Secure Human Centered Network of Intelligent Devices using Human Body Communication and In-Sensor Analytics

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Birck Faculty Seminar

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Purdue University

Who are we ?

PI: Shreyas Sen

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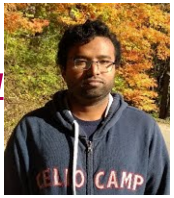
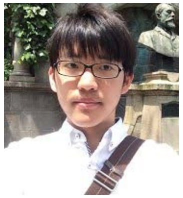
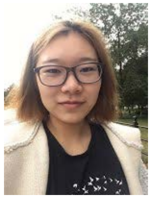
11+ years experience cutting-edge research
Georgia Tech, Intel Labs, Qualcomm, Rambus

SPARC Lab: Sensing, Processing, Analytics & Radio Communication

SPARC Lab:
http://www.shreyassen.info/





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Supported by:

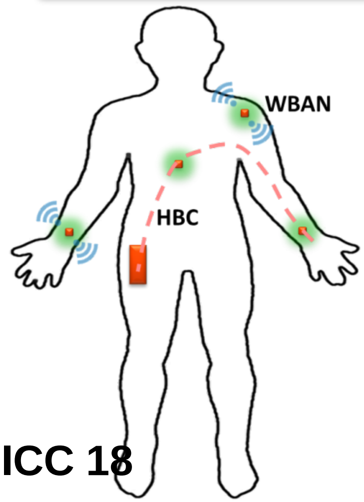
Research Highlights

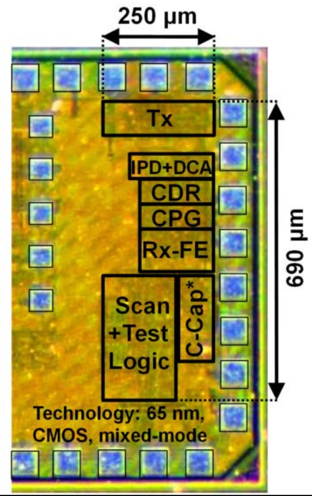
USB-C Type

Intel Labs

ISSCC, JSSC 14

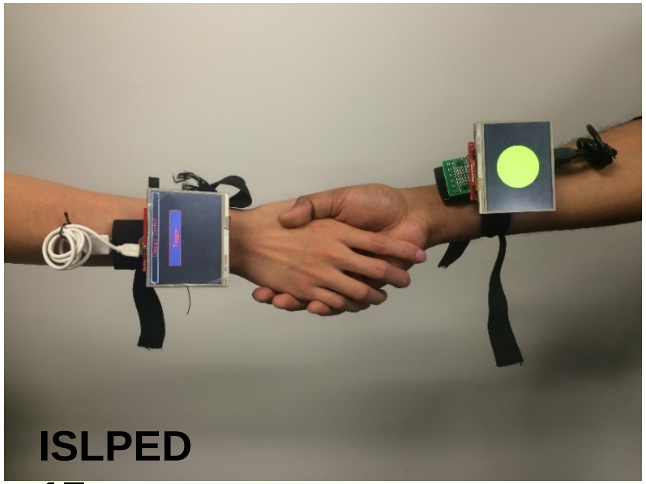
World's lowest energy Human Body Communication





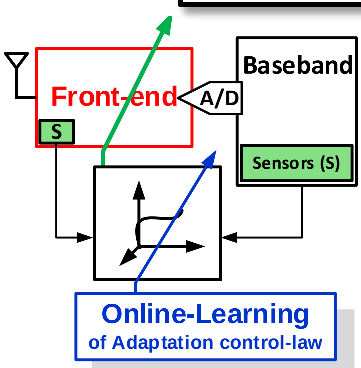
CICC 18

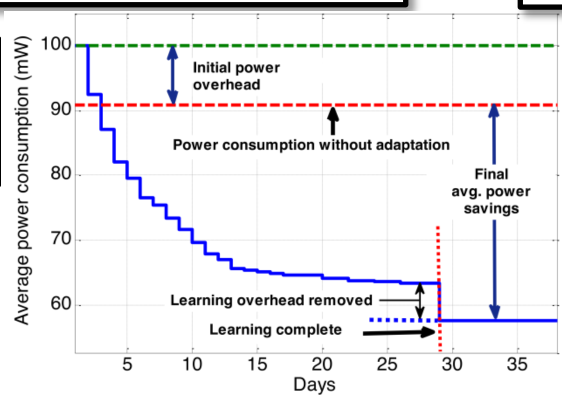
World's first Inter-Human HBC Information Exchange



ISLPED 17

Self-Learning Radio

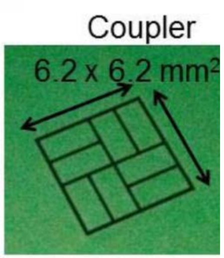


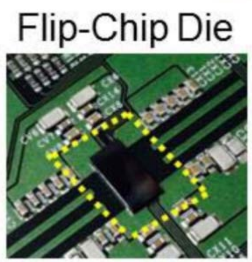


TCAS1

mm-Scale Proximity Communication

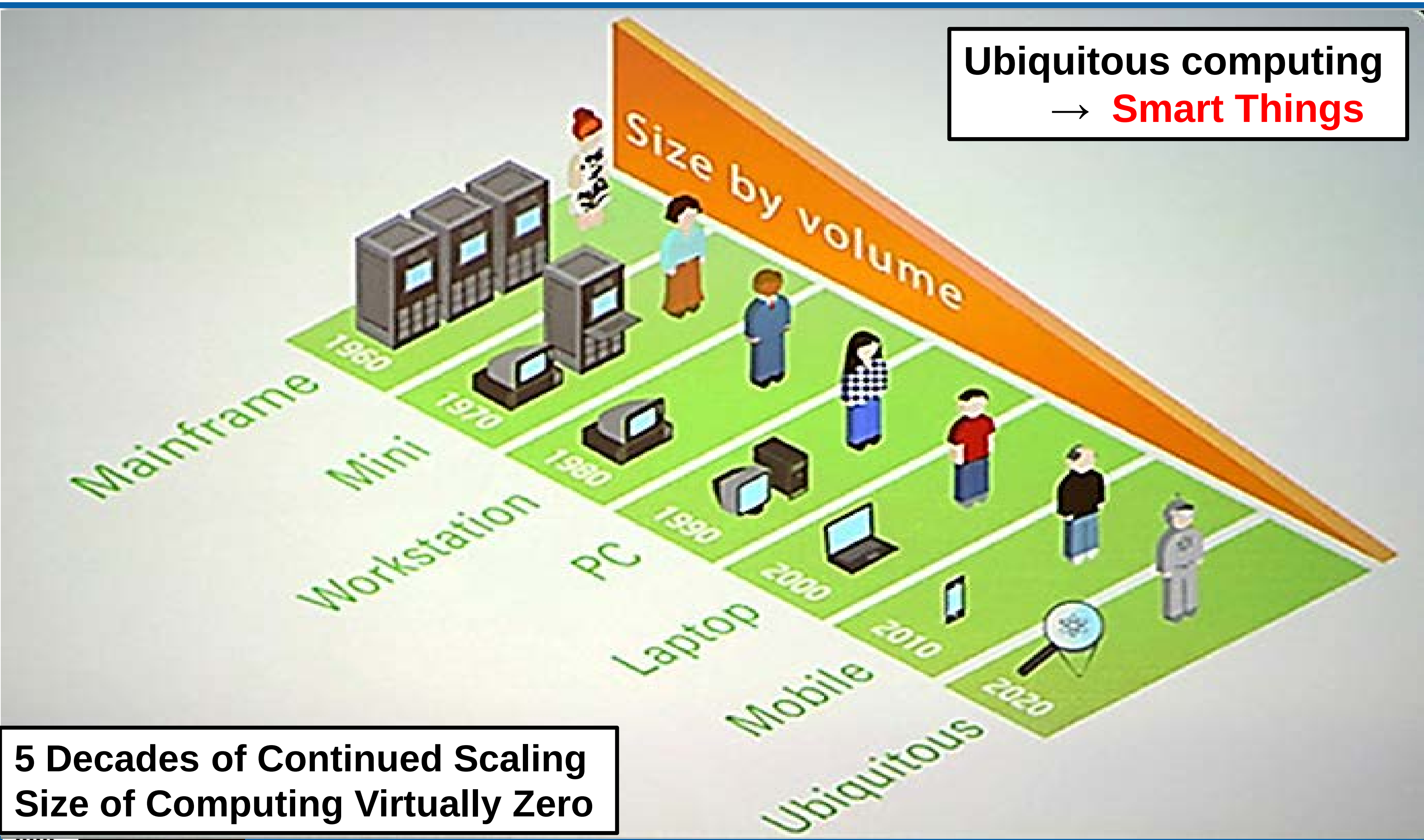
Phone to Laptop/ 2-in-1





ISSCC, JSSC 16

Cheap Computation→ Smartness

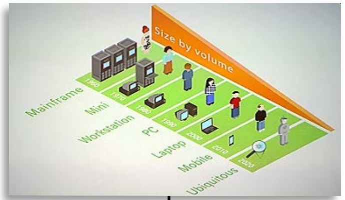


Ubiquitous computing → Smart Things

5 Decades of Continued Scaling
Size of Computing Virtually Zero

Connectivity in IoT

+ Cheap Computing



- Energy Efficiency Security ?

Moore's Law

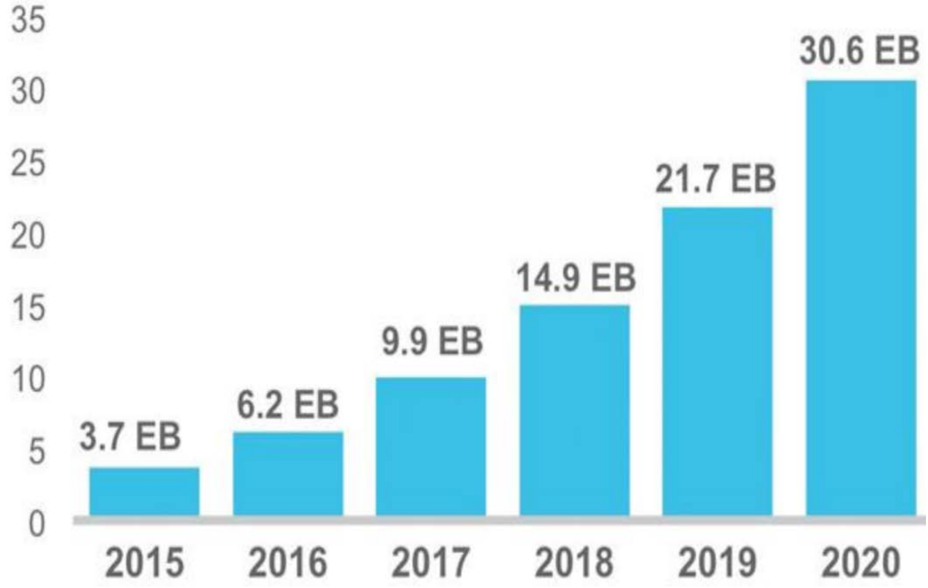
IoT

Shannon's Law

+ Wireless Connectivity

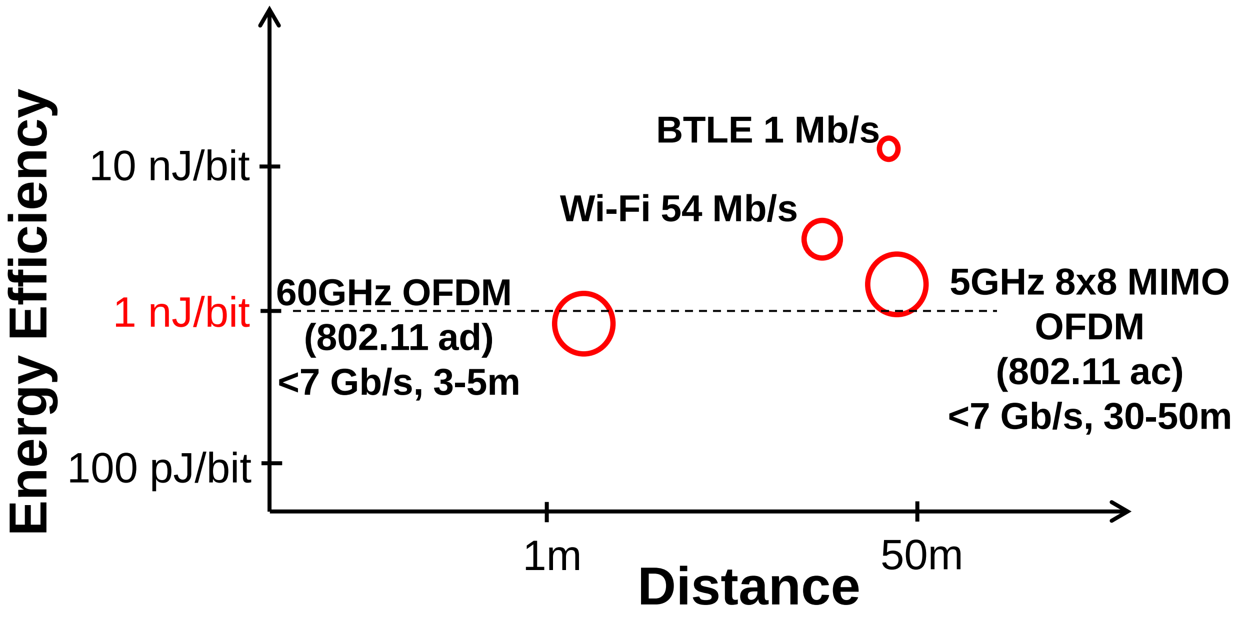
Exabytes of Data per Month

1 Exabyte (EB) = 1 Billion Gigabyte



Energy-Cost of *Connected* Systems

- Typical connectivity: 4G, Wi-Fi, BT, BTLE, WiGig



- Energy-Efficiency > ~1nJ/b

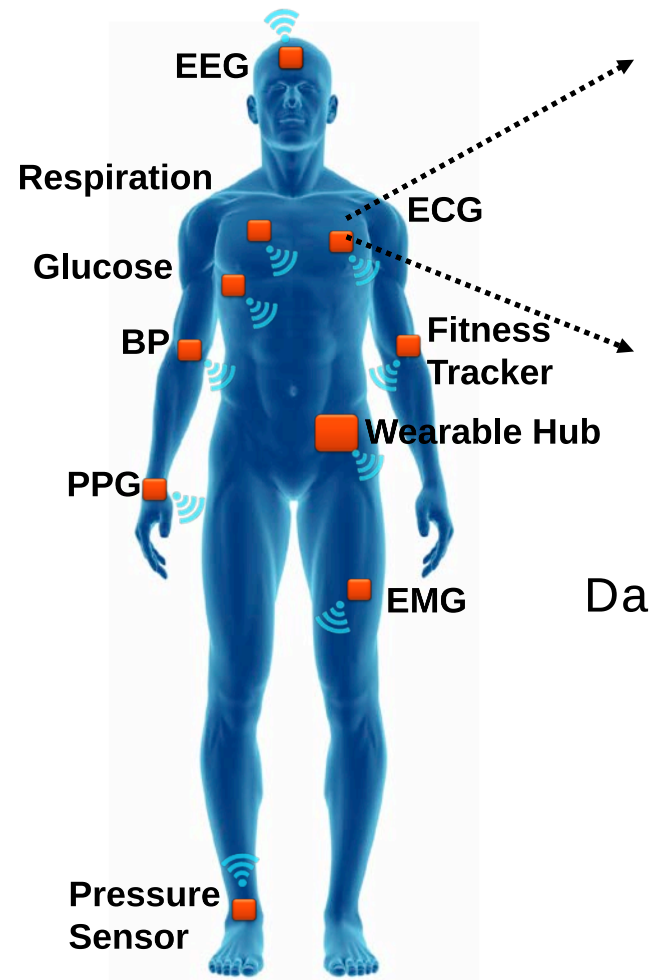
***S. Sen, DAC 16**

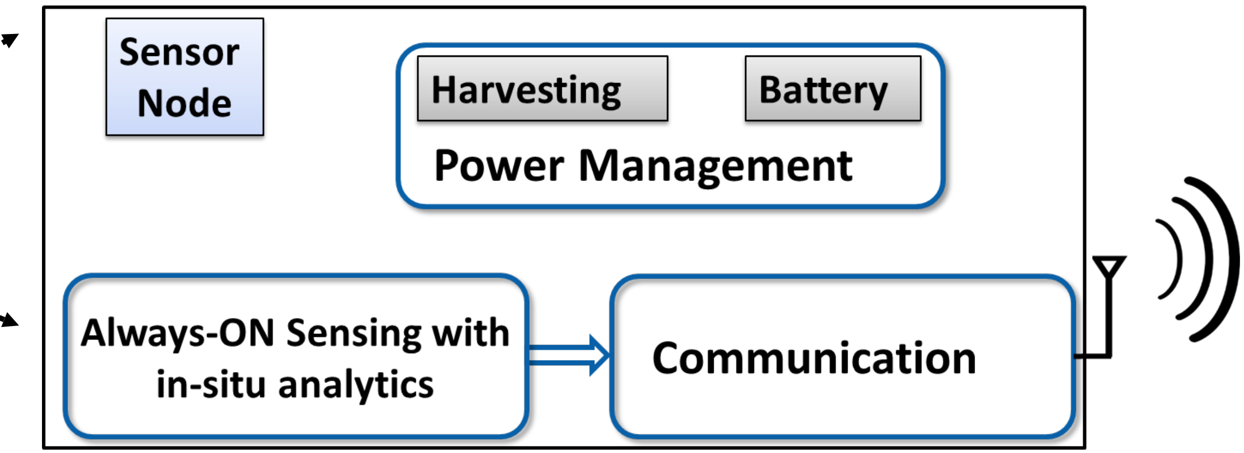
Energy-Gap: *Net-Zero IoT* Sensors

- Sensors with Mbps throughput
  - 1nJ/b, 1 Mb/s → 1mW
    - Small battery will run out in 7.5 days
  - Zero-net energy: runs on harvested energy
    - >10x improvement required

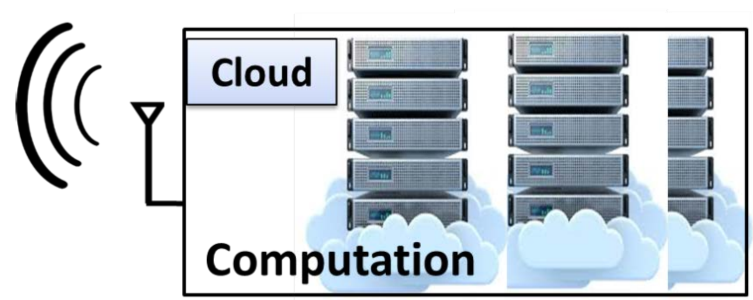
*S. Sen, DAC 16

Present Research Outline





Data Moving from Sensor to Cloud (around human)

