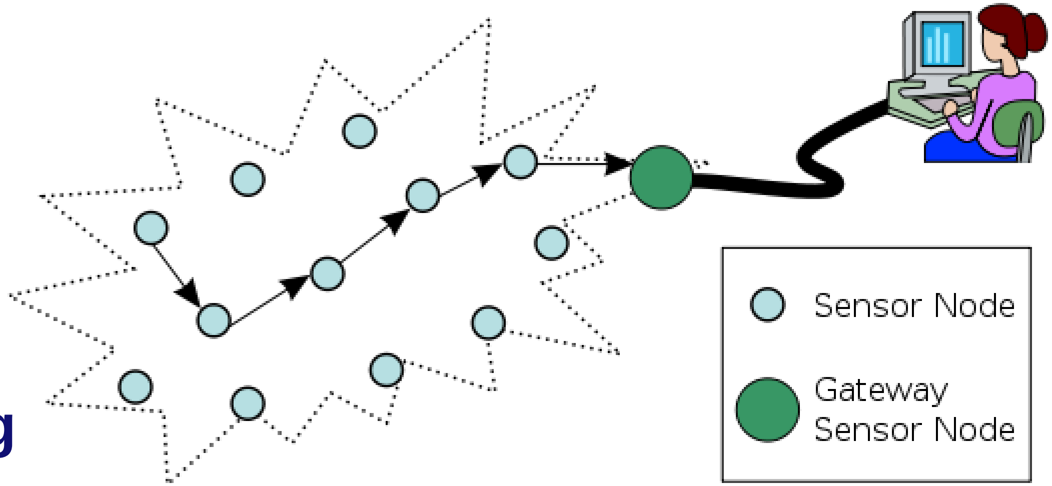
Where innovation starts

Outline

- ***Introduction***
  - Wireless Sensor Networks
  - Ultra-low power wireless design
- **CWTe- Holst Centre Project**
  - Wakeup Radio project
  - Digital baseband project
- **Current Research**
- **Conclusions and Future Work**

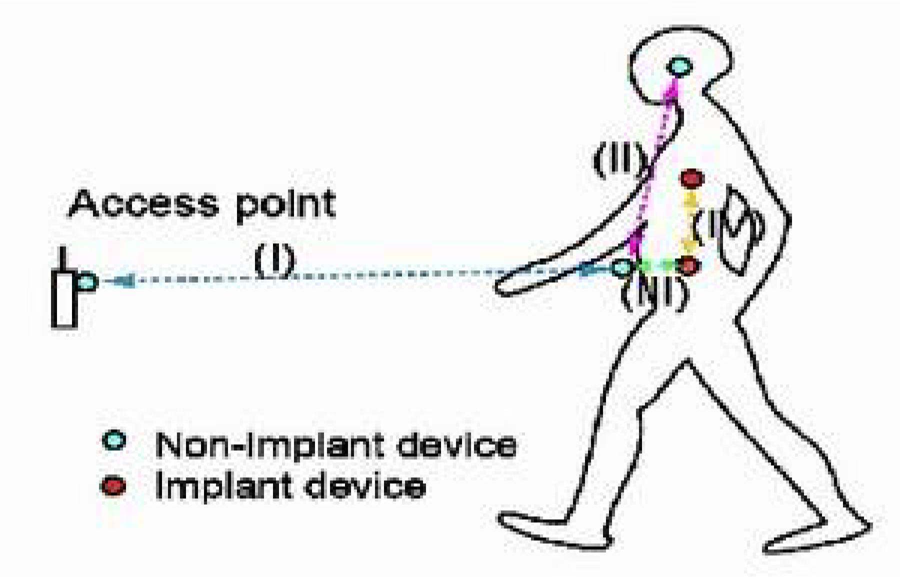
Introduction- WSN

- **Wireless Sensor Network (WSN)**
  - **A large number of spatially distributed autonomous sensors to monitor physical or environmental conditions cooperatively.**
- **Applications**
  - **Military**
  - **Home automation**
  - **Healthcare**
  - **Condition monitoring**
  - **and more**



Wireless Body Area Network (WBAN)

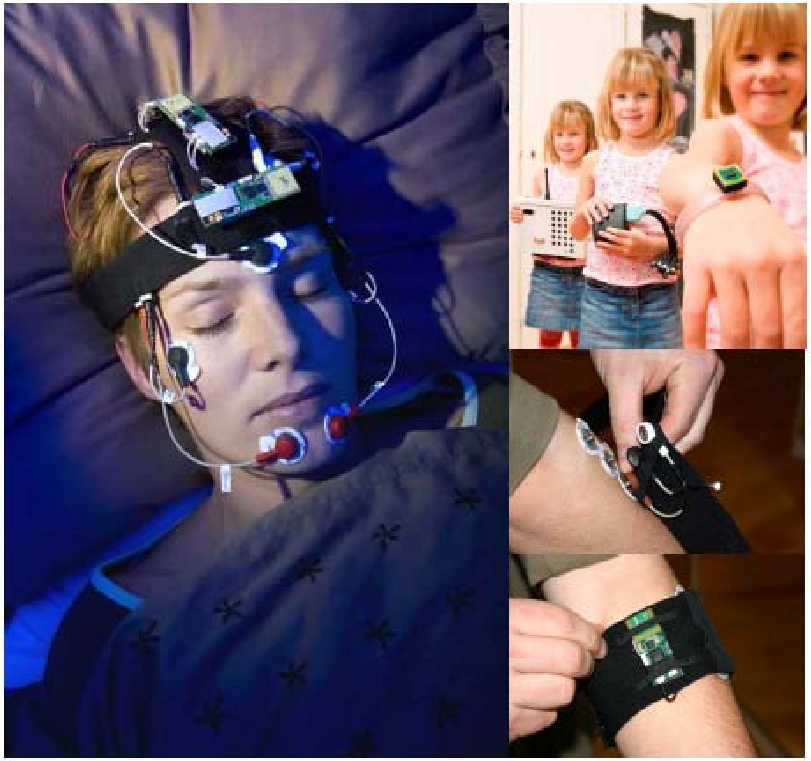
- New application of WSNs
  - Implantable medical devices
  - Swallowable sensors
  - Wearable sensors
  - Implantable sensors
  - Wellness / Fitness sensors
  - Baby care
  - Standard IEEE 802.15.6



Maximize operational life →ultra-low power design

Health Monitoring Systems

- **WBANs at Holst Centre**



Wireless EEG, ECG, EMG and EOG monitoring

Wireless ECG, respiration, Skin Temperature and Skin conductance monitoring

Wireless ECG patch

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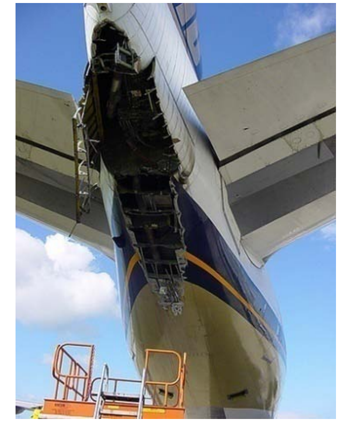
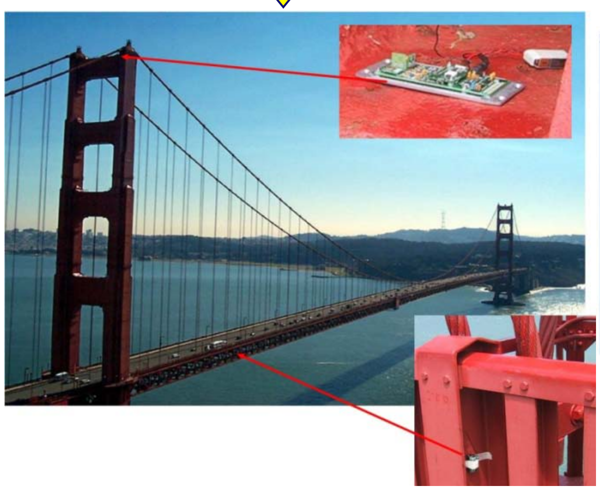
Structural Health Monitoring





Maintenance cost considerations require ultra-low power design!