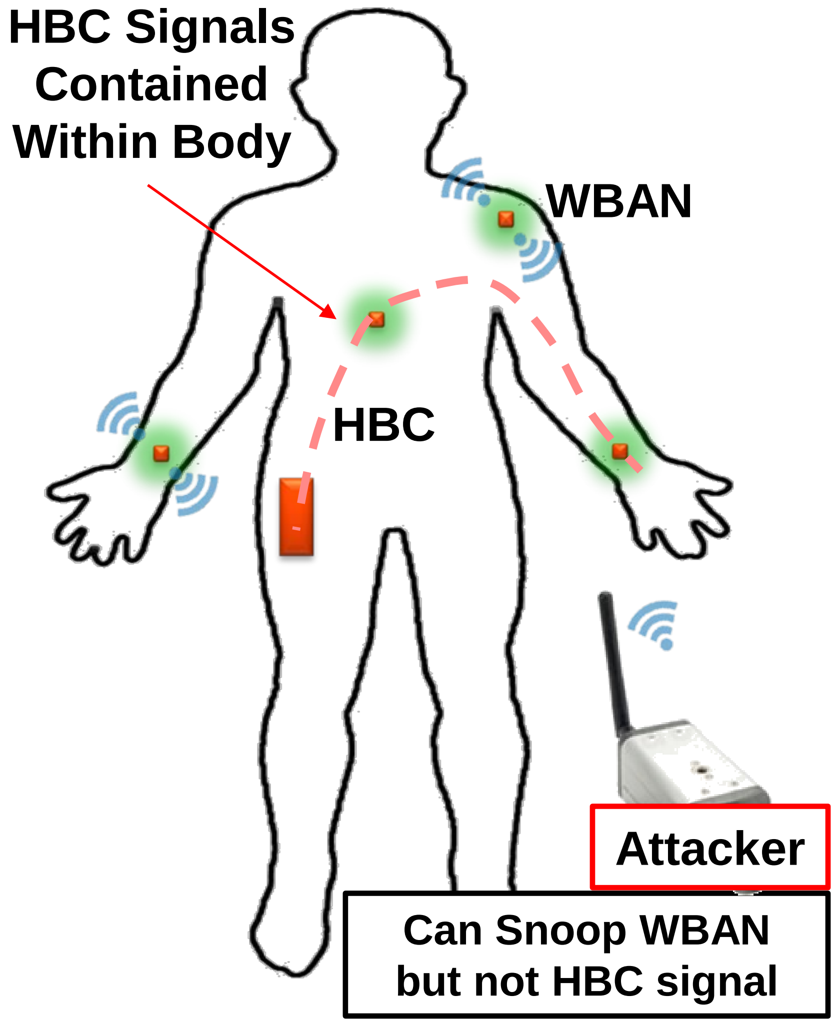


Internet of Body (IoB)

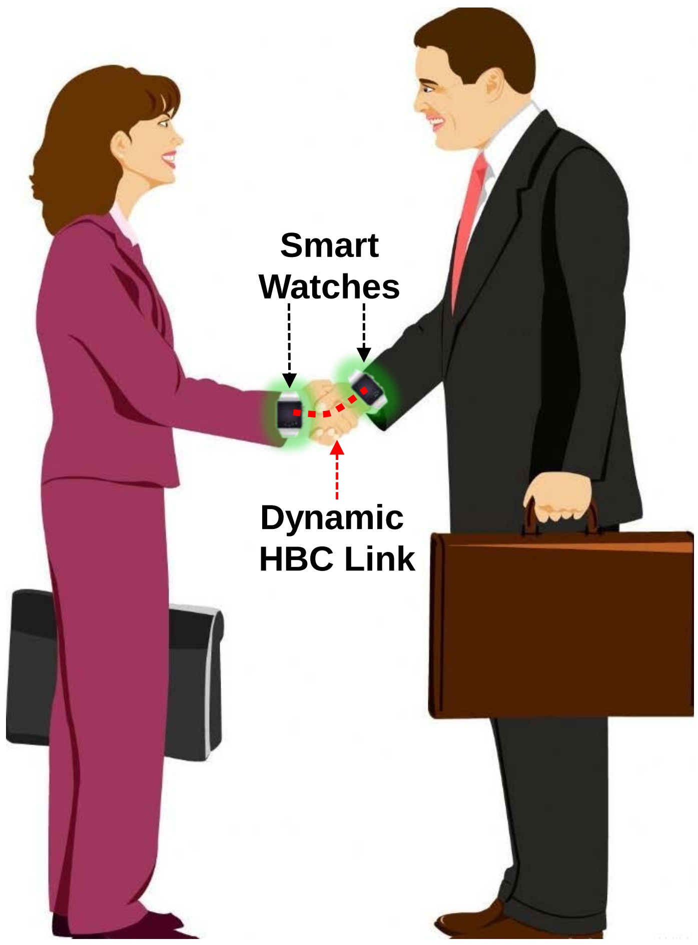
Talk Outline

- Motivation: Internet of Body
- Human Body Communication (HBC)
- In-Sensor Analytics in IoT Sensor Node
- Other Related Work
- Societal Impact of On-device Analytics + HBC

Concept: Human Body as a Comm Medium



Human-Intranet



Human-Internet

Health Monitoring using Human Body Communication (HBC)

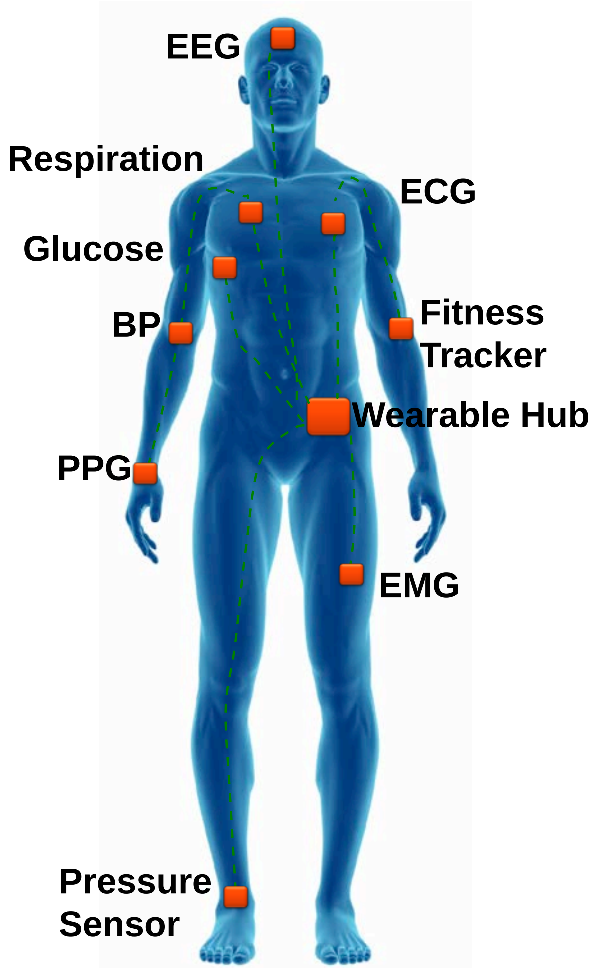
- Human Body Communication:
  Energy efficient , Secure, robust to Inter-Sensor Interference

Comparison

	WBAN	HBC
Secure	✗	✓
Energy-Efficient	✗	✓
Inter-Sensor Interference	✓	✗
Robustness to FM interference	High	Low

Safety

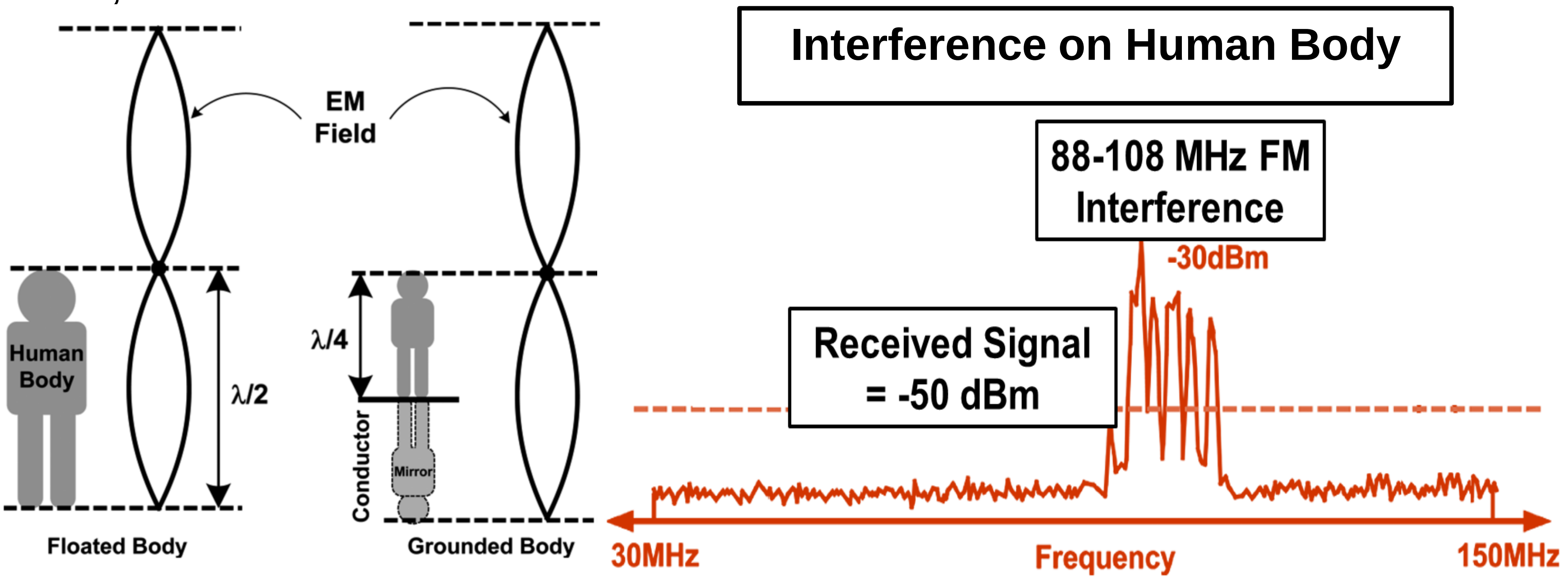
Frequency (f)	Maximum Current (mA)
< 2.5 kHz	0.5
2.5-100 kHz	0.2f
100KHz-110MHz	20
HBC	0.003-0.06



But suffers from environmental interference

Broadband HBC Bottlenecks

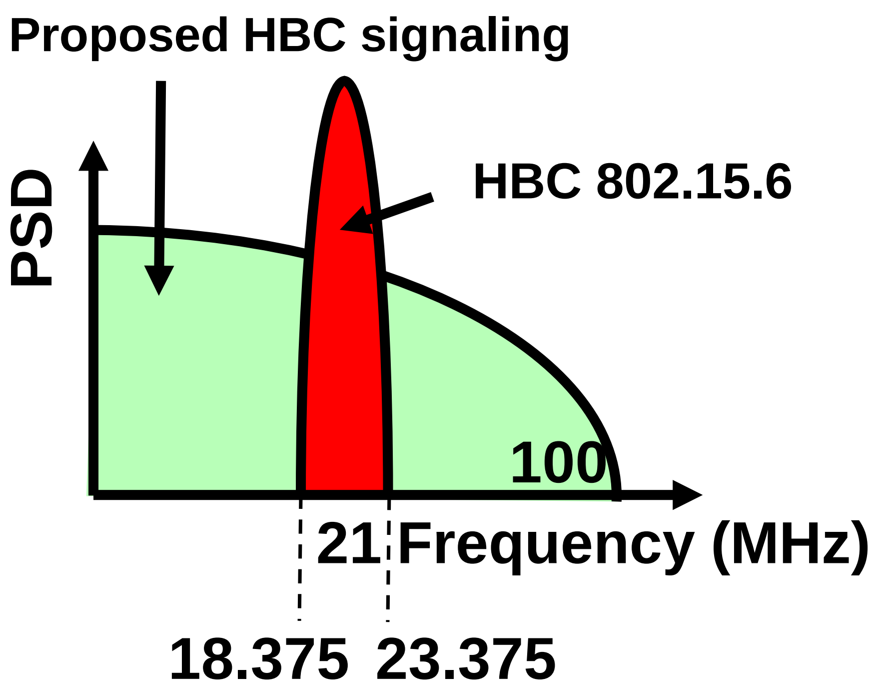
*N. Cho, JSSC 09



- **HBC bottleneck**
  - Human body acts like an antenna in the 40–400 MHz frequency range
  - FM radio frequency band (88–108 MHz) falls in this range

HBC Technology

Broadband HBC

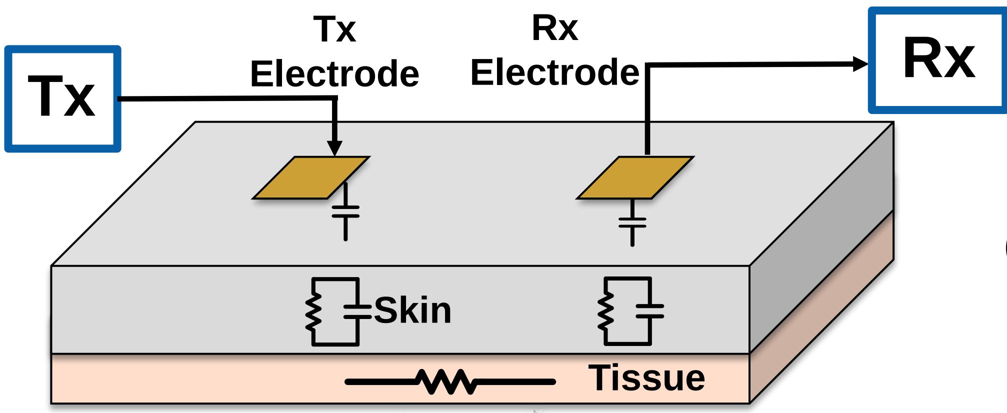


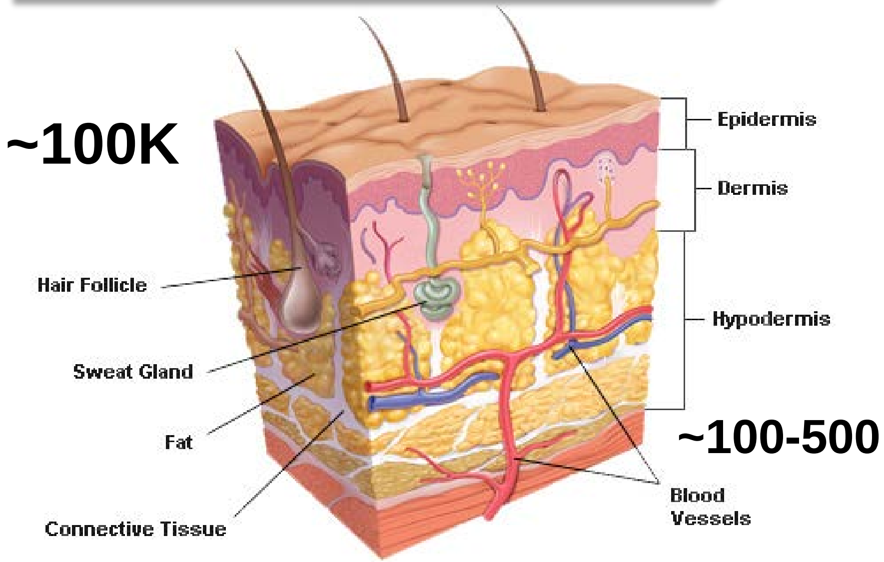
- **IEEE 802.15.6 standard**
  - Narrowband
  - Energy-inefficient (~nJ/b)
- **Proposed HBC Signaling**
  - Broadband
  - Energy-efficient (~pJ/b)
    - No up-conversion and down-conversion
    - Low loss in human body
  - Suitable for energy-harvested sensors

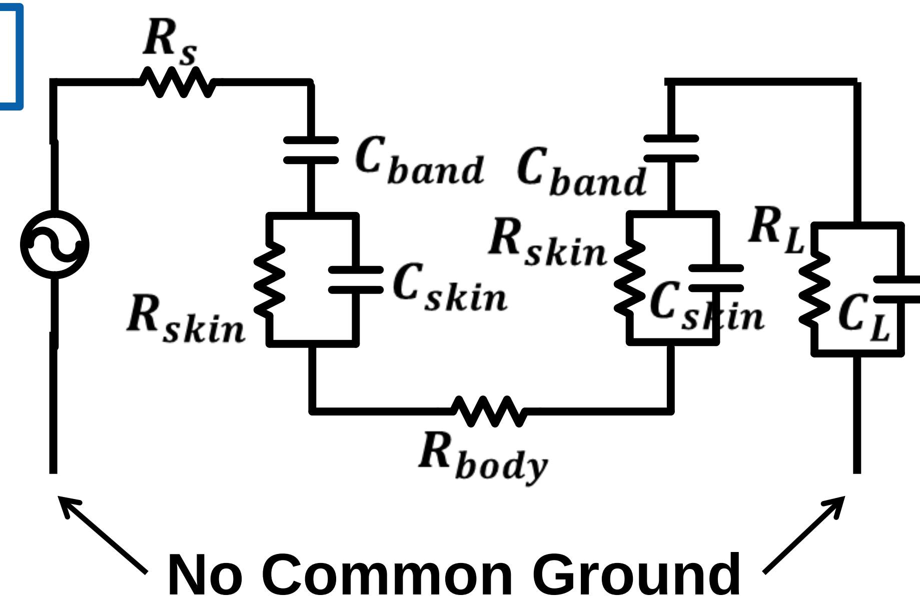
Key enablers of Broadband HBC:

1. Capacitive Voltage Mode HBC
2. Integrating Receiver

Human Body Circuit Model







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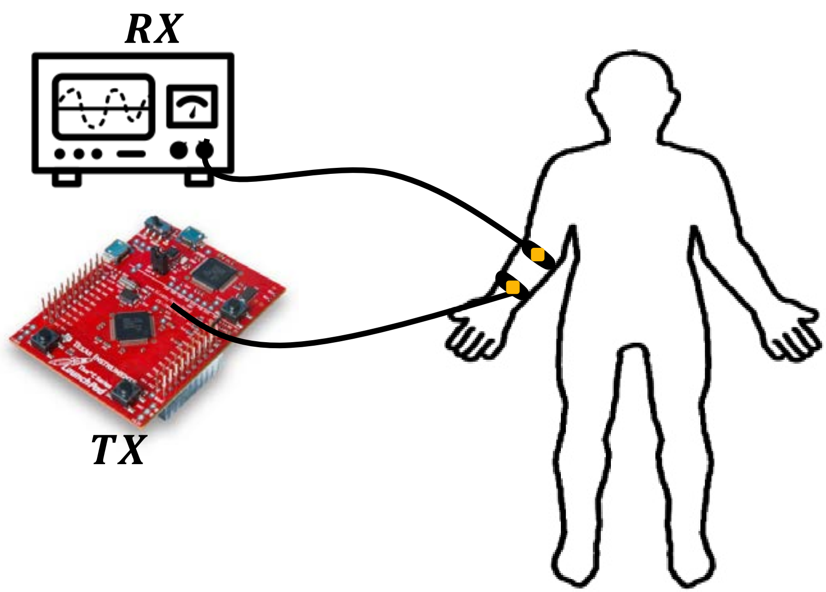
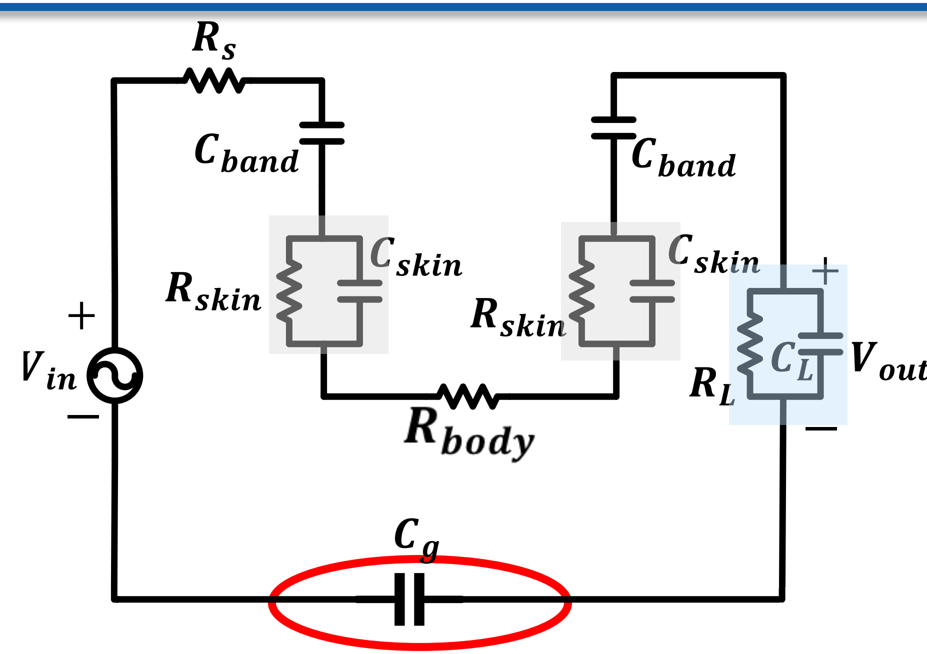
- **Key Question: How is the closed path formed between Tx and Rx?**

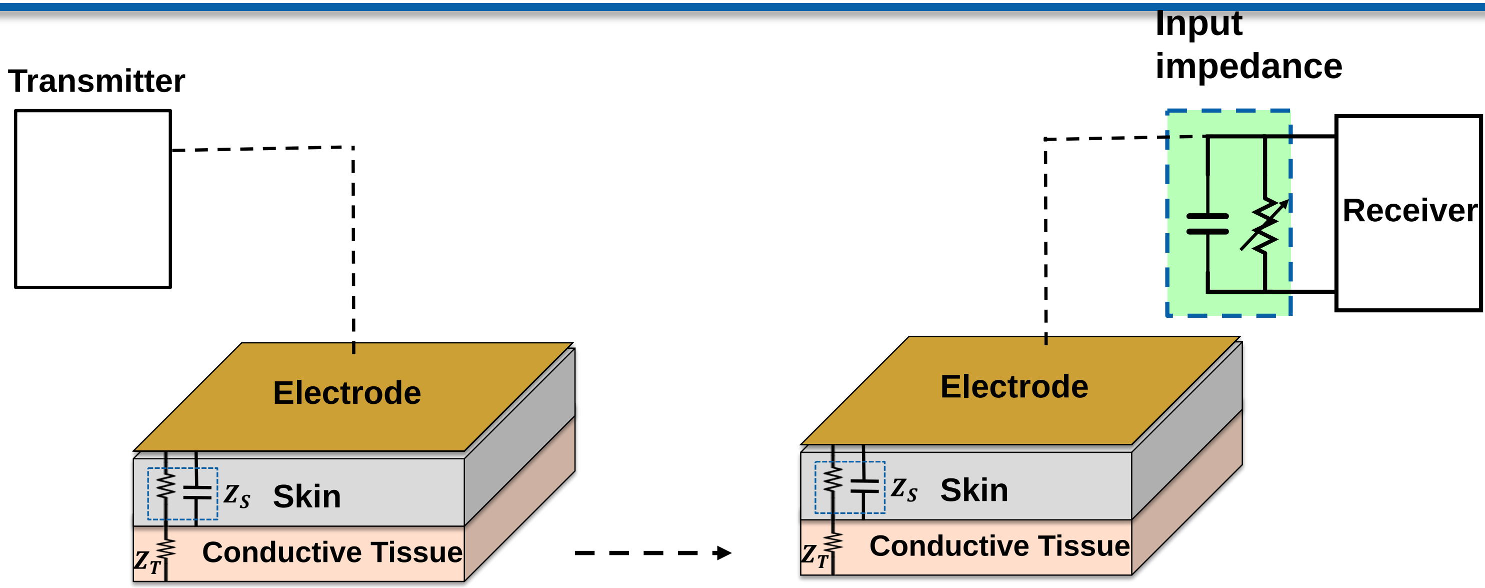
Capacitive HBC: Return Path capacitance





- **How is the closed path formed between Tx and Rx?**
- **Primarily by capacitance formed between transmitter, receiver through the surroundings**

1. Capacitive Voltage Mode HBC (CVM-HBC)



- System Loss dependent on receiver input impedance
- High input impedance → Lower loss

- Capacitive Termination → Flat Frequency Response → Wider BW

$$Channel\ Loss = \frac{V_{rx}}{V_{tx}} \cong \frac{C_{ret}}{(C_{ret} + C_L)}$$

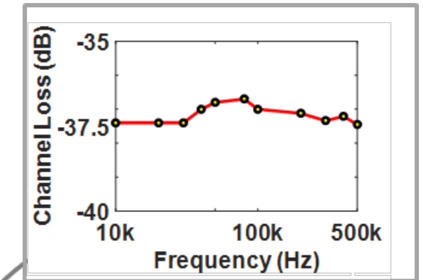
1. Capacitive Voltage Mode HBC (CVM-HBC)

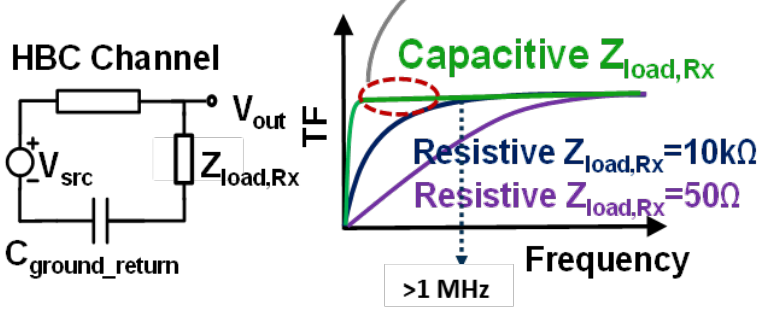
Lower Frequency Loss Reduction by Capacitive Voltage-Mode Signaling

a)

Capacitive Termination:

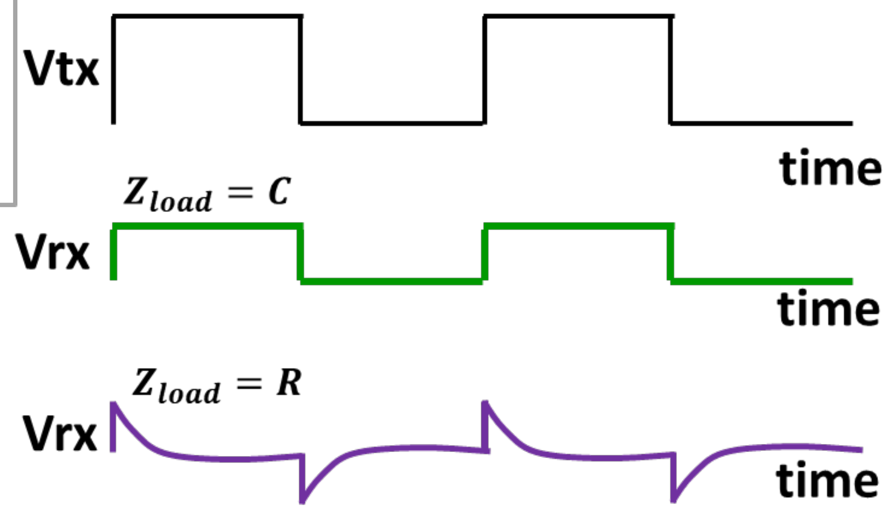
($Z_{load,Rx}$=C) to enable larger Bandwidth BB Channel





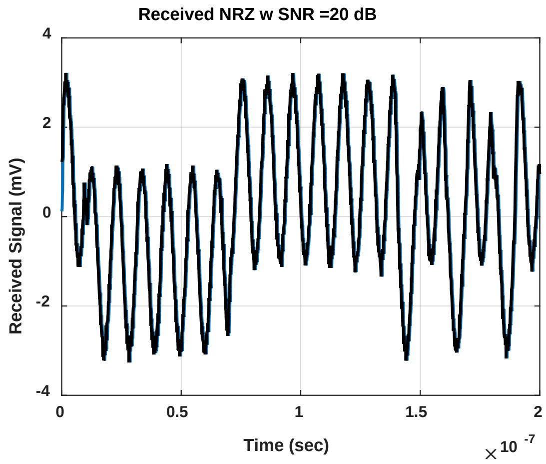
Time-Domain Received Signals

b)

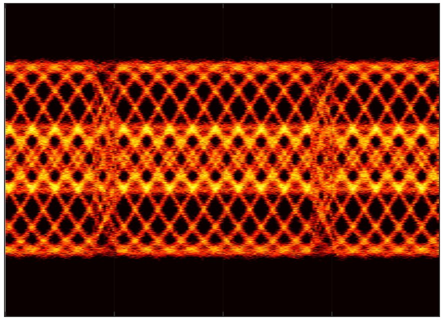


$$Channel\ Loss = \frac{V_{rx}}{V_{tx}} \cong \frac{C_{ret}}{(C_{ret} + C_L)}$$

2. Integrating Receiver (IR-HBC)

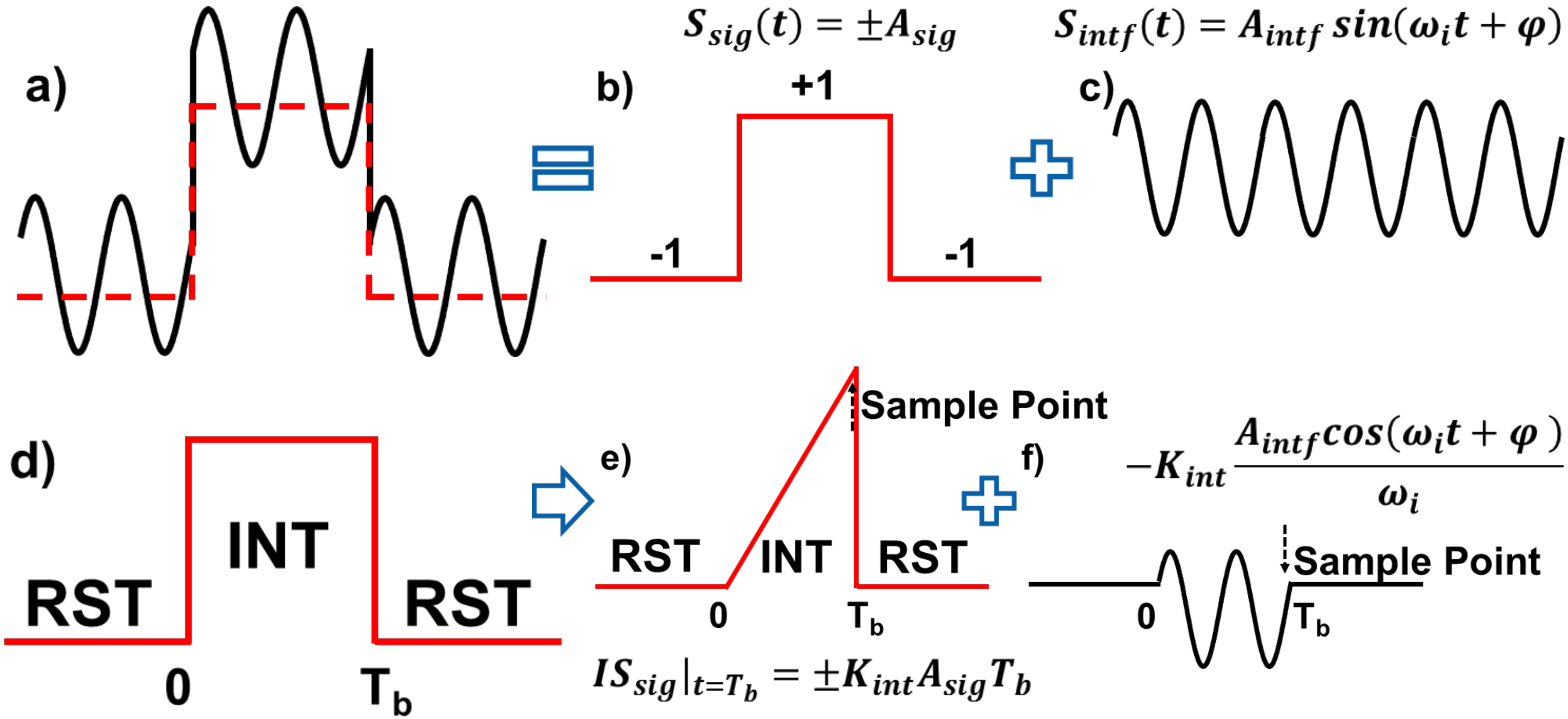


- Non-integrated signal: no eye opening



Solution

Theory: Interference Suppression using Integrating DDR Receiver as Notch Filter

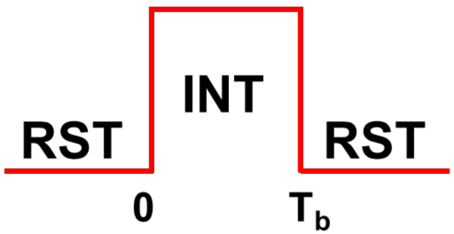


- **Signal :** NRZ signal + CW interference
- **Problem:** $Aintf \gg Asig \rightarrow$ closed eye-diagram $\rightarrow$ impossible to sample accurately
- **Solution:** Integrating for the bit-period (Tb) and then sample

Solution

Working Principle

$\varphi = Arbitrary\ Phase\ Difference$
$Between\ NRZ\ and\ Interference$
$\omega_i = \frac{2\pi}{T_i} = Interfernce\ Frequency$
$K_{int} = Integrator\ Gain$`



$$S_{RX} = S_{sig} + S_{intf} \quad (1)$$

$$S_{sig}(t) = \pm A_{sig} \quad 0 \le t \le T_b \quad (2)$$

$$S_{intf}(t) = A_{intf}\sin(\omega_i t + \varphi) \quad \forall t \quad (3)$$

$$IS_{sig}(t) = \int_0^t S_{sig} = \begin{cases} \pm K_{int}A_{sig}t, & 0 \le t \le T_b \\ 0, & T_b \le t \le 2T_b \end{cases} \quad (4)$$

$$IS_{intf}(t) = \int_0^t S_{intf} \quad (5)$$

$$= \begin{cases} -K_{int}\frac{A_{intf}\cos(\omega_i t + \varphi)}{\omega_i}, & 0 \le t \le T_b \\ 0, & T_b \le t \le 2T_b \end{cases}$$

$$IS_{sig}|_{t=T_b} = \pm K_{int}A_{sig}T_b \quad (6)$$

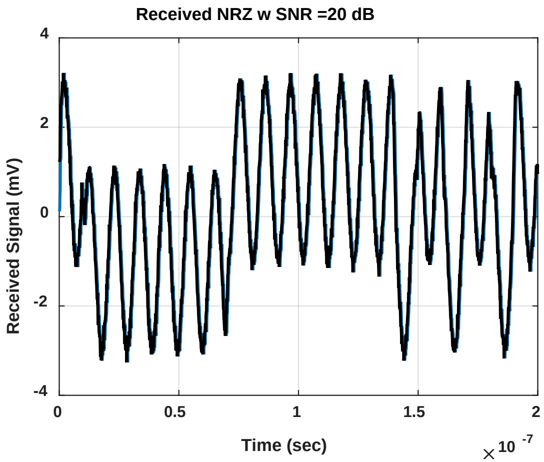
$$IS_{intf}|_{t=T_b} = K_{int}\frac{A_{intf}[\cos(\varphi) - \cos(\omega_i T_b + \varphi)]}{\omega_i} \quad (7)$$

$$= K_{int}\frac{A_{intf}\left[\cos(\varphi) - \cos\left(2\pi\frac{T_b}{T_i} + \varphi\right)\right]}{\omega_i} \quad (8)$$

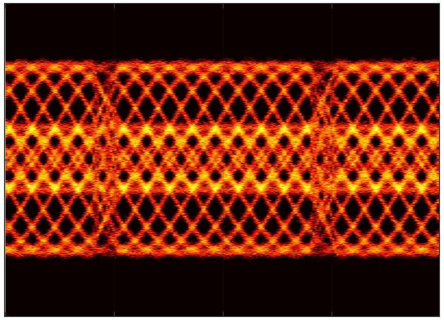
$$= 0, \quad \forall\ T_b = nT_i;\ n = positive\ integer$$

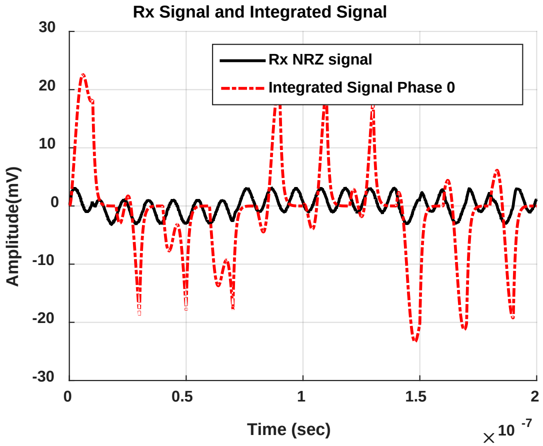
2. Integrating Receiver (IR-HBC)