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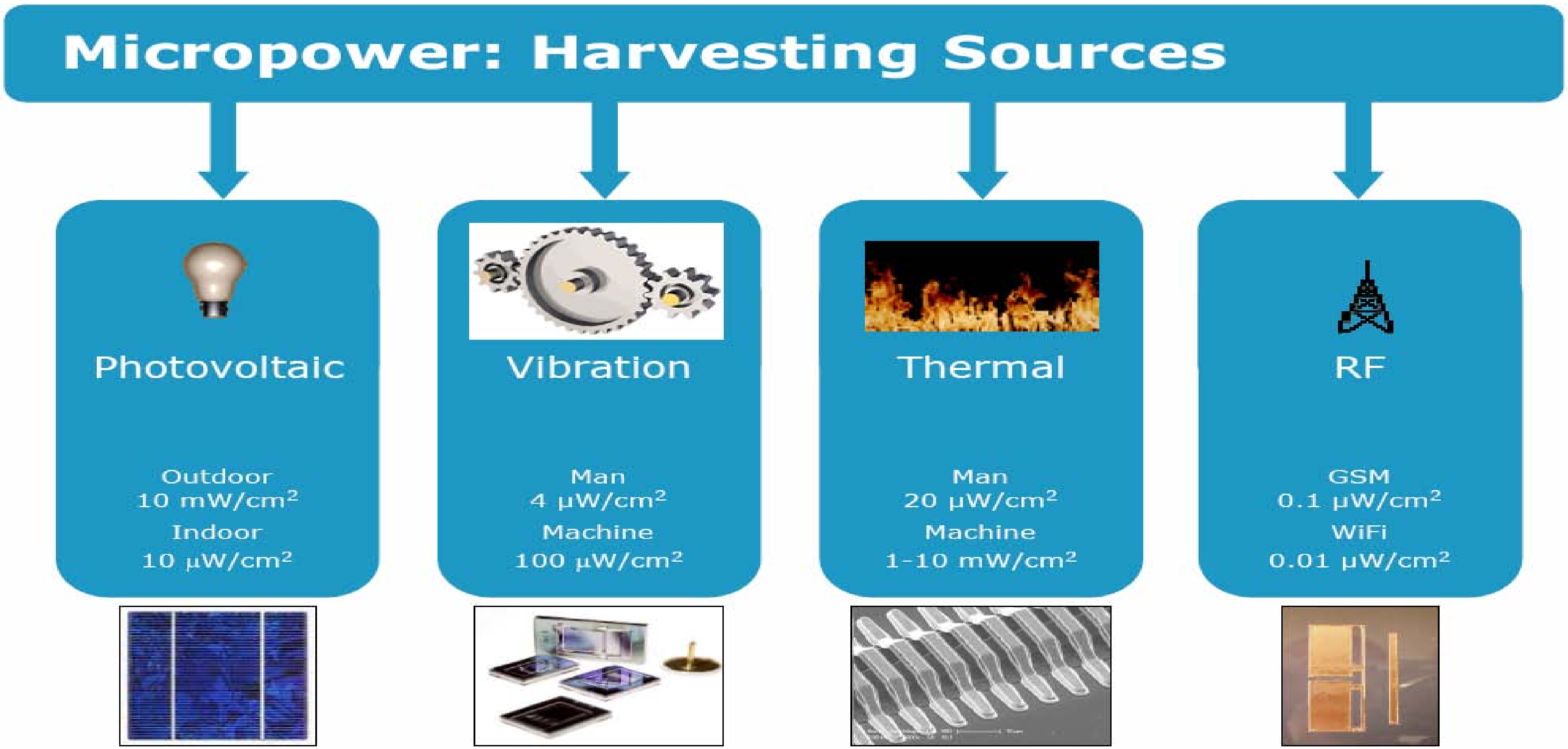
Energy Harvesting

- **Autonomous WSN→ Energy Harvesting (scavenging)**



- **10 uW~1mW** for 1 cm^2 device area

Low Power Commercial Chipset

Standard	Proprietary	Zigbee		Bluetooth
Manufacturer	Nordic	Ti	Freescale	Skyworks
Product Number	RF24L01	CC2420	MC13192	CX72303
RX power [mW]	33.3	33.8	99.9	43.2
TX power [mW]	33.9	31.3	82.0	34.2
Max data rate [kbps]	2000	250	250	1000

- **Power in the order of 10 to 100 mW for 200 to 2000 kbps**
- **Current energy harvesting hardly supports (even for transceiver)**
- **Reduce power consumption -> Ultra-Low Power (ULP) design**

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Ultra-Low Power Design Principles

- **System level**
  - **Simple modulation and baseband algorithms**
    - **OOK or FSK modulation schemes**
  - **Latency (increase)**
    - **Exploit duty cycle**
  - **Data Rate (decrease)**
    - **Spreading**
  - **Complexity shift for asymmetric systems**
- **Hardware implementation**
  - **Simple architecture**
    - **Least number of components**
    - **Energy-efficient components**
    - **super-regenerative receiver**