- Integration at the receiver → reduces effect of environmental interference

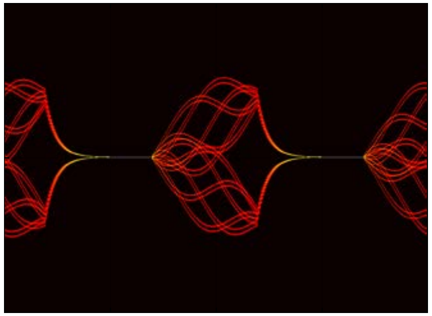


- Non-integrated signal: no eye opening



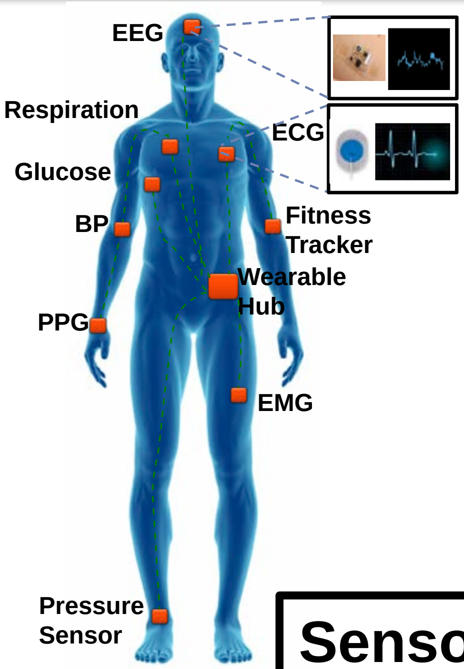


- Integrated Signal: clear eye opening

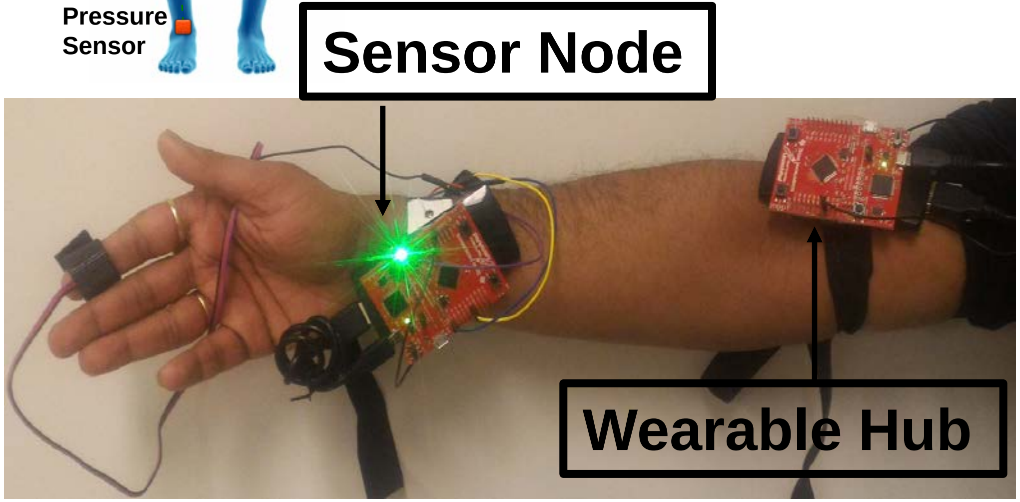


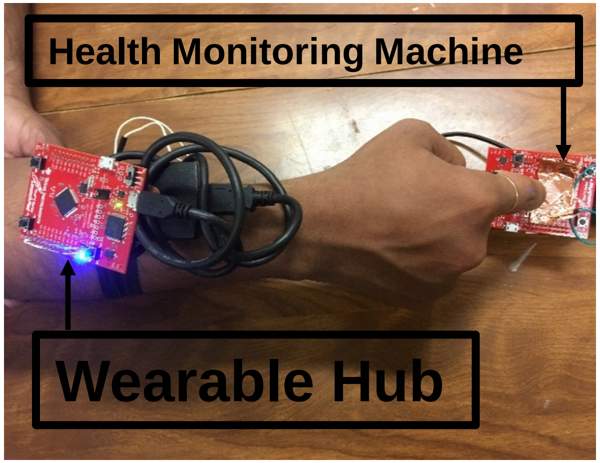
*S.Sen, ISLPED 16, *S. Maity, DATE 17

Application: HBC based Health Monitoring

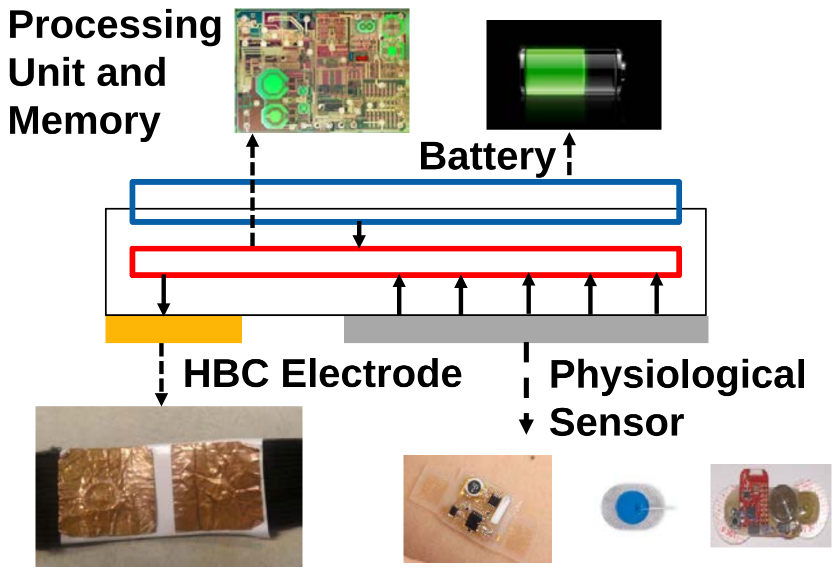


- **Intra-body health monitoring**: transmission of data from sensors to Wearable Hub
- **Human Machine Interaction**: health data upload from Wearable Hub to Health Monitoring Machine





Wearable Health Monitoring Node



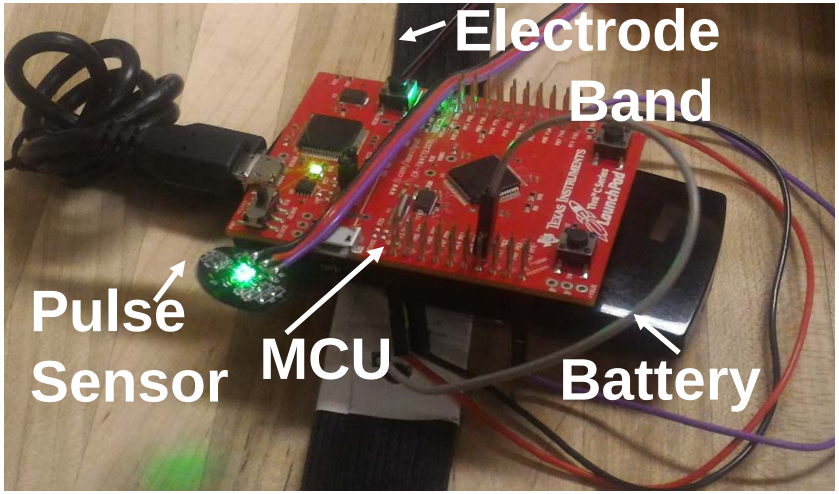
Sensor Node: Collects physiological data

- Physiological sensor: Acquires physical data
- Processing Unit: Processes data from sensors
- HBC electrodes: coupling signal to and from the body
- Battery: Source of power, **very limited due to small size**

Wearable Hub: Aggregates data, sends for further analysis

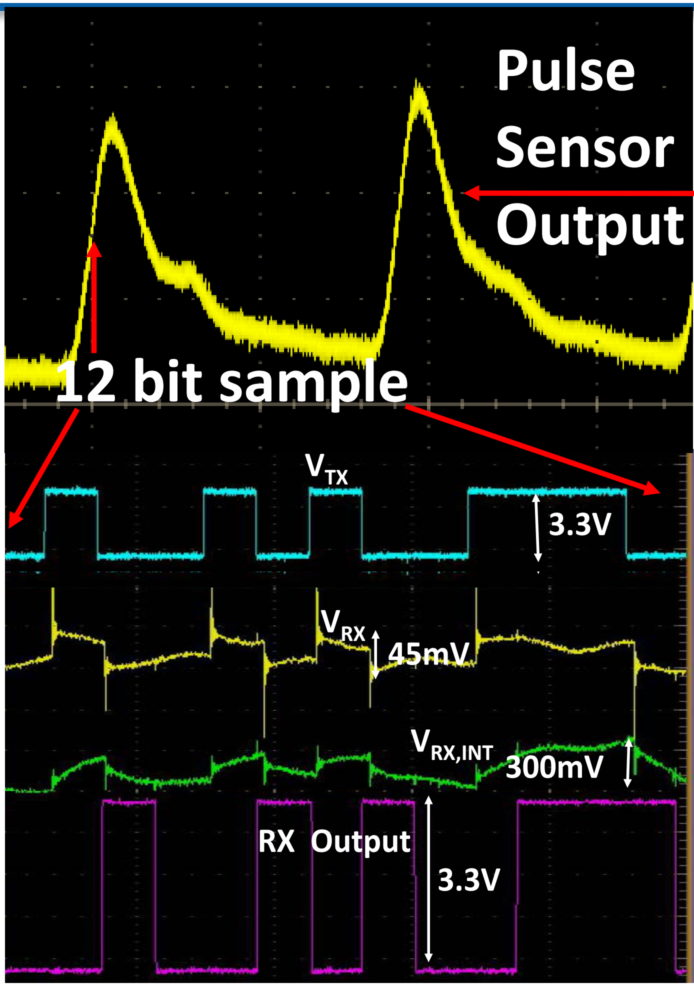
- Battery: Bigger battery, higher battery life

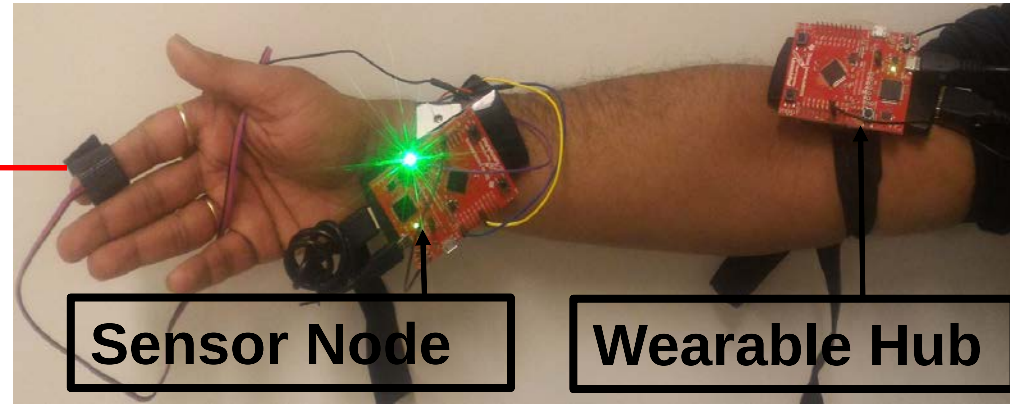
Wearable Health Monitoring Node: Implementation



- Processing Unit: TIVA-C 123GXL Microcontroller Unit (MCU)
- Battery: Rechargeable Li ion battery
- Physiological Sensor: Pulse Sensor

Signal Transmission Characteristics





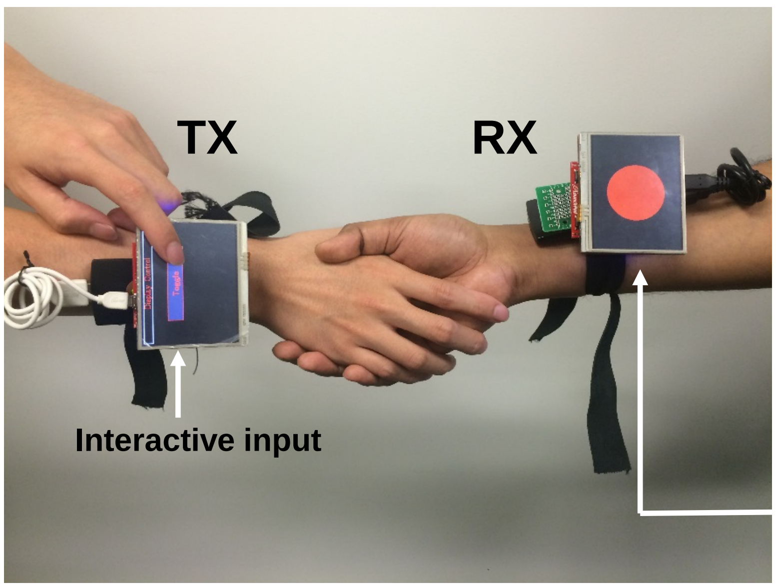
- Pulse Sensor output is digitized using a 12 bit ADC
- Digitized signal transmitted, amplitude : 3.3V
- Received signal amplitude 45mV
- Signal integrated to reduce effect of environmental interference
- Integrated signal decoded in digital domain

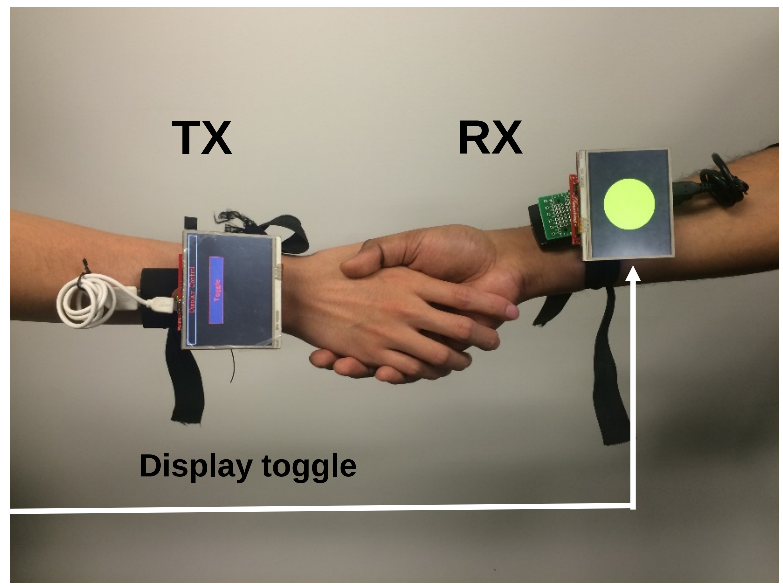
Type of HBC	Rx signal Amplitude (mV)	Loss (dB)
Intra-body HBC	45	37.3
HBC-HMI	57	35.2

Dynamic HBC

Application: Business Card/Password Exchange

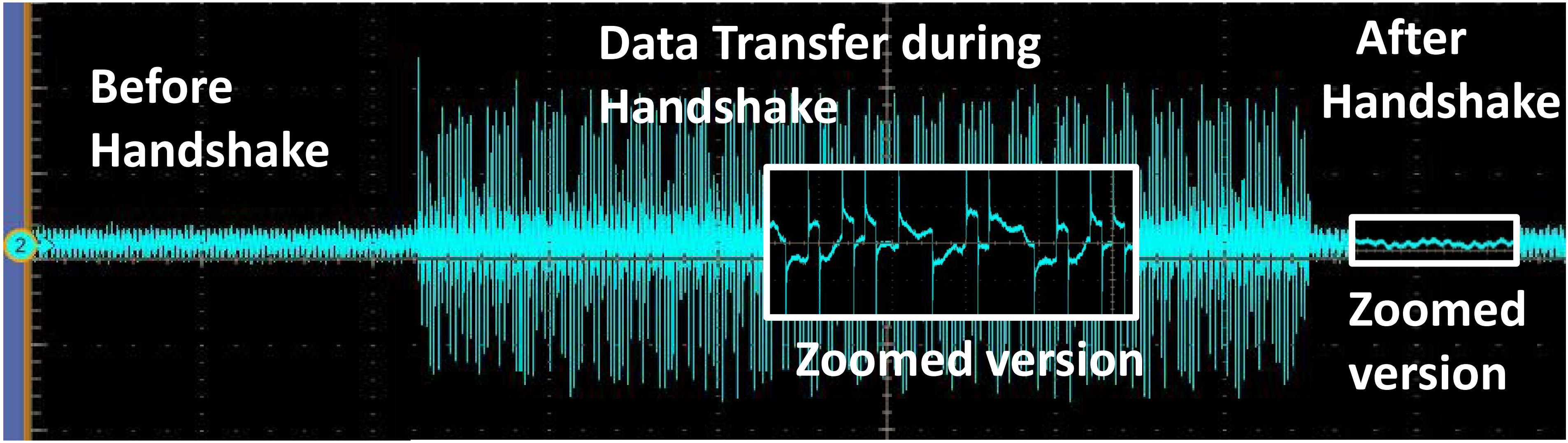
- Interactive input provided by user to toggle display
- A series of bit sent by transmitter and decoded by the receiver





Dynamic HBC: Data Transfer

- Transient Signal Characteristics : data transfer during a handshake event

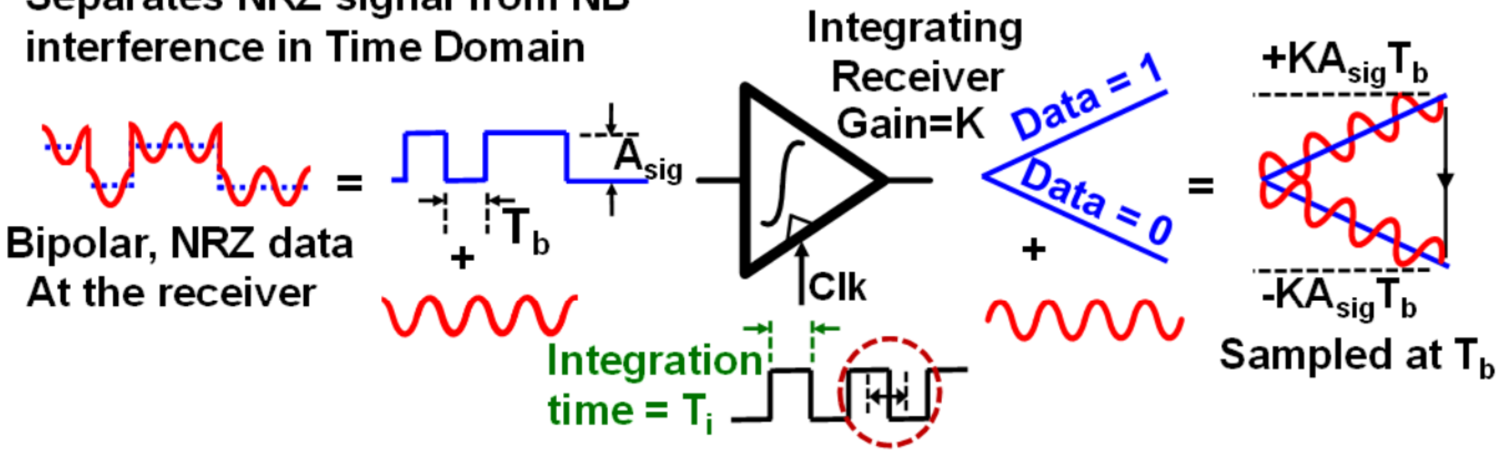


>100X LOWER-ENERGY BAN

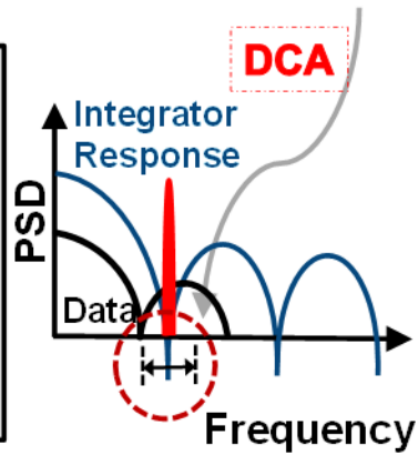
IC Details

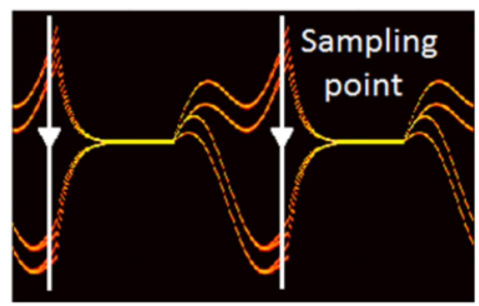
Integrating Receiver:

Separates NRZ signal from NB interference in Time Domain



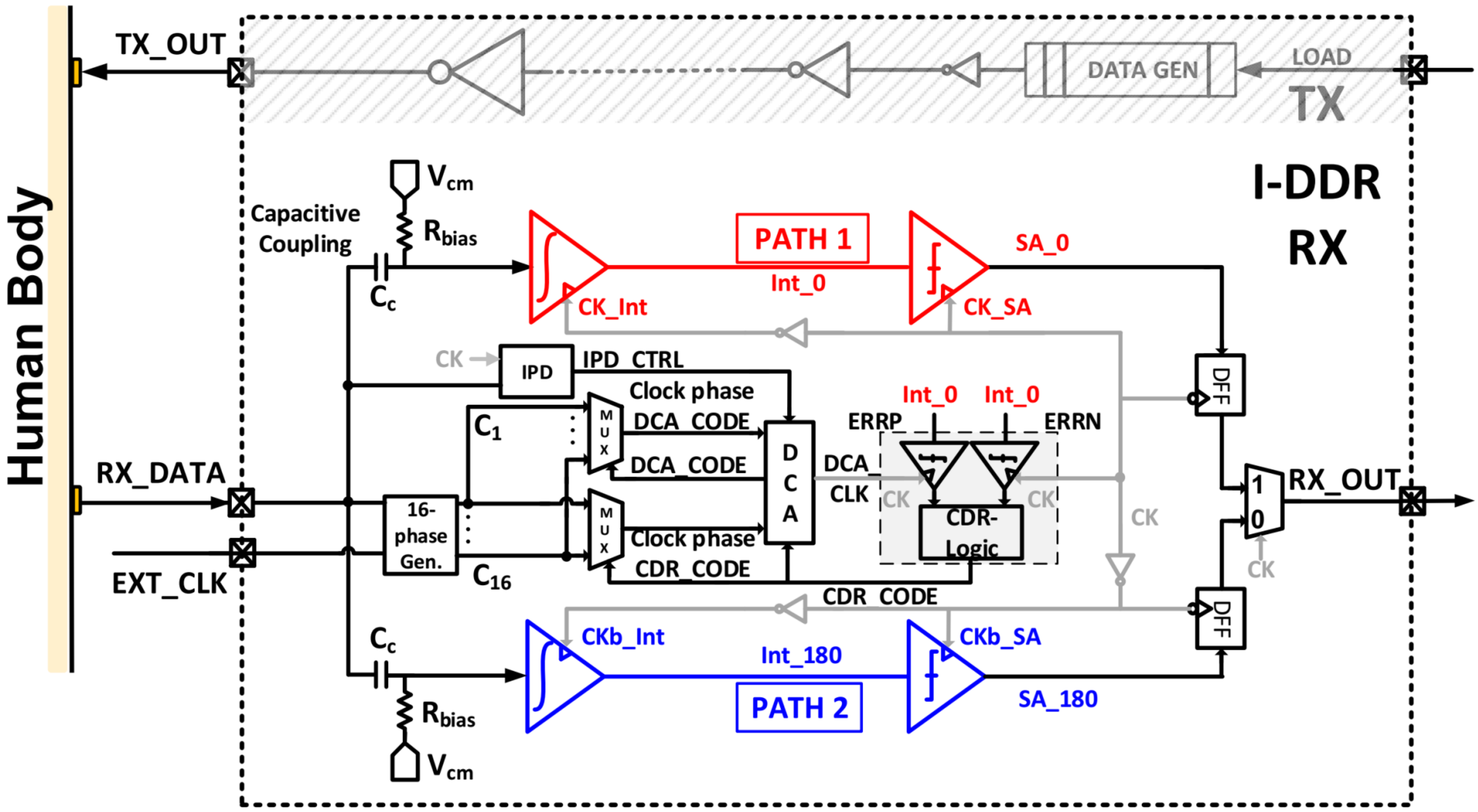
Duty cycle adaptation of Integrating clk ⇒ Moves the TF notch ⇒ Suppresses interference frequencies which are both integral or non-integral multiples of data rate (DR)



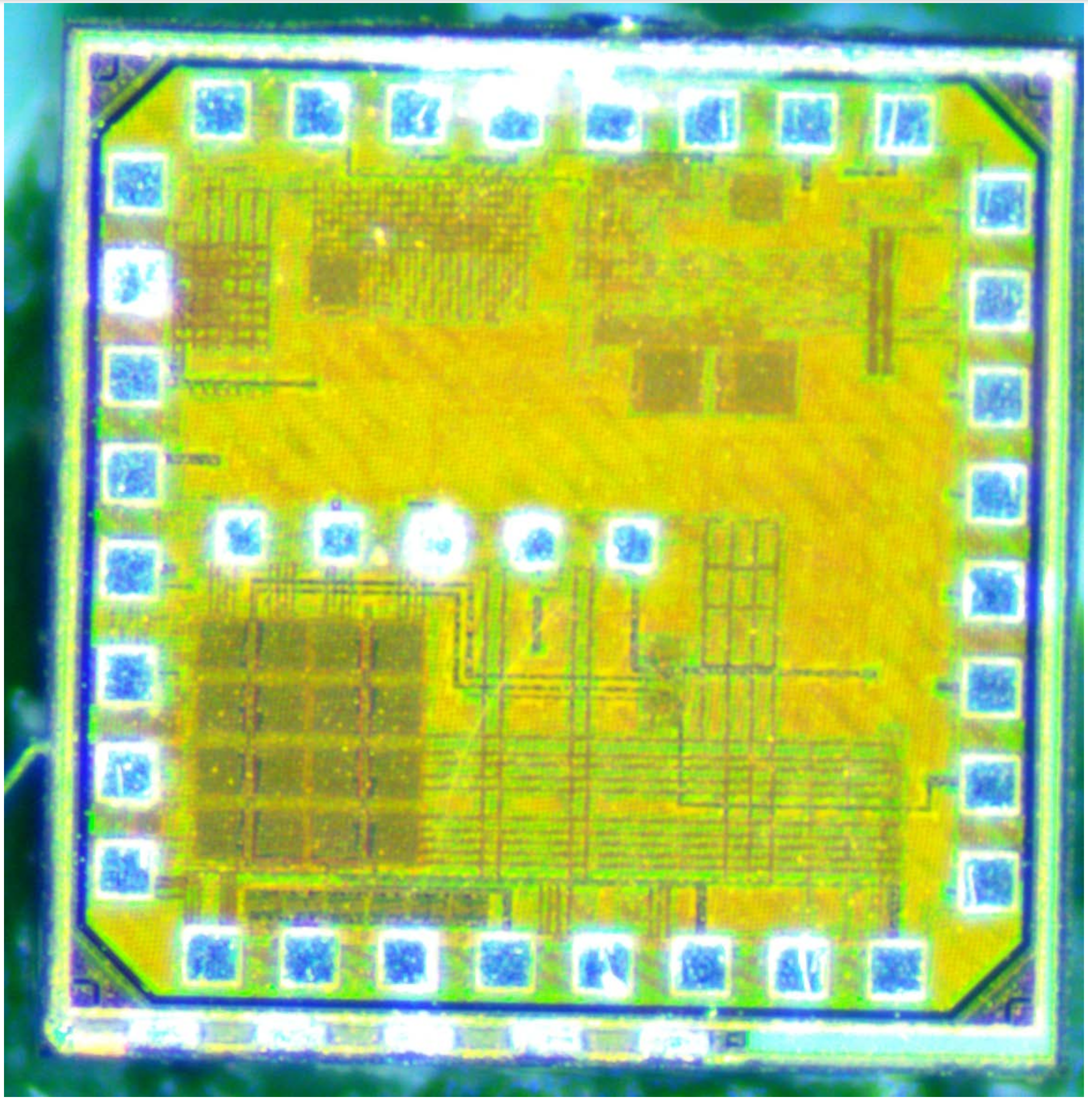


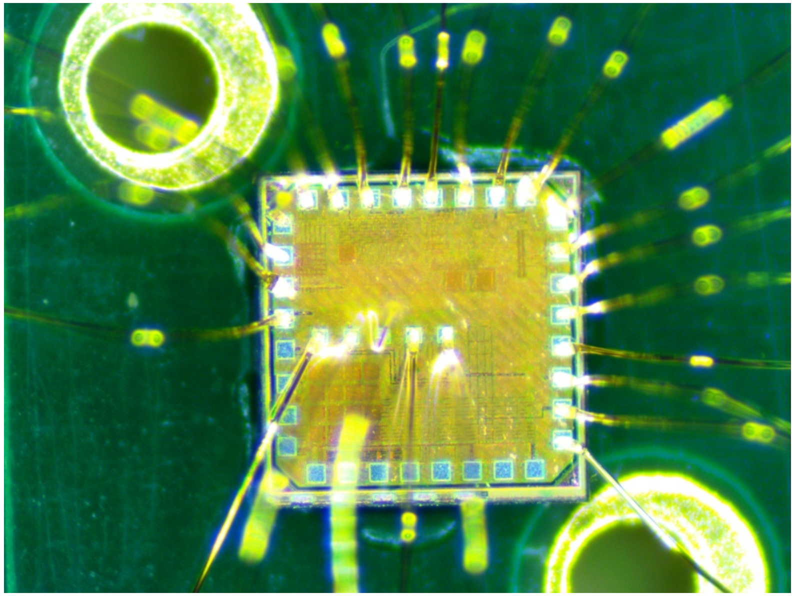
Integrated Eye With Interference

IR-HBC Overview



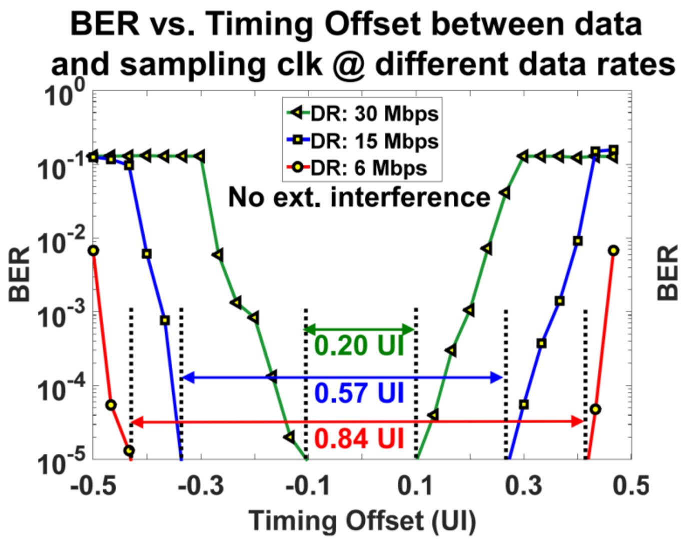
Fabricated Die (65nm Die)

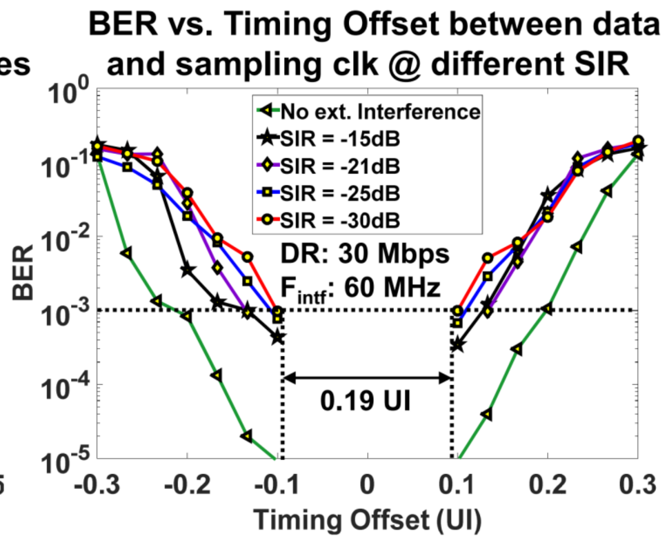


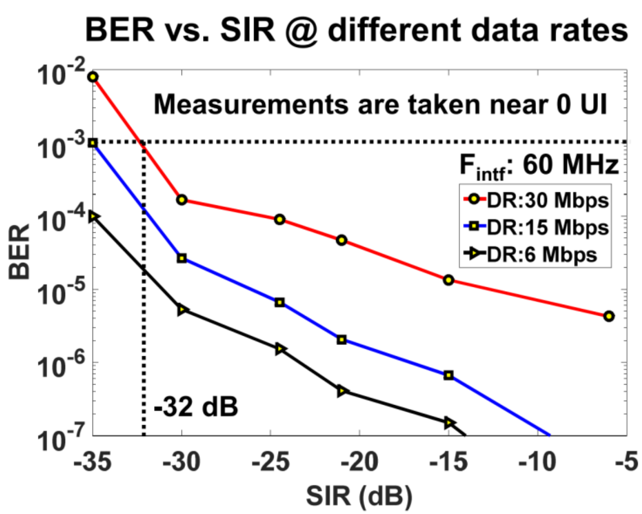


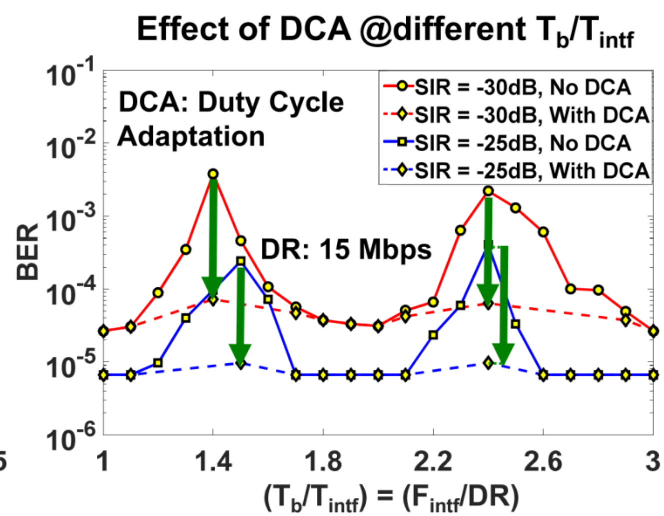
Wire bonding: Thanks Birck!

Measurement Results



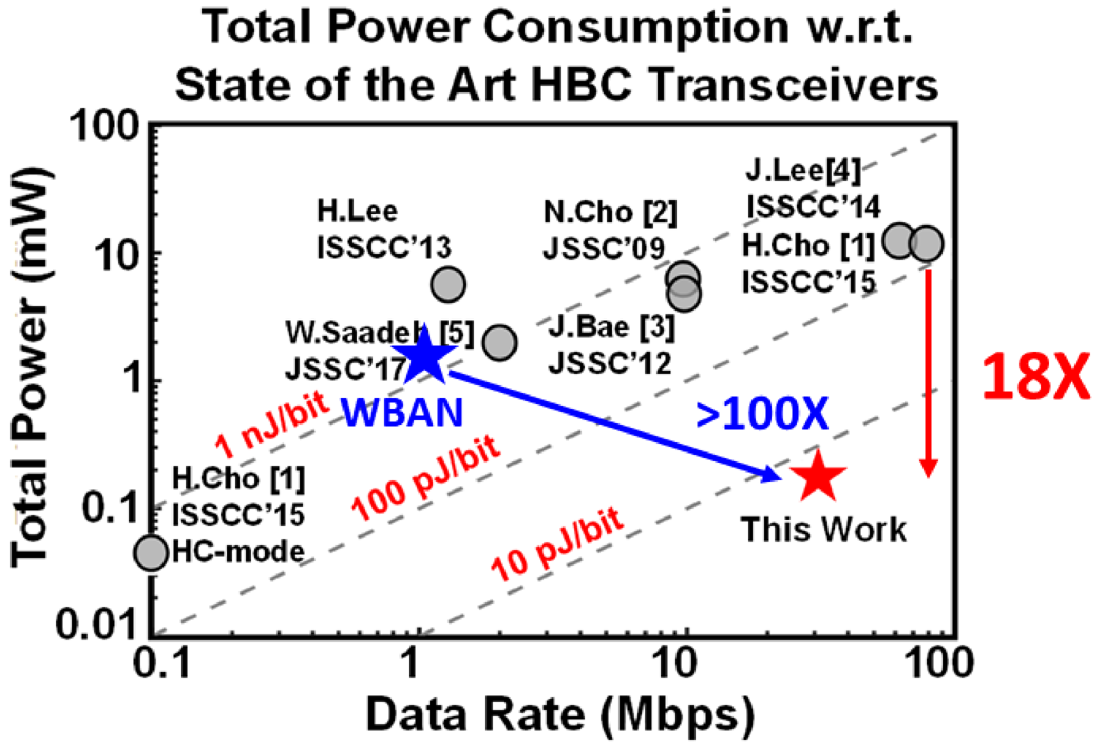






IR-Human Body Comm (6.3 pJ/b)

- **SparcLab recent results (world record: 18x more efficient HBC th**
  - **30 Mbps, 6.3pJ/b Transceiver (3.2 pJ/b Rx only measured)**
  - **-30 dB SIR tolerance**
  - Comparison: WBAN ~ 1nJ/b



CICC 18

Our Work in the News and Radio

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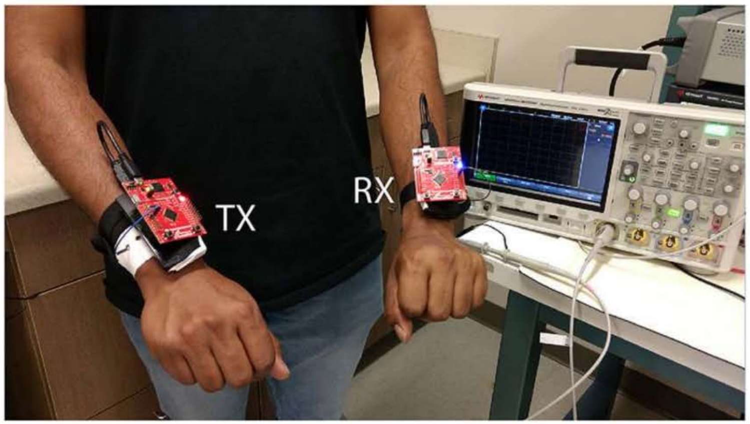
Home » Technology » Engineering » December 14, 2017

Discovery clears way for human body to work as robust communication network for electronic devices

December 14, 2017, Purdue University



Smart wearable devices allow for the exchange of information using the human body as a robust communication medium for networking electronic devices. In this photo, a researcher wears devices that allow for the exchange of information using … more

A group of Purdue University researchers have discovered a new way to use the human body as a robust communication medium for networking electronic devices in and on the body that promises to be far more s… and low-energy than any wireless system.