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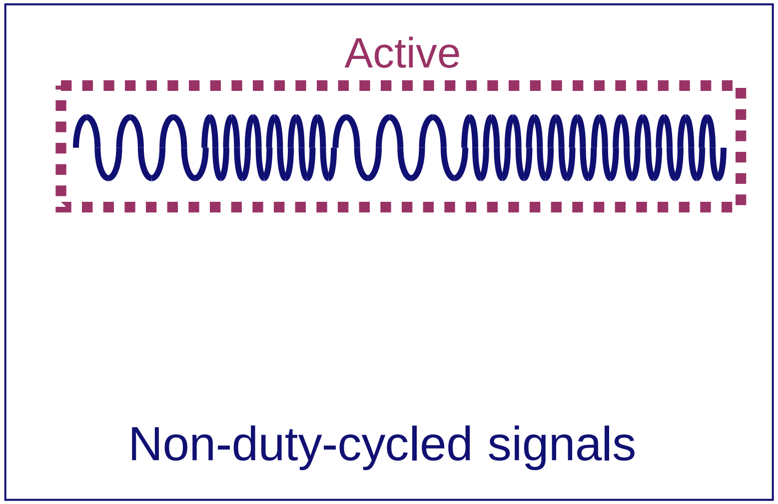
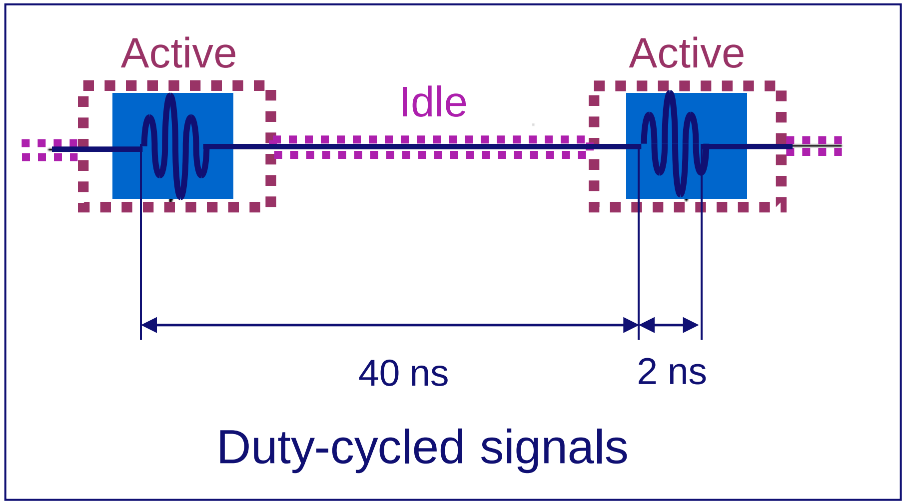
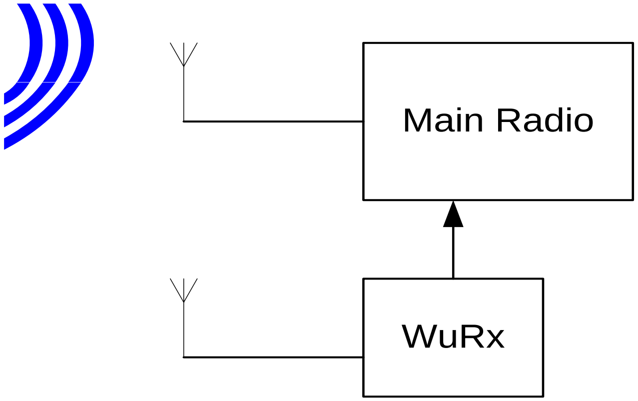
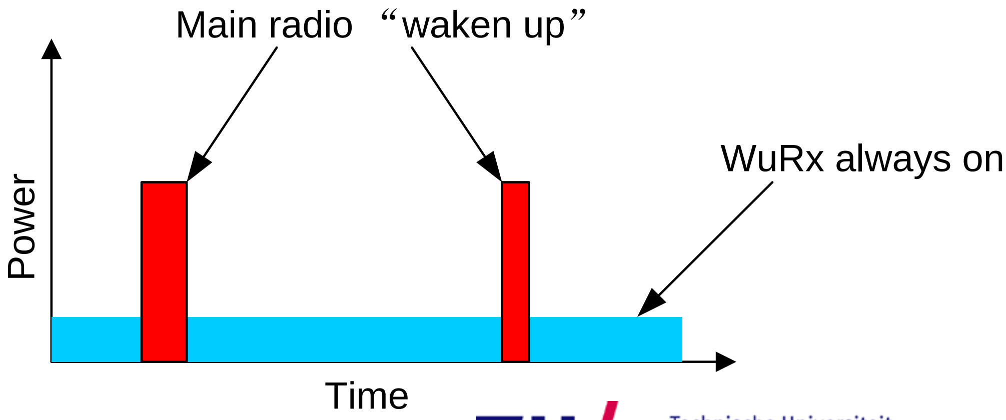
Duty Cycling Reduces Power Consumption





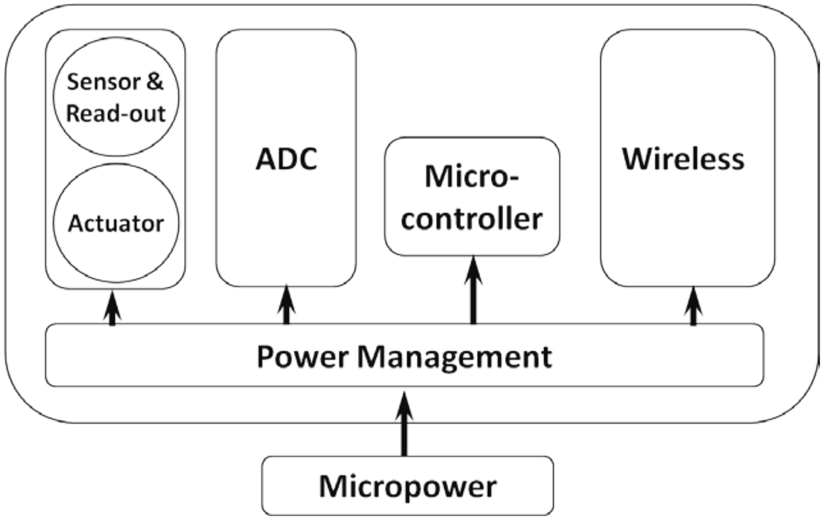


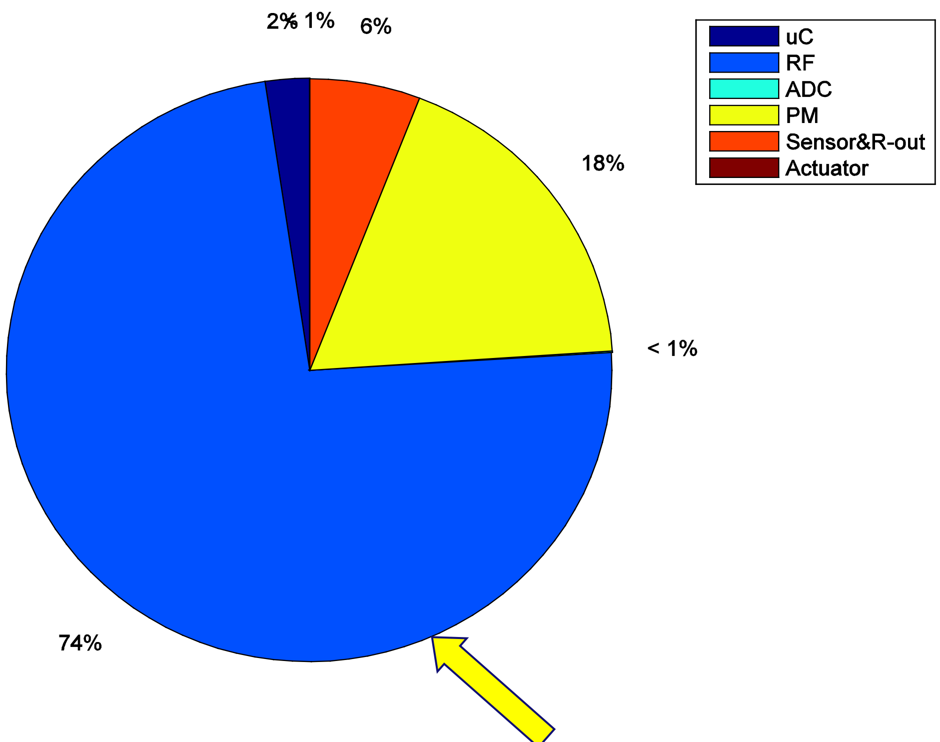
Wakeup radio (WuRx) is needed



Power Consumption Breakdown

- **Duty cycling considered (25%)**
- **Transceiver Nordic's RF24L01**





Wireless Transceiver

- total power consumption equals 1.29 mW
- energy harvesting still can not facilitate autonomy for small device
- Wireless transceiver consumes most power