PHYS ORG

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S & P 500	NASDAQ 100	DJIA	NIKKEI 225
16.36	60.57	91.69	-20.00
2,712.17 (0.61%)	6,571.91 (0.93%)	24,915.70 (0.37%)	22,575.00 (-0.09%)
03:59:04 PM EST	03:59:04 PM EST	03:59:04 PM EST	11:07:32 PM EST 12/8/2017

Purdue discovery clears way for human body to work as robust communication network for electronic devices

PRESS RELEASE GlobeNewswire

Dec. 14, 2017, 10:39 AM

SHARE

West Lafayette, IN, Dec. 14, 2017 (GLOBE NEWSWIRE) -- A group of **Purdue University** researchers have discovered a new way in using

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Researchers Use Human Body As Communication Network

By JILL SHERIDAN • DEC 29, 2017

Coverage: 30+ News Sites

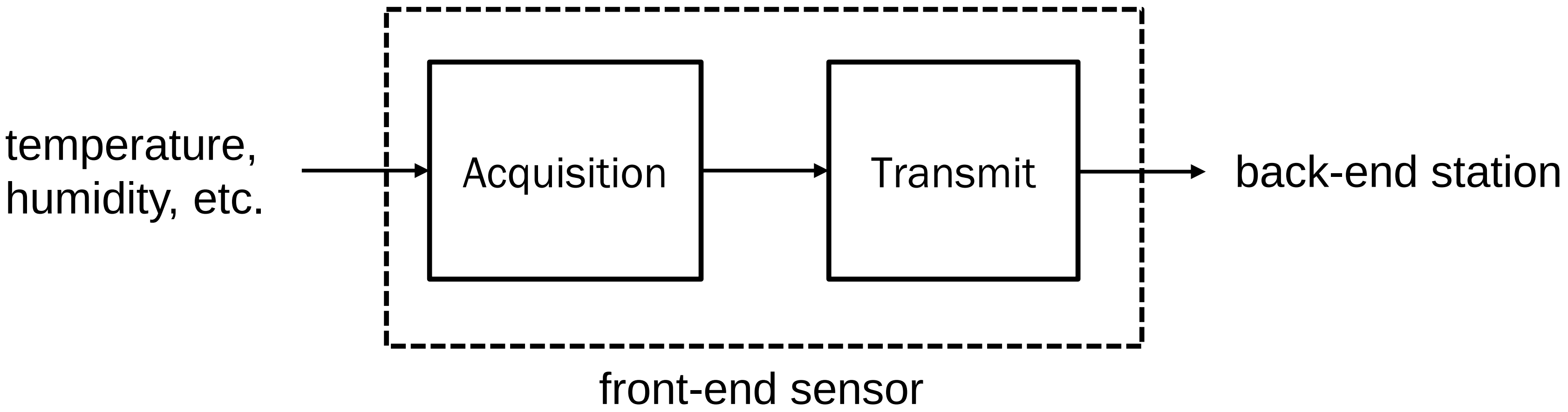
WBOI/NPR/BBC

BUSINESS INSIDER

Talk Outline

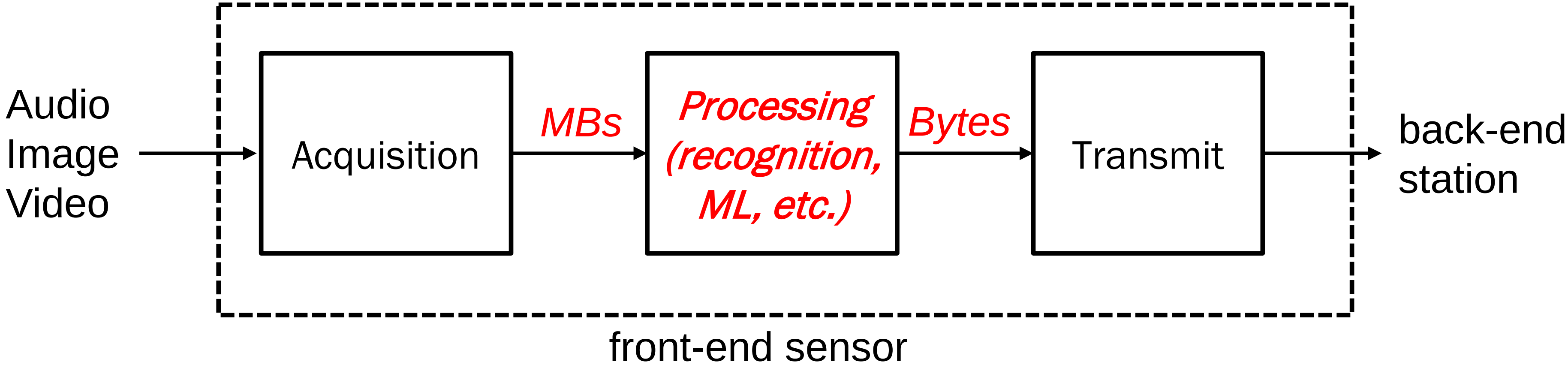
- Motivation: Internet of Body
- Human Body Communication (HBC)
- In-Sensor Analytics in IoT Sensor Node
- Other Related Work
- Societal Impact of On-device Analytics + HBC

Traditional Sensors



Direct transmit without embedded processing.

In-sensor Analytics



Embedded processing significantly **reduces TX data volume** thus improving both congestion problem and TX energy problem

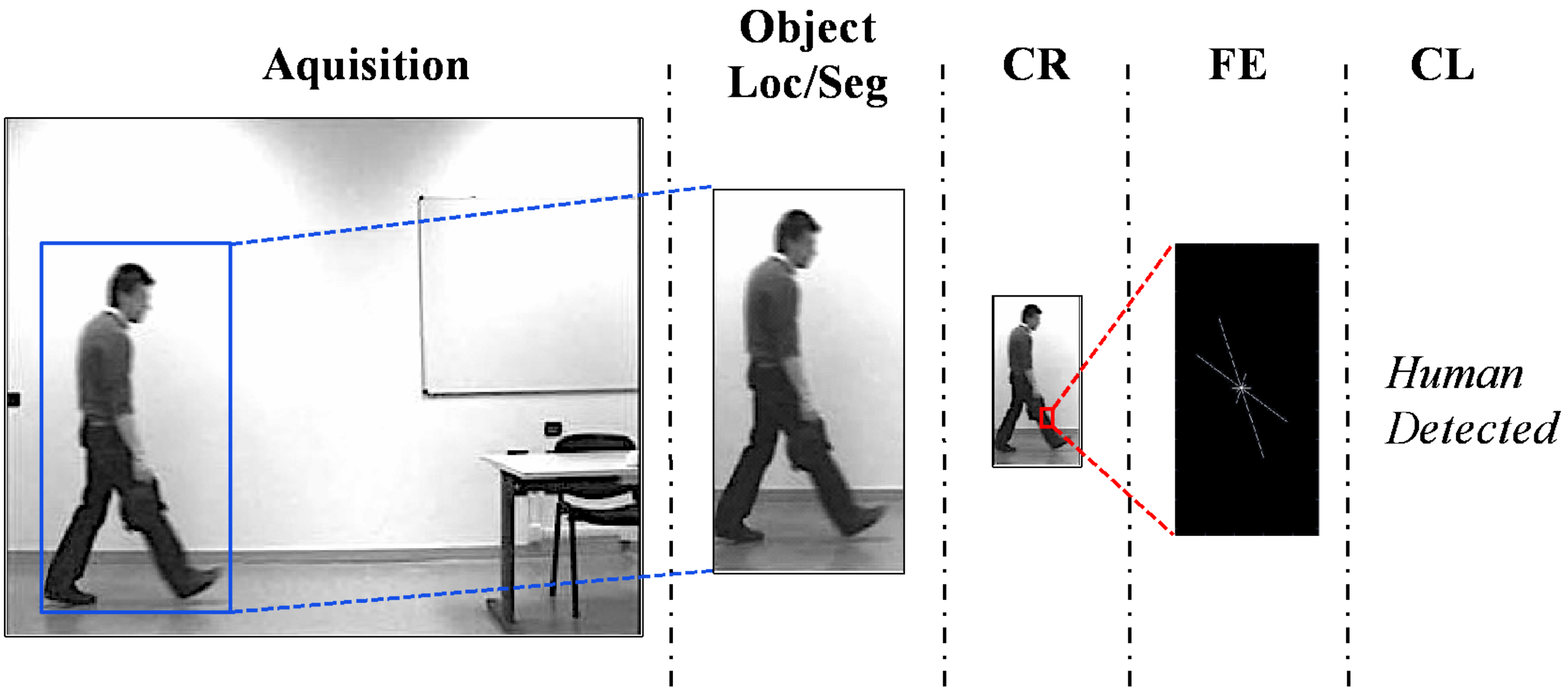
$$Total\ Comm.Energy/information = Energy/bit * bits/information$$

ULP Comm. (Energy/bit)

In-Sensor Analytics (bits/information)