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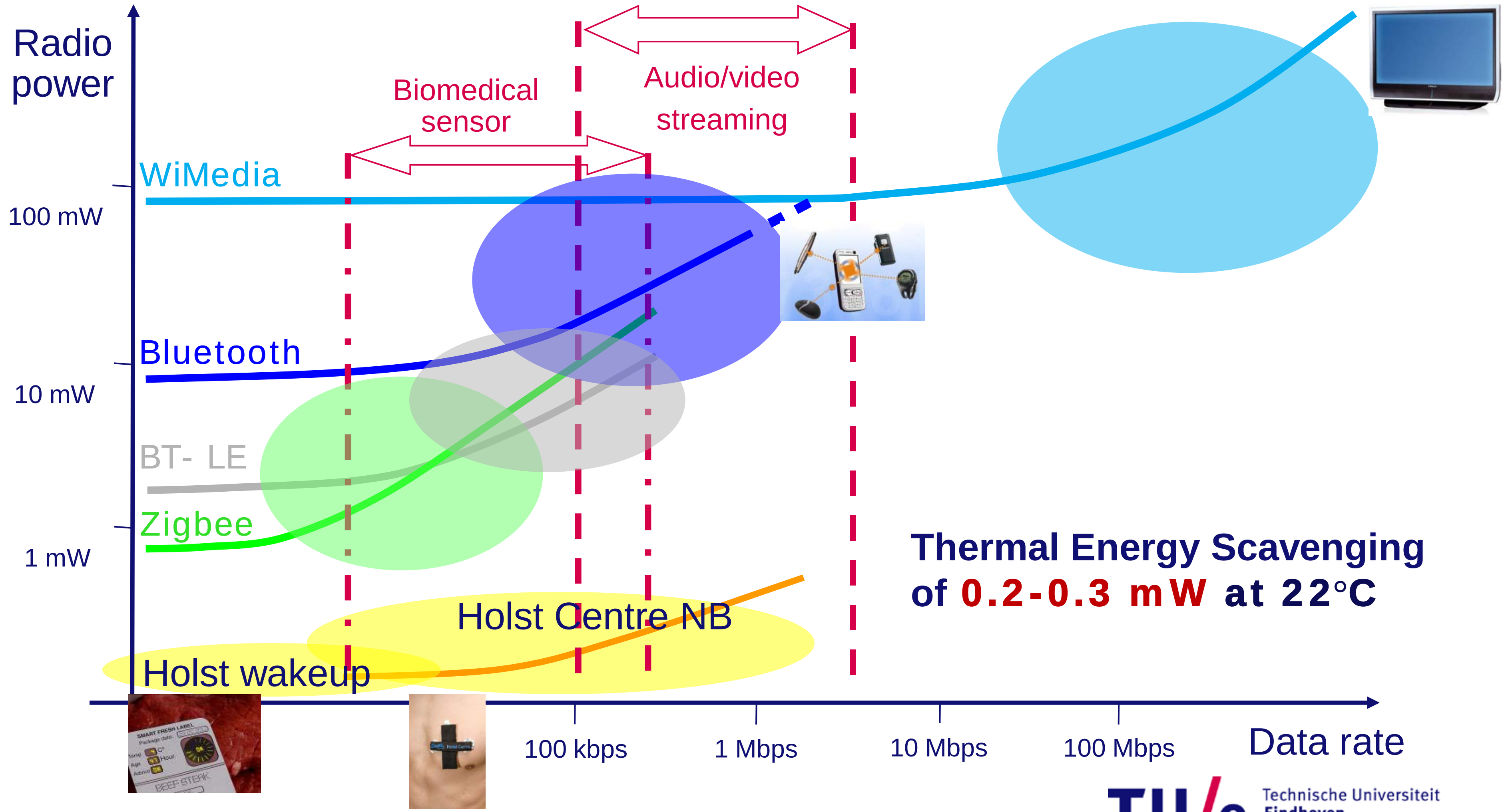
ULP Target at Holst Centre



Thermal Energy Scavenging of 0.2-0.3 mW at 22°C

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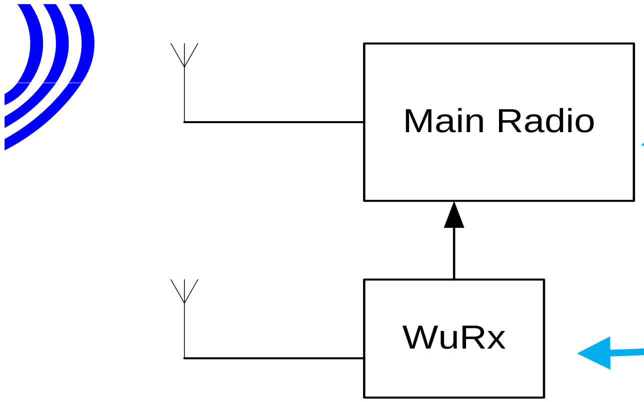
CWTe-Holst Centre Joint Project

- **Joint project collaborating with CWTe at TU/e**
  - **Project challenges**
    - **Minimize power consumption globally**
    - **Optimize over multiple layers: RF, baseband, etc**
  - **Two topics (PhD projects):**
    - **RF front-end design: ULP Wakeup Radio (WuRx)**
    - **Digital baseband design: Robustness and reliability for WBANs**



Project of Low-Power WURx design

- Design a ultra-low power WURx front-end

- Exploit WURx requirements
  - Low sensitivity / high noise figure (NF < 25dB)
    - Short Range (low path loss)
    - Asymmetric link (High transmit power)

  - Band-width efficiency not important (modulation)
    - Low bit rate

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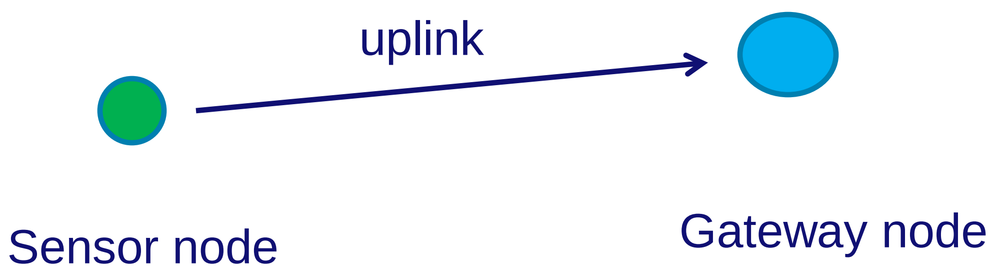
Project of ULP Digital Baseband

- **Current subject**
  - **Channel coding study for WSNs**
    - **Enhance reliability, robustness in low SNR environment**
    - **Decrease transmit power/ increase coverage range for certain performance**



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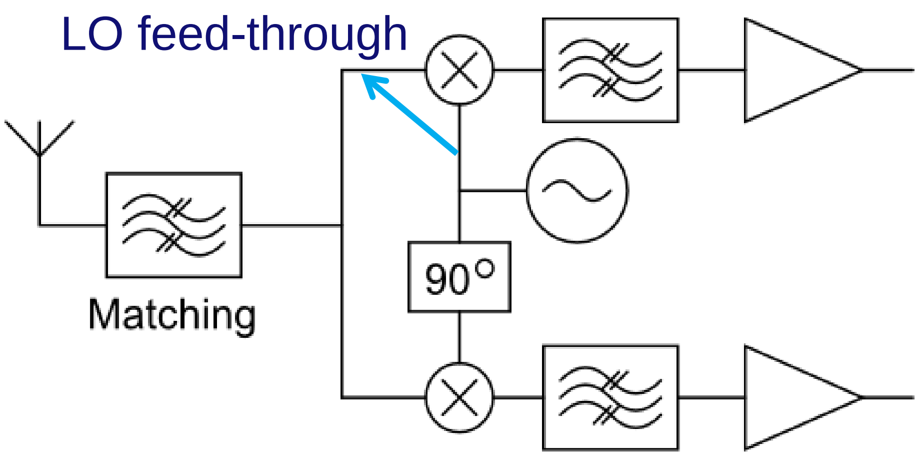
Zero-IF architecture

- **High NF allowed -> No LNA**

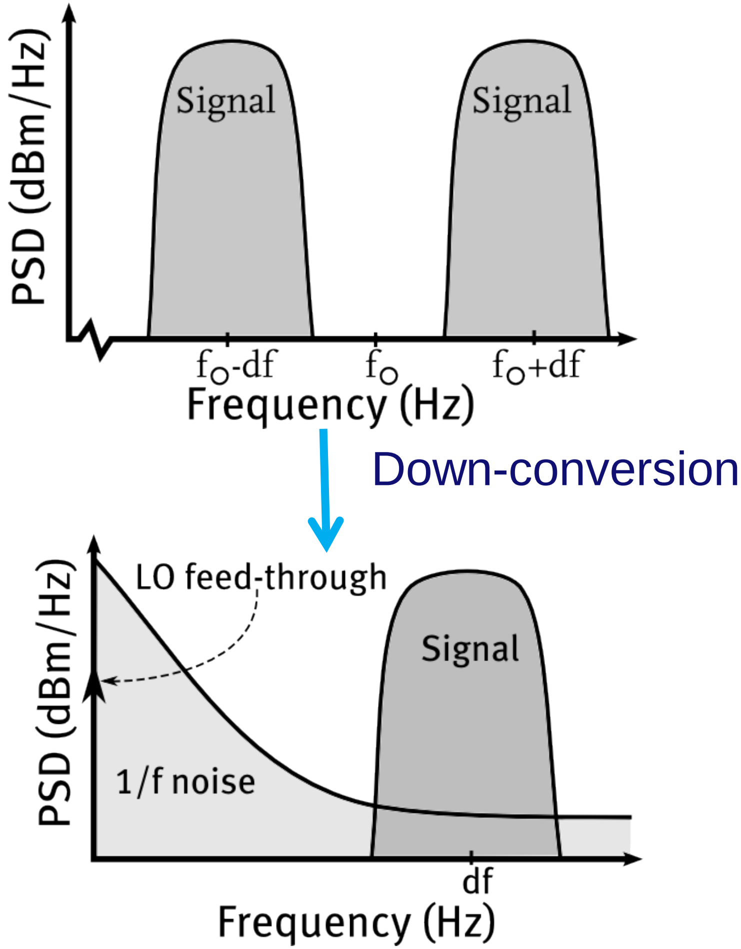
- **Advantages**
  - **Better interferer rejection than envelope detection**

- **Challenges**
  - **LO needed (power consuming)**
  - **1/f Noise**
  - **LO feed-through**
    - **LO at DC output**



Wide-band FSK

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



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Digital Baseband -- Channel Coding

- **Objective:**
  - **Find suitable error correction schemes**
  - **complexity v.s. performance**
- **Procedure:**
  - **Codes : shortened Hamming code ← Holst Centre**
    BCH code ←IEEE 802.15.6 (WBAN)
  - **Modulations: BPSK, On-Off keying (OOK)**
    - **Channel: Additive White Gaussian Noise (AWGN)**

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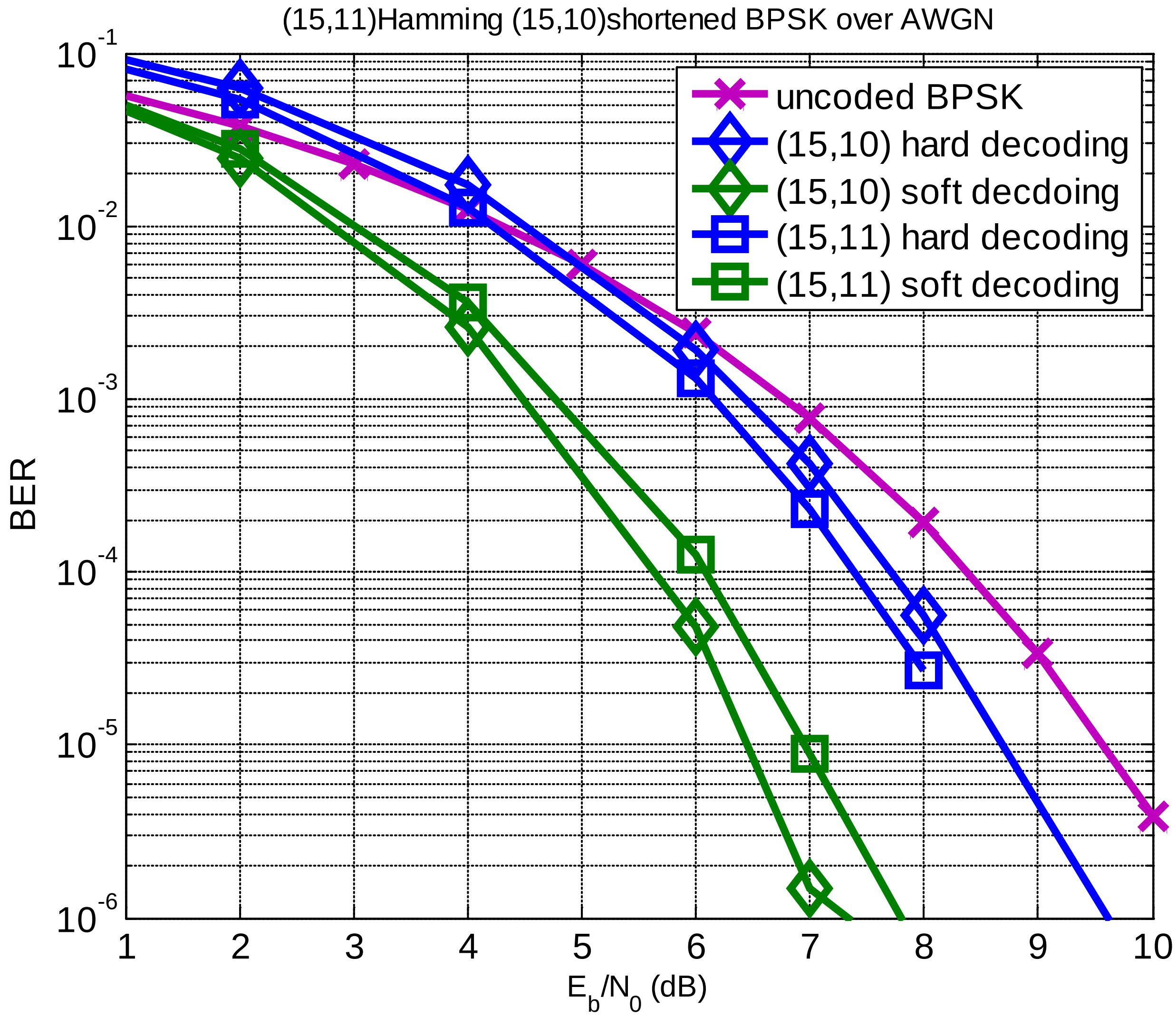
Shortened Hamming code