Context-Driven IoT Video Sensor Node

Embedded Processing Algorithm



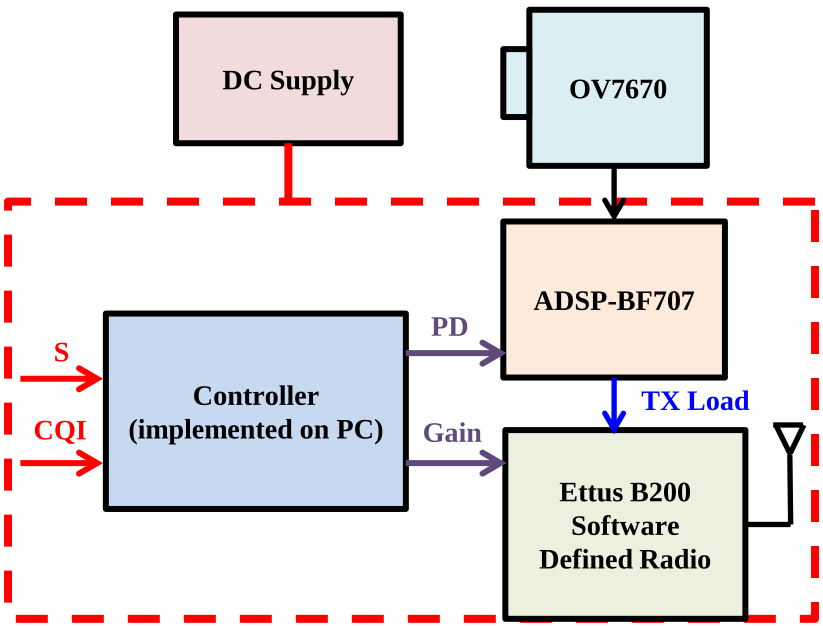
Temporal Difference

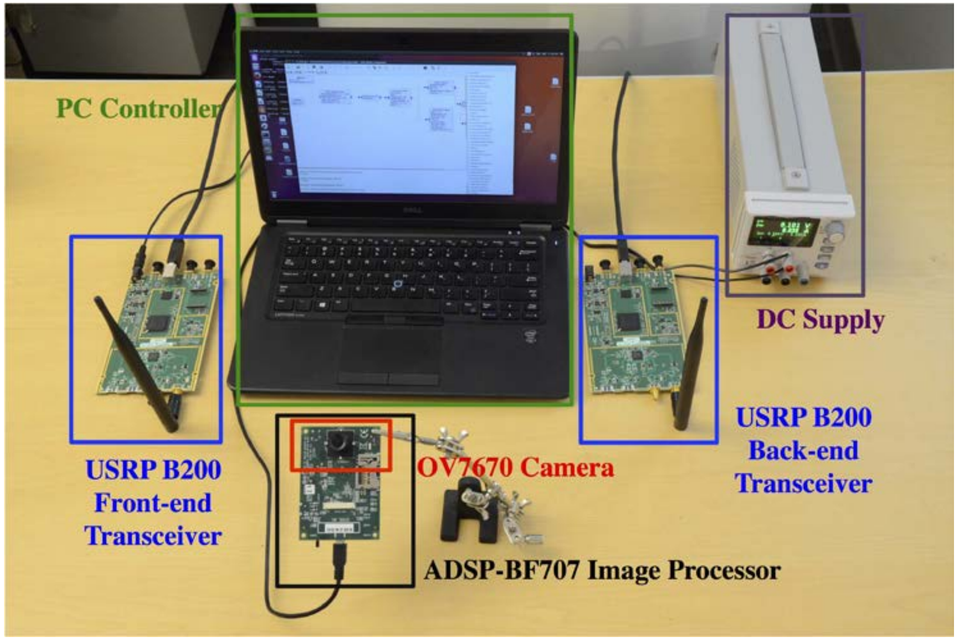
Averaging

Histogram of Oriented Gradient

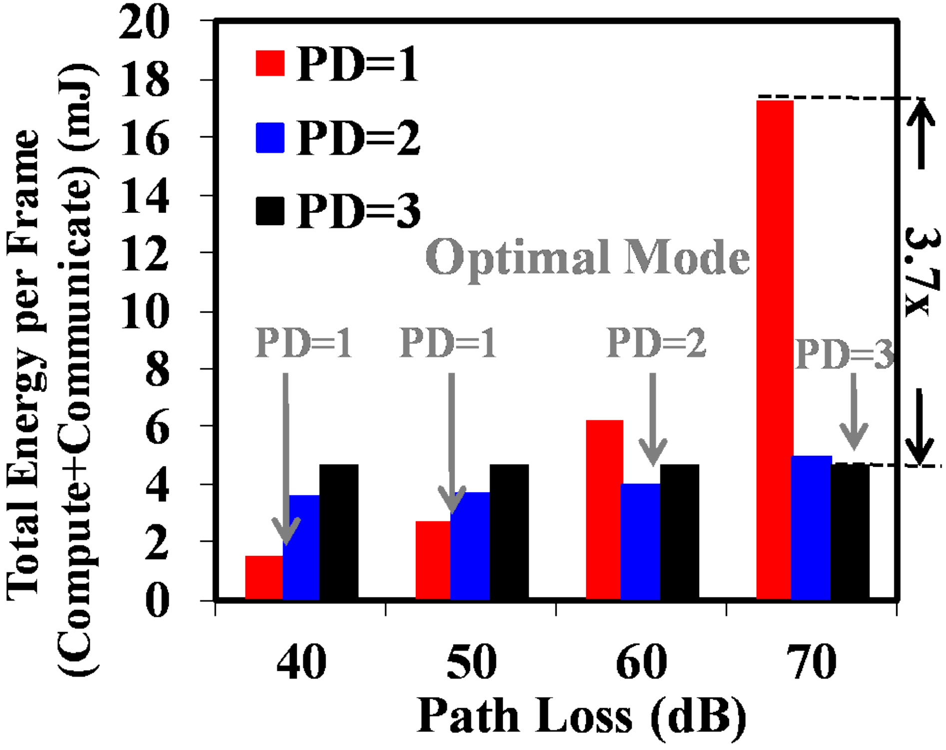
Naïve Bayes

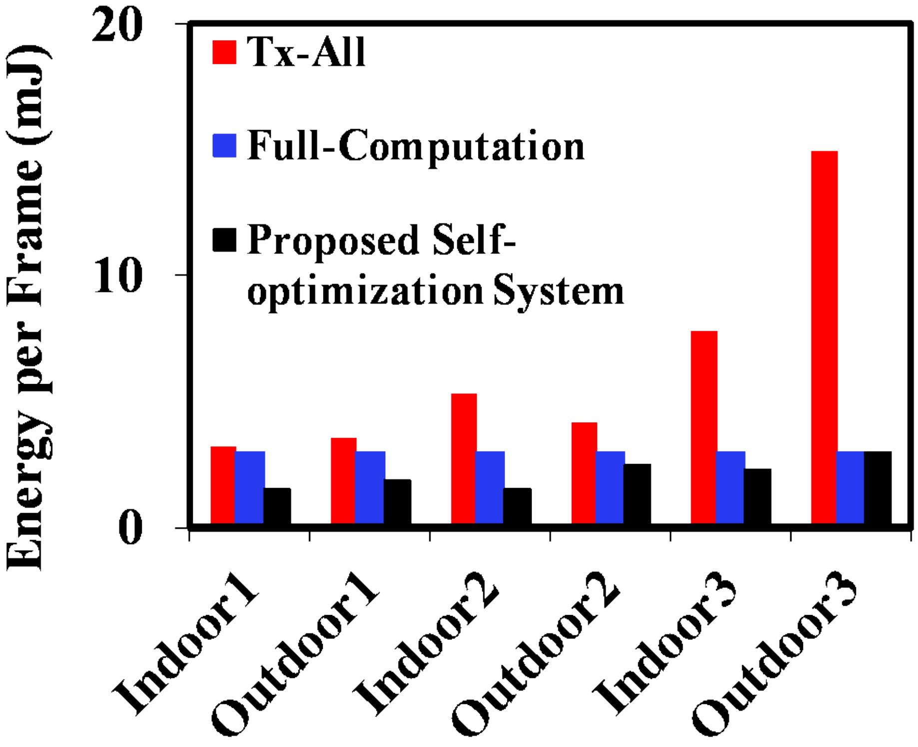
Hardware Setup





Measurement Results





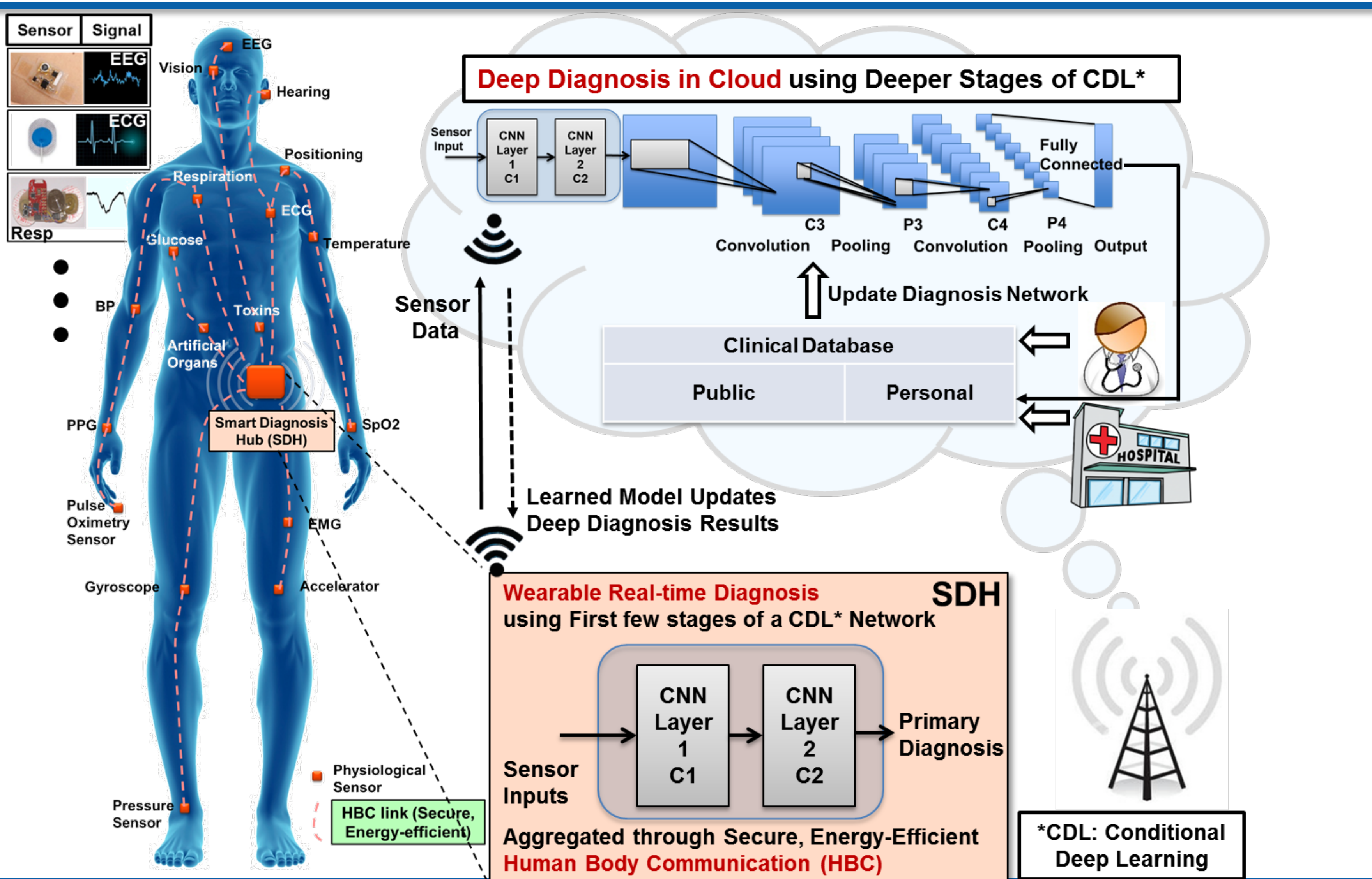
Maximum 3.7x energy saving

Guarantees energy saving

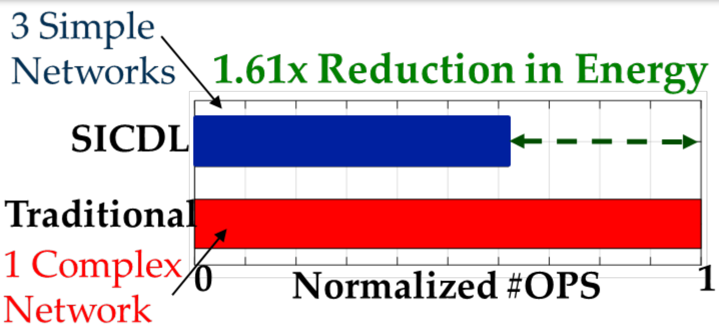
IMS 17, TCAS1 18

Real-time Diagnosis using Staged Inference

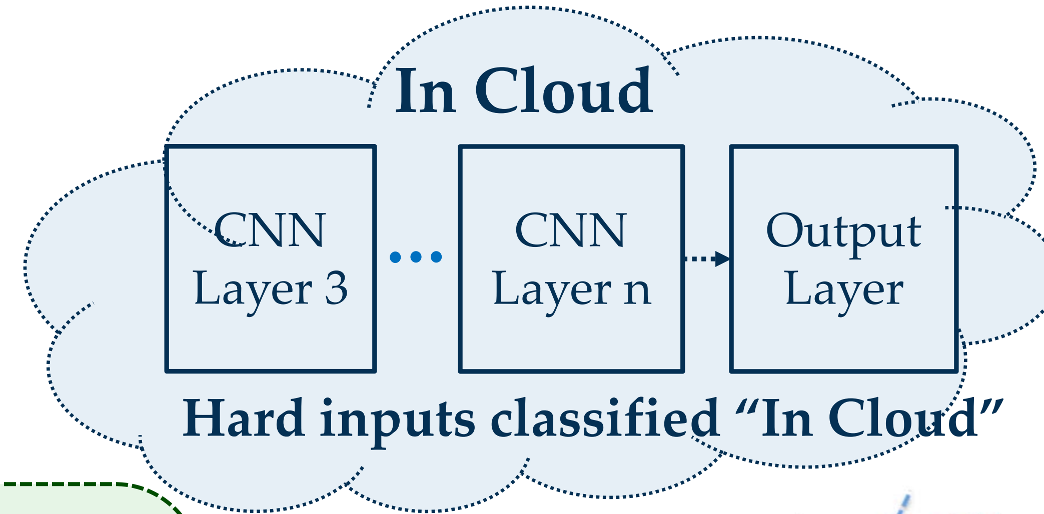
Vision

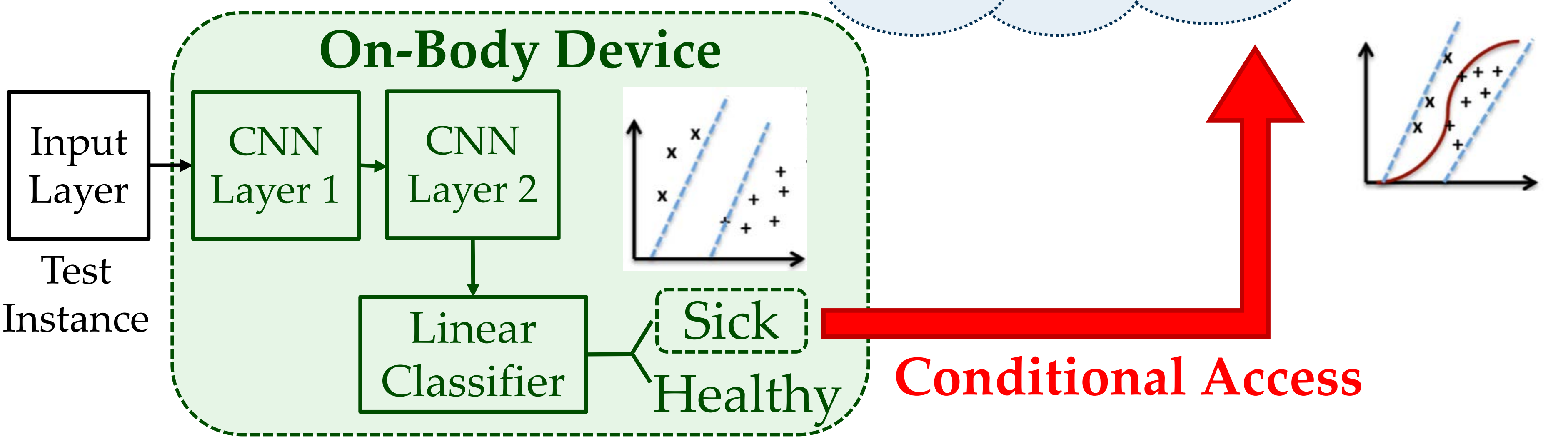

Sensor
Signal
EEG
ECG
Resp
EEG
Vision
Hearing
Positioning
Respiration
ECG
Glucose
Temperature
BP
Toxins
Artificial Organs
Smart Diagnosis Hub (SDH)
PPG
SpO2
Pulse Oximetry Sensor
EMG
Gyroscope
Accelerator
Physiological Sensor
HBC link (Secure, Energy-efficient)
Pressure Sensor
Deep Diagnosis in Cloud using Deeper Stages of CDL*
Sensor Input
CNN Layer 1 C1
CNN Layer 2 C2
Fully Connected
C3
P3
C4
P4
Convolution
Pooling
Convolution
Pooling
Output
Update Diagnosis Network
Clinical Database
Public
Personal
HOSPITAL
Sensor Data
Learned Model Updates
Deep Diagnosis Results
Wearable Real-time Diagnosis
using First few stages of a CDL* Network
SDH
CNN Layer 1 C1
CNN Layer 2 C2
Sensor Inputs
Primary Diagnosis
Aggregated through Secure, Energy-Efficient
Human Body Communication (HBC)
*CDL: Conditional Deep Learning

Staged Inference Conditional Deep Learning



Cloud or deeper layers are only accessed when the patient is sick





Easy inputs classified in "On-Body" Device

EMBC 17

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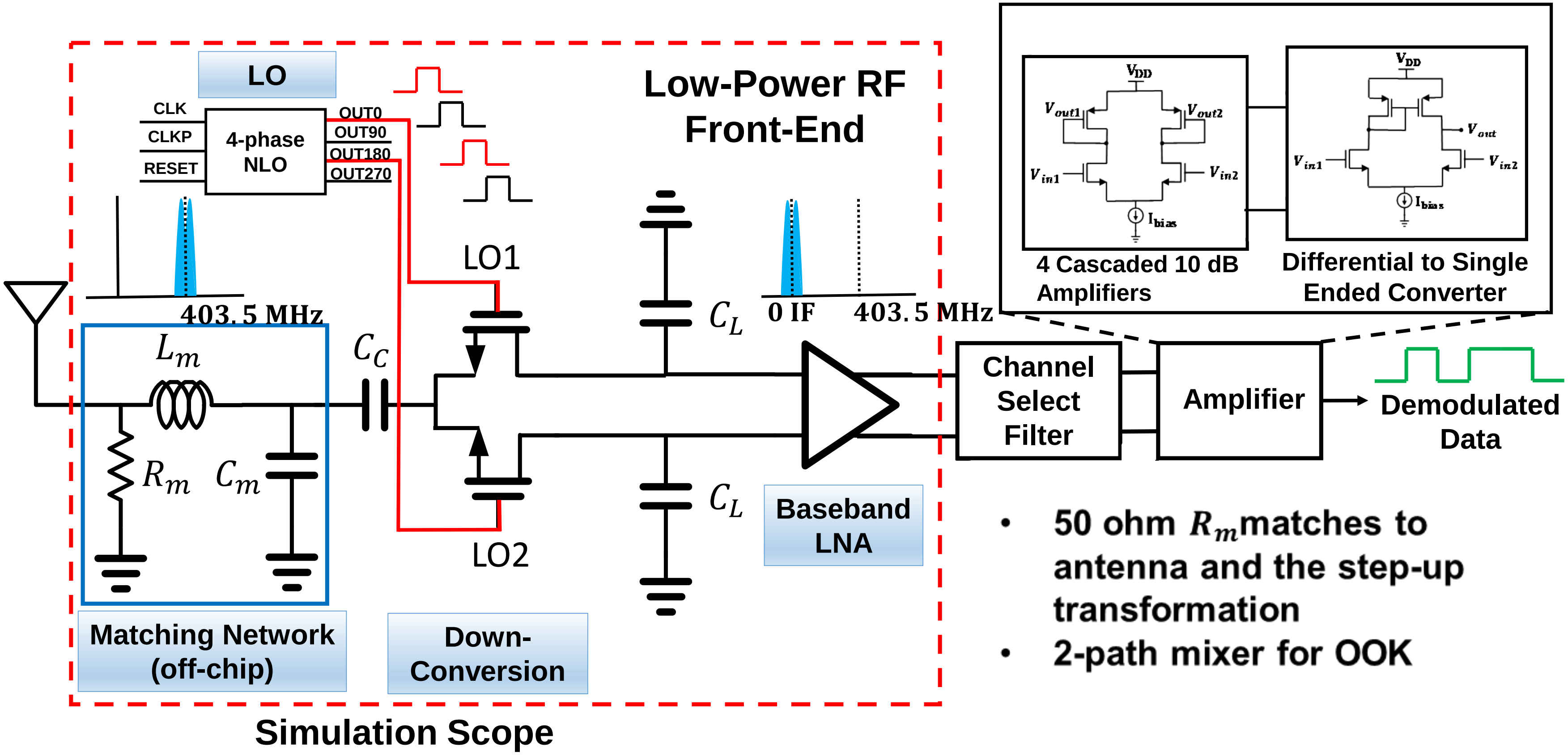
ULP Wireless

Sub-50 µW Medradio Receiver Front-end



- 50 ohm R_m matches to antenna and the step-up transformation
- 2-path mixer for OOK

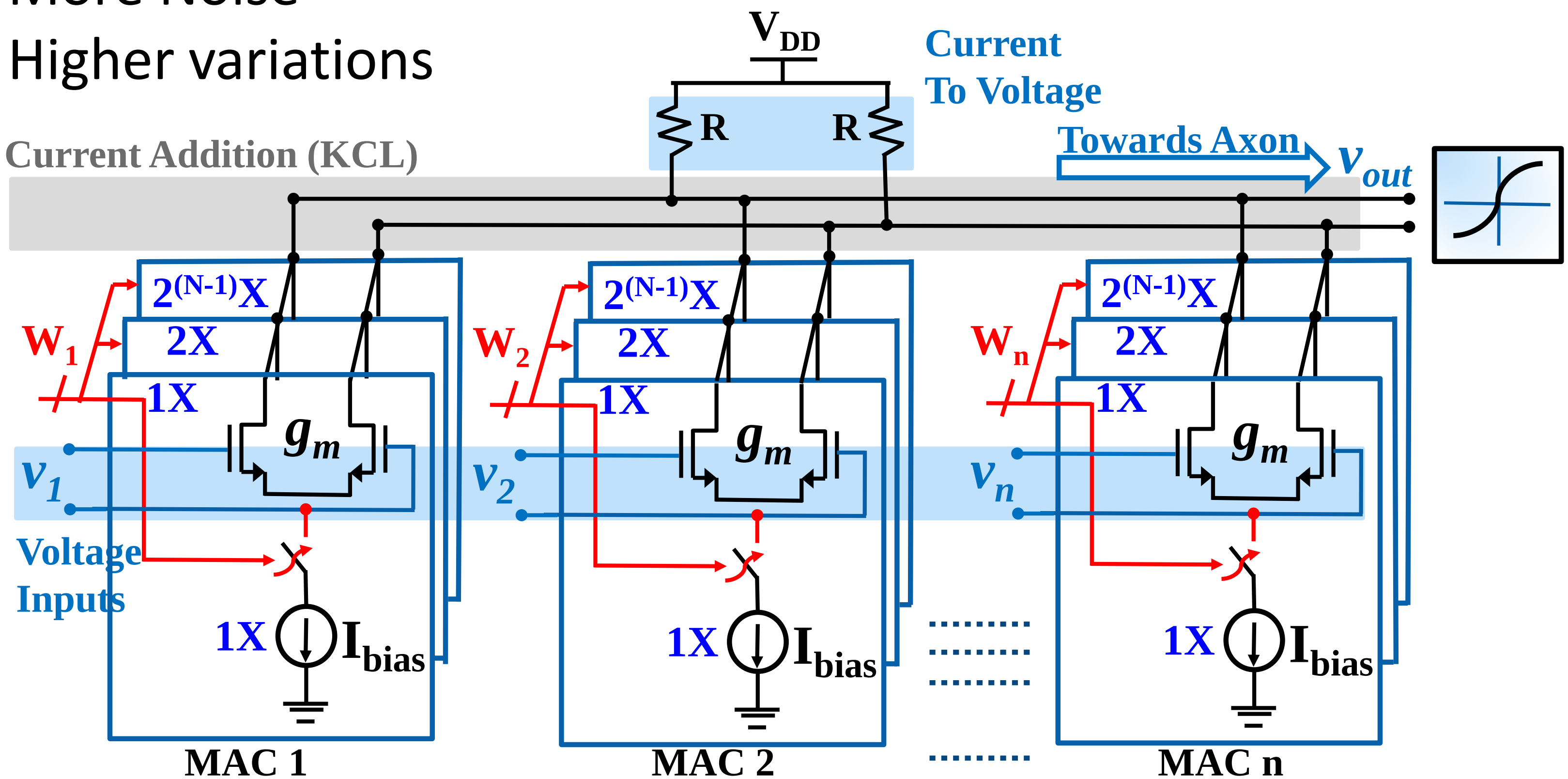
VLSI Design 17

Efficient Mixed-Signal Neural Networks

Mixed-Signal NN: MAC with Intrinsic Dynamics

- Less Number of transistors
- Less leakage
- More Noise
- Higher variations

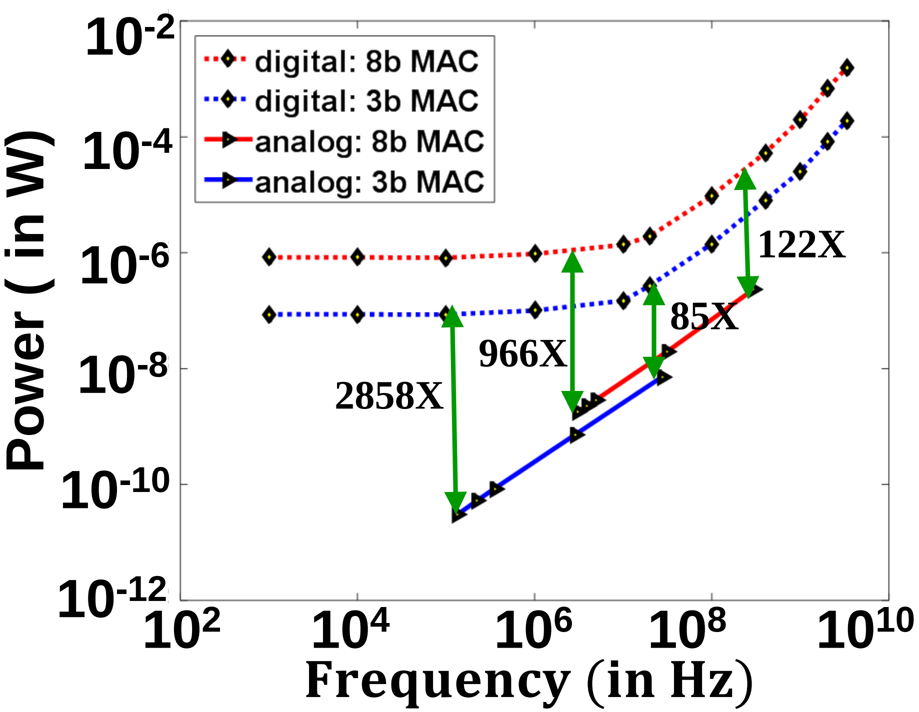
$$v_{out} = F\left(g_m R \sum_{k=1}^{n} W_k v_k \right)$$