- (15,10) shortened Hamming code
  - 10 info bits 5 parity bits; Code rate: 2/3
  - Hard decoding:
    - decide 1 or 0 bit by bit
    - correct 1 error or detect 3 errors
  - Soft decoding:
    - Take reliability of the bits into account
    - BCJR decoding (optimal)
    - High decoding complexity
- (15,11) standard Hamming code
  - 11 info bits 4 parity bits; Code rate: 2/3 approx.
  - Hard decoding: Correct 1 error or detect 2 errors
  - Soft decoding: BCJR

BER performance (15,10) V.S. (15,11) BPSK AWGN

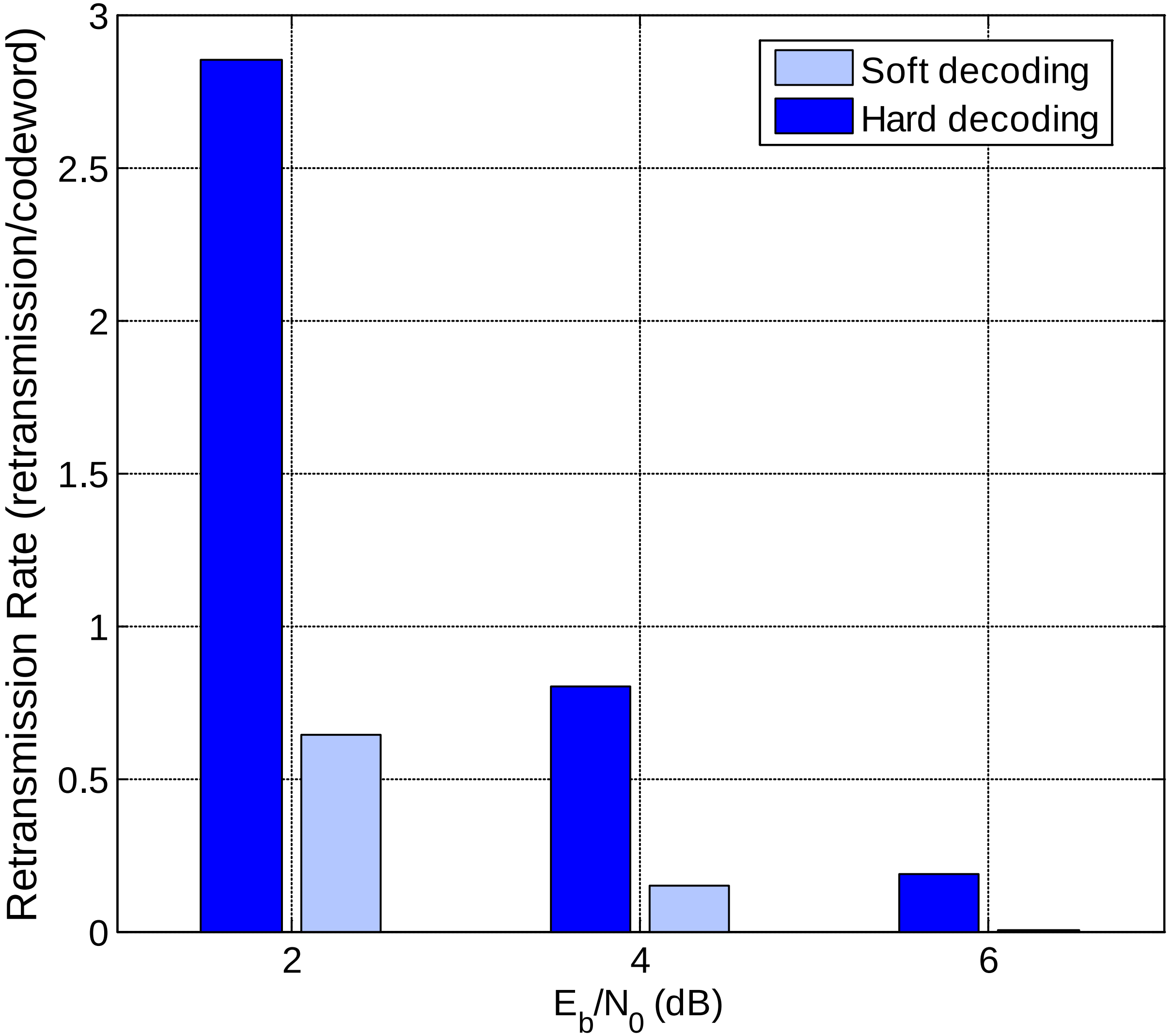


- BCJR decoding > Syndrome decoding

- BCJR Decoding complexity:

(15,10) > (15,11)

Retransmission based on Hamming codes



- Fix energy per bit for first transmission (received power)
- ack. loss is ignored
- Same BER value.

➢Retrans. time is reduced by BJCR based scheme

Channel Coding

- **BCH codes**
  - **IEEE 802.15.6 standard draft.**
  - **Three BCH codes: (63,39), (63,45), (63,51)**
  - **Different code rates and error correction capabilities**
  - **Generation: shift register with more delay elements**
  - **Hard decoding**
    - **Low decoding complexity**
  - **Soft decoding:**
    - **More complicated**

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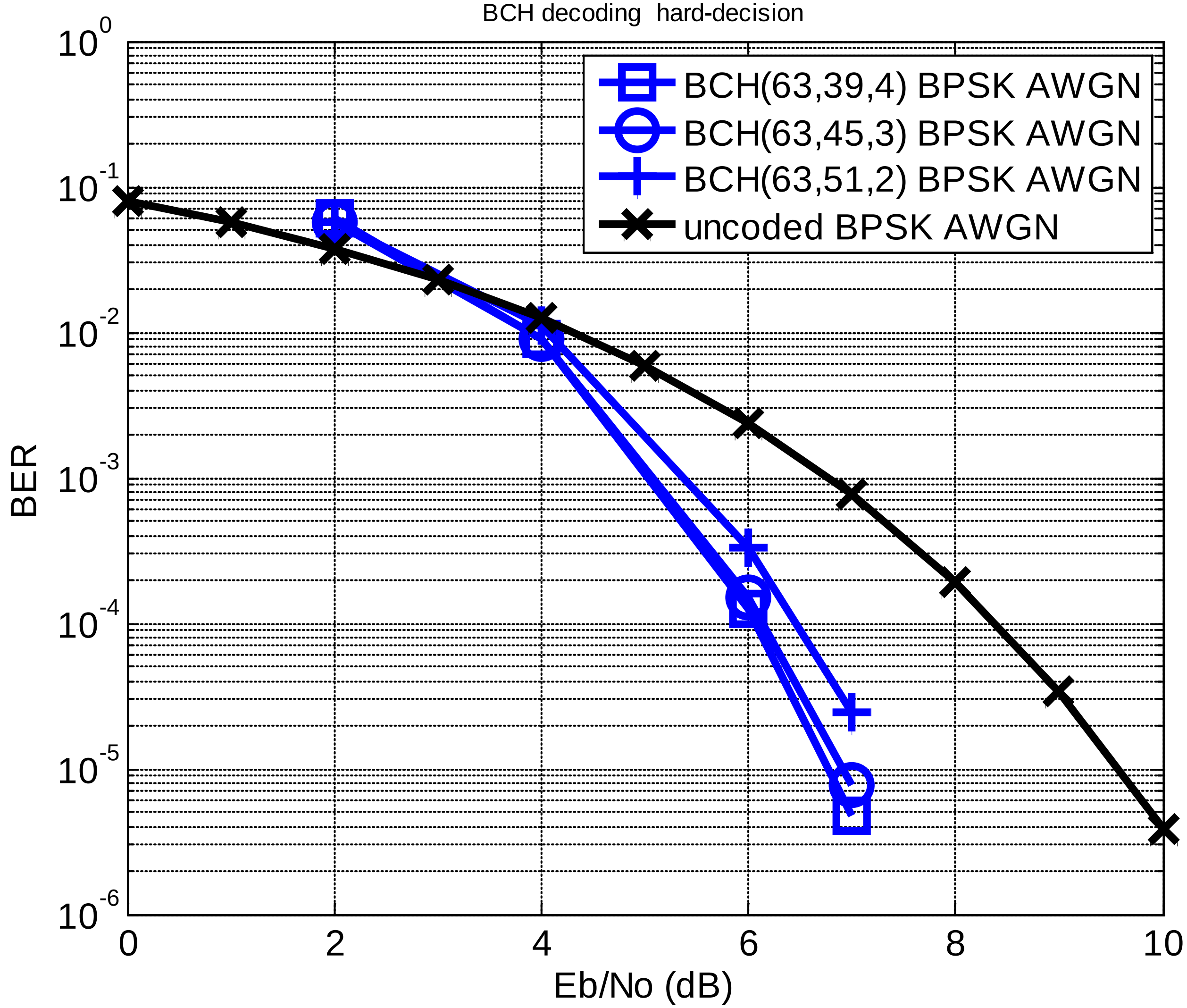
BER performance BCH codes BPSK AWGN

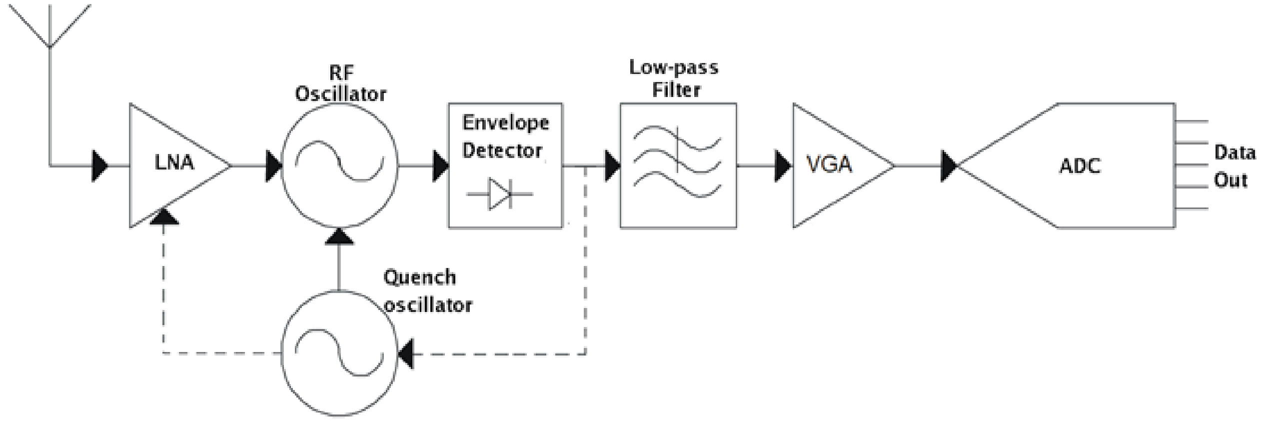


2.5 dB coding gain for BER at 10^{-4}

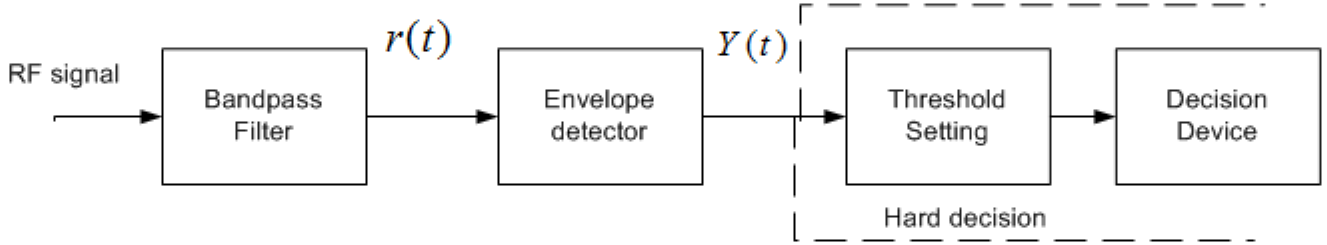
(63,39) BCH code has best performance. 4 errors corrected

Noncoherent OOK modulation

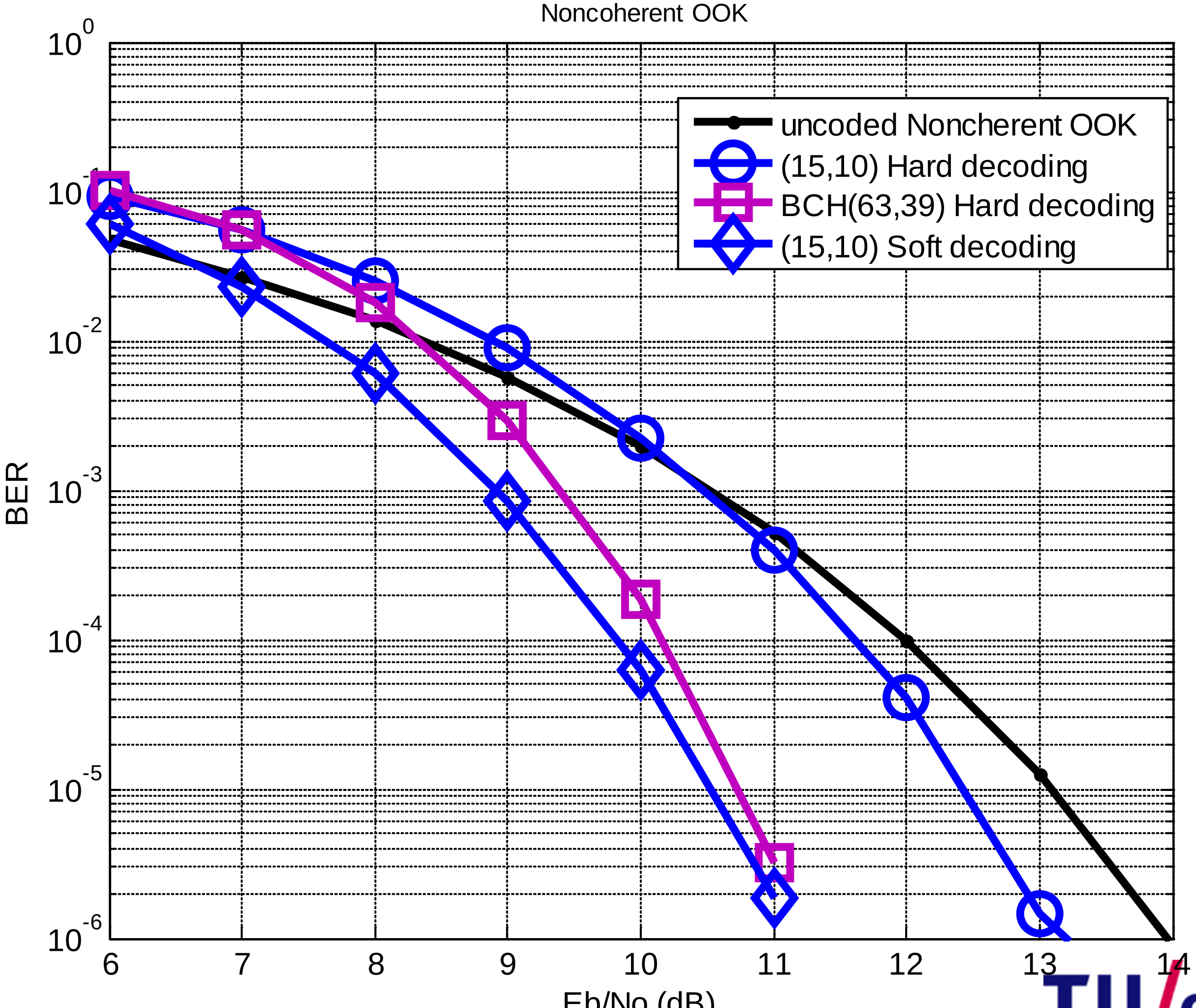
- **Super-regenerative receiver (main radio)**
  - **Low RF power design for on-off keying (OOK)**