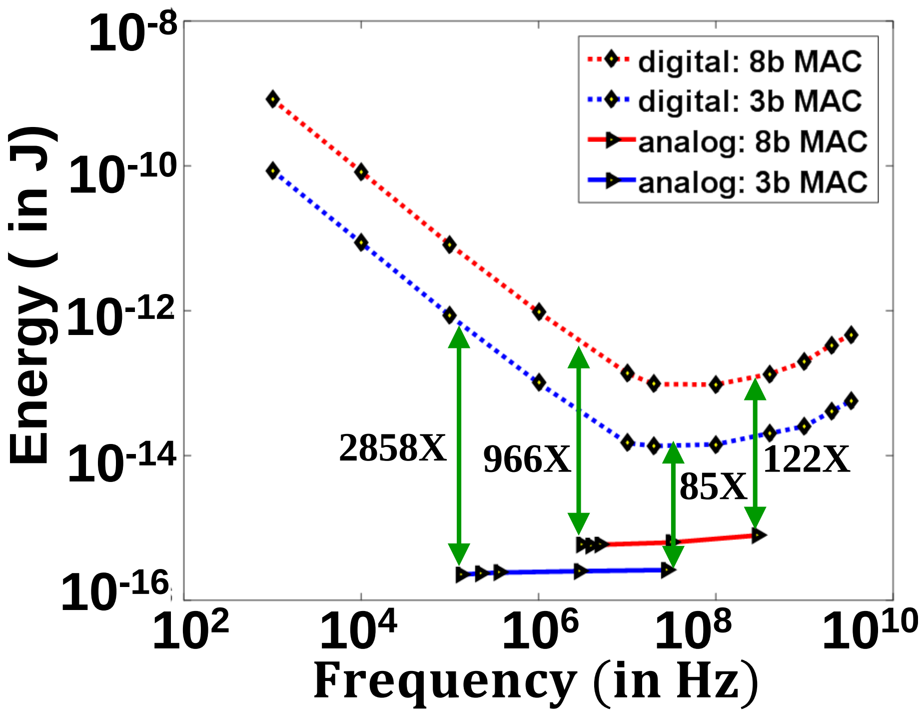


W_1, W_2, …, W_n: Synaptic Weights (N-bits)

ICRC 17

Power/Energy Efficiency w.r.t. Digital MAC





Energy Efficiency: ~ 1fJ/MAC for 8 bit unit (without Memory fetch)

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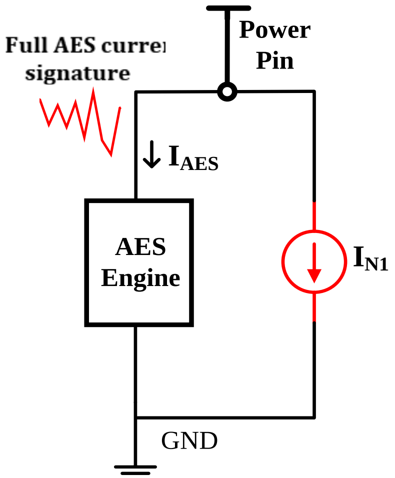
Hardware Security: Power/EM Side-Channel Attack RF-PUF

Power SC Signature Suppression using Shunt LDO

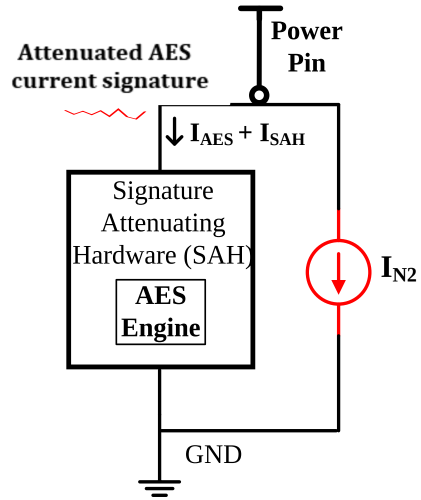
Traditional AES



$\mathbf{I_{Ov1} = I_{N1}}$

$$\rho_{T'H_1} = \frac{Cov(T,H)}{\sqrt{\sigma_T^2 + \sigma_{N_1}^2} * \sigma_H}$$

AS-AES



$\mathbf{I_{Ov2} = I_{N2} + I_{SAH}}$

$$\rho_{T'H_2} = \frac{\frac{1}{AF} * Cov(T,H)}{\sqrt{\frac{1}{AF^2} * \sigma_T^2 + \sigma_{N_2}^2} * \sigma_H}$$

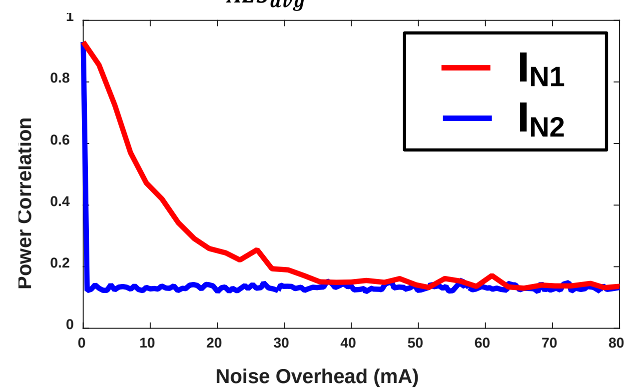
Overhead Comparison

$$\sigma_{N_2}^2 = AF^2 * \sigma_{N_1}^2$$

$$I_{N2} = \frac{I_{N1}}{\sqrt{AF}} \ll I_{N1}$$

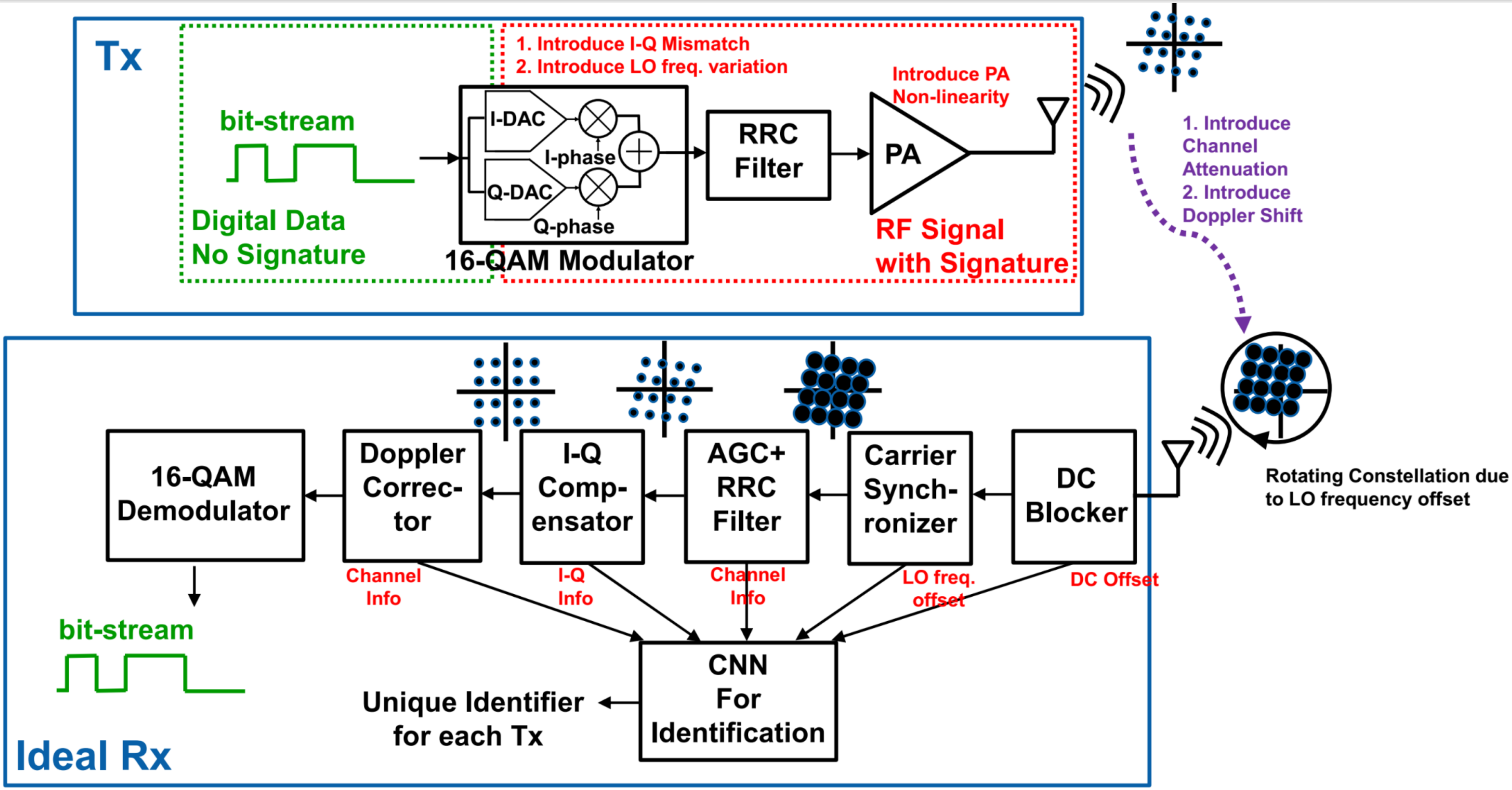
$$I_{Ov_2} \sim \frac{I_{Ov_1}}{\sqrt{AF}} \ll I_{Ov_1}$$

$$I_{AES_{avg}} = 18.89\ mA$$



HOST 17 Best Paper, TCAS1 18

RF-PUF for IoT Security using In-situ Machine Learning



HOST 18

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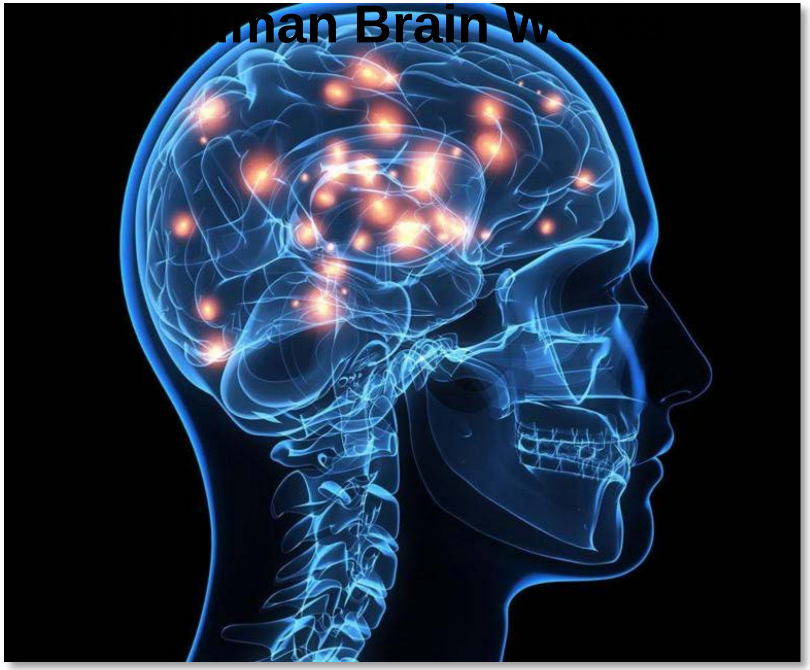
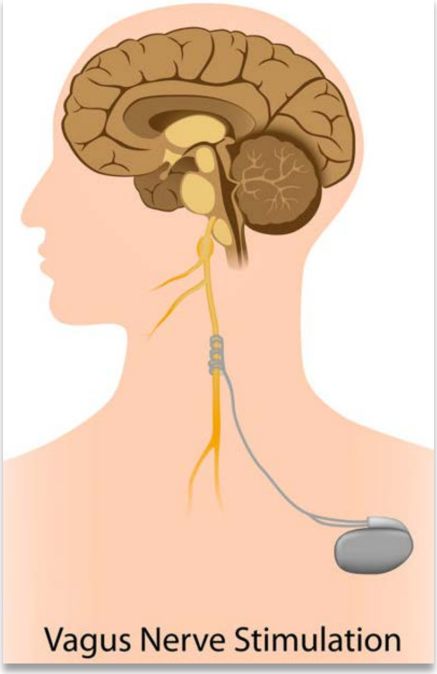
Societal Needs

Neuroscience – Understand How Human Brain Works



- **High-resolution Multi Channel Spatiotemporal Observability Required**

Electroceuticals – Closed Loop Neuromodulation



- **Continuous Observability and opportunistic/appropriate neurostimulation promises to replace/augment pharmaceuticals,**

AR/VR
Smart Glass/Contacts

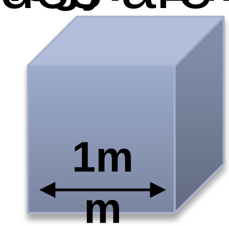
Camera Pill

Neuroscience, Healthcare, AR/VR needs High-Speed *Data Transfer* within the Body

Neuroscience's limitation - *Observability*

- Today, neuroscience observability is limited by the data-rate and *energy-availability at the implanted nodes*
  - Tethered probes impede normal behaviors, socially awkward.
  - ected nodes are energy-li

Today's battery technology: ~2 J/cm³



mm³ neural implant → 2 Joules

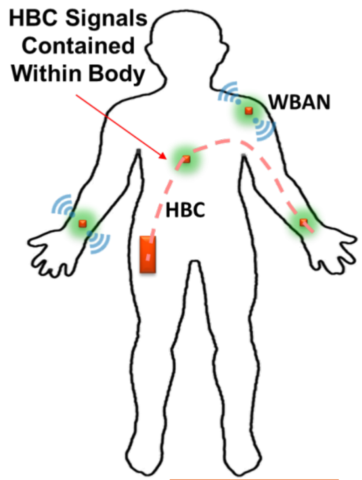
Today's wireless: 1-10nJ/bit

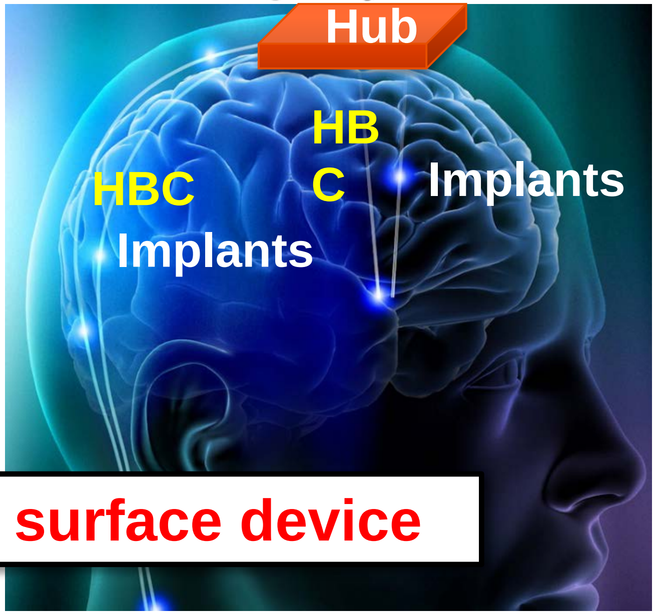
→ @0.18 Gbps Battery runs out in 1 Second !!!

Needs new Communication/Embedded Analytics Techniques for Neuroscience Data Transfer

Key Technology: On-device Analytics + HBC

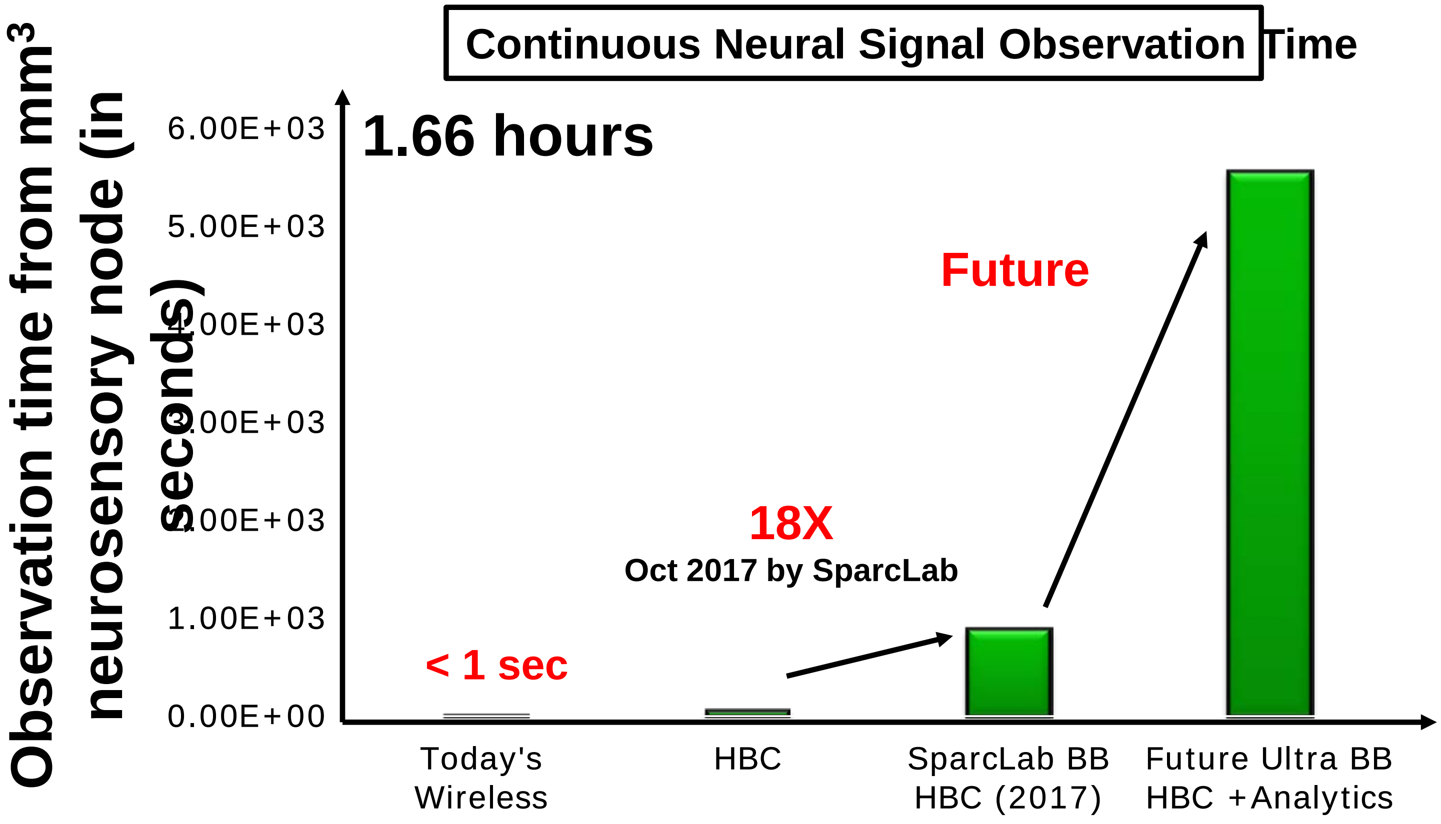
- **Human Body Communication**
  - Provides a *low-loss broadband* connectivity medium
    - → Fraction of wireless energy
  - Signals remain within the body
    - → Private, Secure Communication
- **On-Device Analytics/Machine Learning**
  - Converts from data to information
    - → Fraction of total energy, Real-Time
  - Reduces Data volume drastically
    - → Lower Congestion, Longer Lifetime





Connect Brain Implantable/Injectable with surface device using HBC

Sustainable Neuroscience/Healthcare Observability



HBC: Human Body Communication; BB: Broad

THANK YOU