- **Noncoherent OOK receiver**
  - **Envelope detection of passband signal**



BER Performance Comparisons



•BCH is preferred ← performance VS complexity

Conclusions and Future work

- **Conclusions**
  - **Discussed Autonomous WSNs**
  - **Global optimum (RF, baseband, modulation, MAC, etc.)**

  - **CWTe-Holst Centre joint project**
    - **Use Zero-IF and WBFSK**
    - **(15,10) Shortened Hamming code can be used for efficient retransmission scheme**
    - **(63,39) BCH code is preferred**

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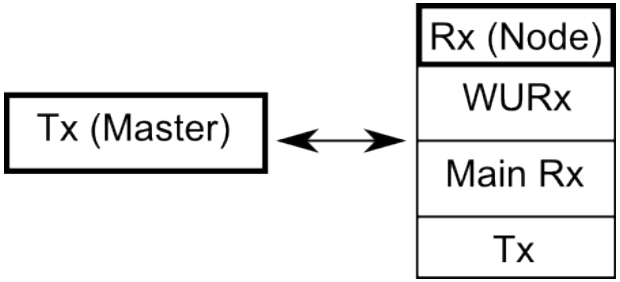
Conclusions and Future work

- **Future work**
  - **Evaluate coding schemes on Holst Hardware**
  - **Investigate coding on WuRx**
  - **Design RF front-end**

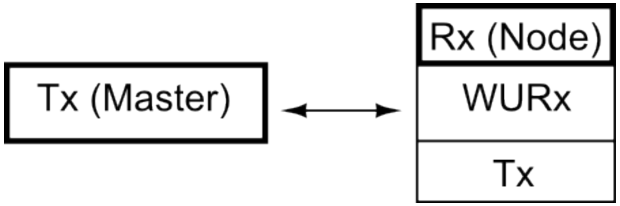
Thanks for your attention

WURx Design-- Scenarios

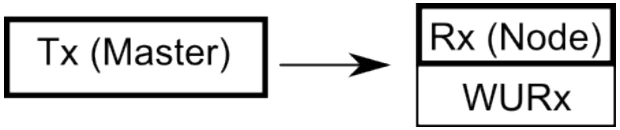
- **<u>Multimedia, ECG, etc.</u>**
- **WURx can't handle bit rate**
- **Main Rx needed**



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

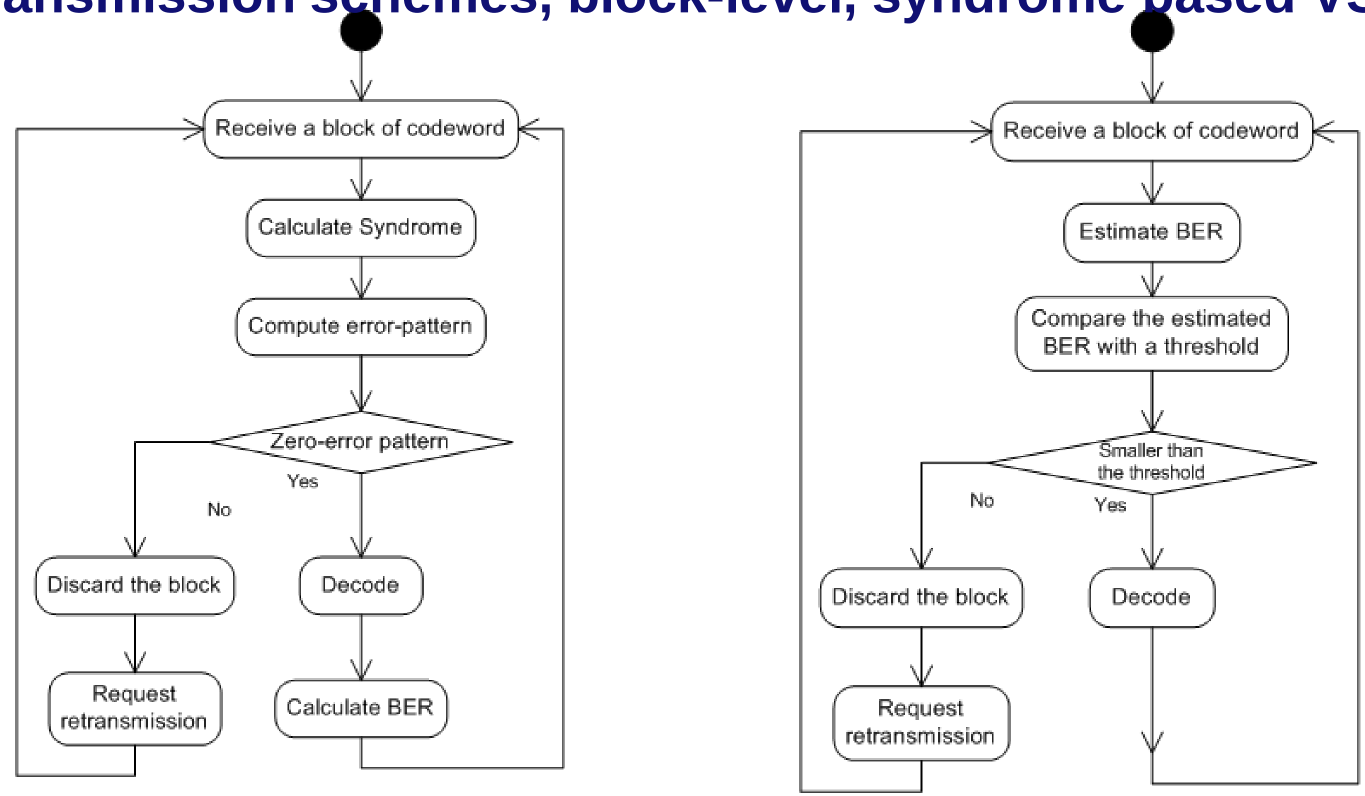


- **<u>Remote control</u>**
- **One-way communication**



Channel Coding

- **Retransmission schemes, block-level, syndrome based VS BCJR based**



•Syndrome based: decode valid codeword; → improved BER→ retrans.time
•BCJR based: Same BER→ retrans.time
•Compare retrans. time