Security and Conduction Properties of Human Body as a Communication Medium

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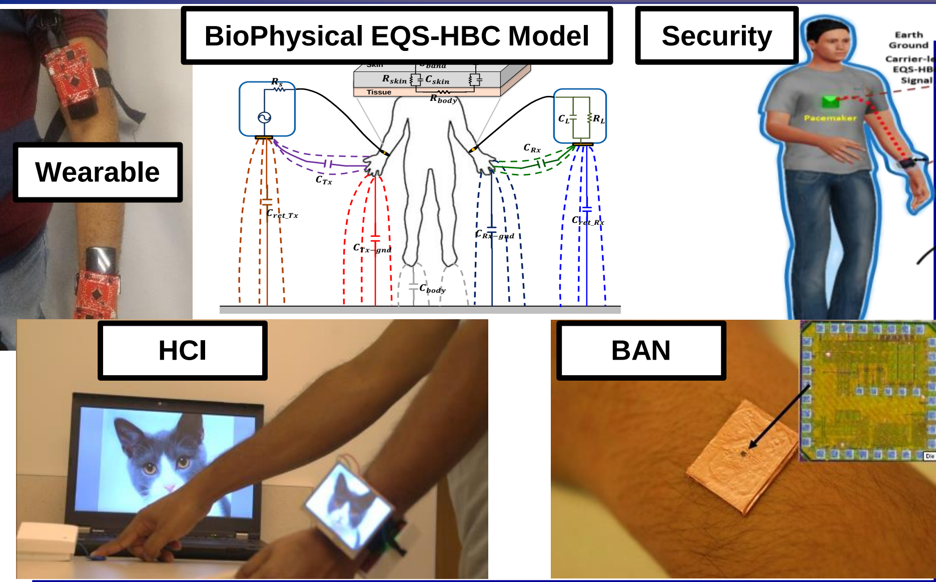
AFOSR YIP, Dr. Patrick Bradshaw

September 6th, 2019

PURDUE UNIVERSITY

Security and Conduction Properties of Human Body as a Communication Medium (FY19)



Problem / Objective

- Understand Conduction and Security properties of Human Body Communication

Technical Approach

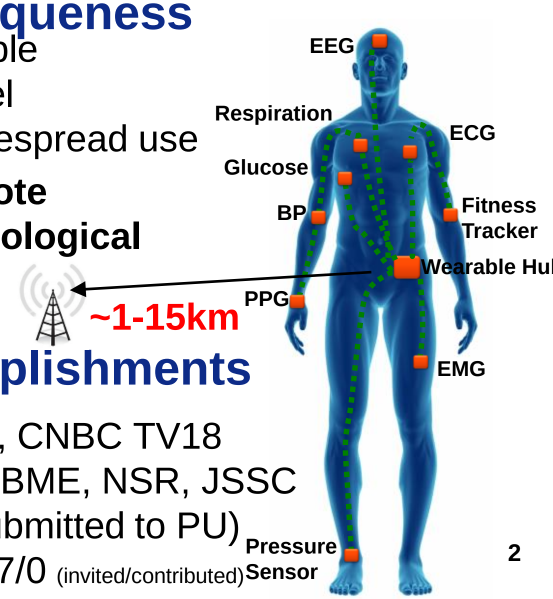
- Determine Key Influencers, Repeatable Measurement, Develop Wide-Frequency Scalable Channel and Interference Models. Dynamic HBC.
- Mixed-Signal Processing for Interference Robust HBC. On-Hub Analytics for Long-Range Data Compression

Key Findings of Research

- **HBC Channel:** (1) Return path cap is self-capacitance of ground plate (2) Primary Loss is ratio of return path cap to body cap (3) EQS (<MHz) and EM region (>10 MHz) noticeable (4) Capacitive EQS-HBC is safe (5) Interference measured
- **HBC Security:** (1) Inter-Human additional loss due to inter-human cap (2) Cap region 20dB/dec and EM region 40dB/dec slope of coupling (3) Inter-Human coupling >20dB below channel loss at >1m
- **Applications:** (1) World's power BAN (2) First Communication 'Strictly' through Touch (3) Wearable-wearable demo: handshake info exchange (4) Band-demo: secure authentication

Uniqueness

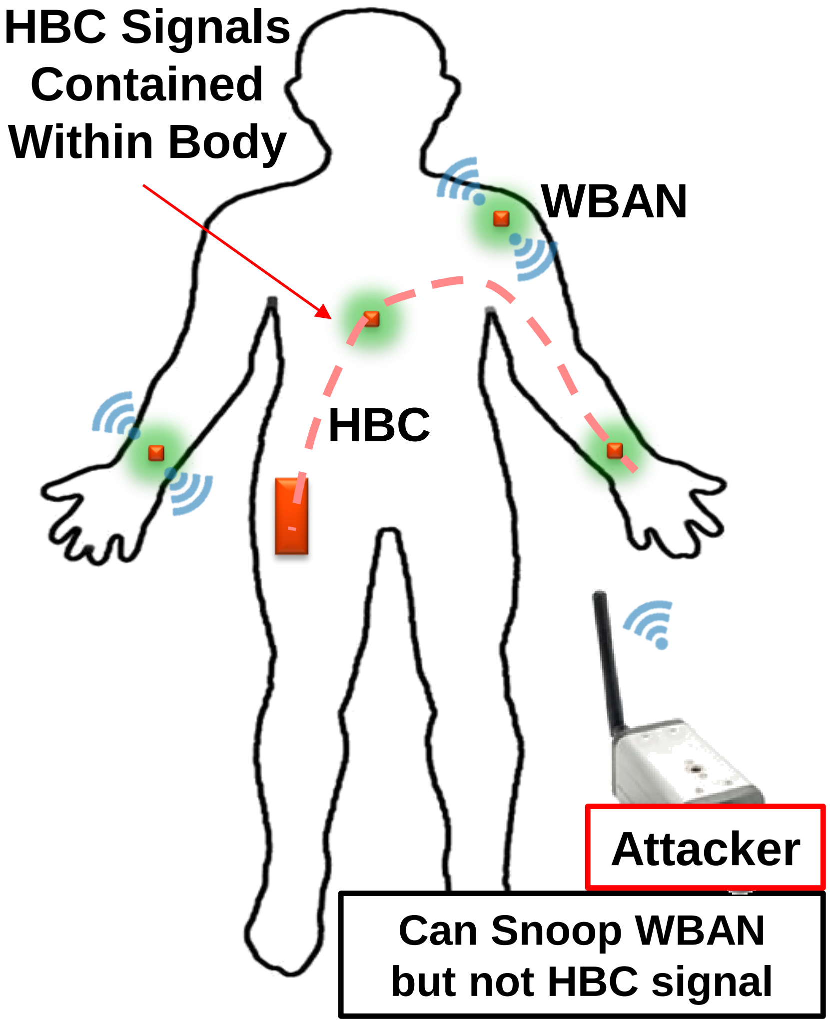
- Systematic Repeatable Measurement / Model Development for widespread use
- **DoD: Efficient Remote Monitoring of Physiological Signals**
- **Neuroscience, HCI**



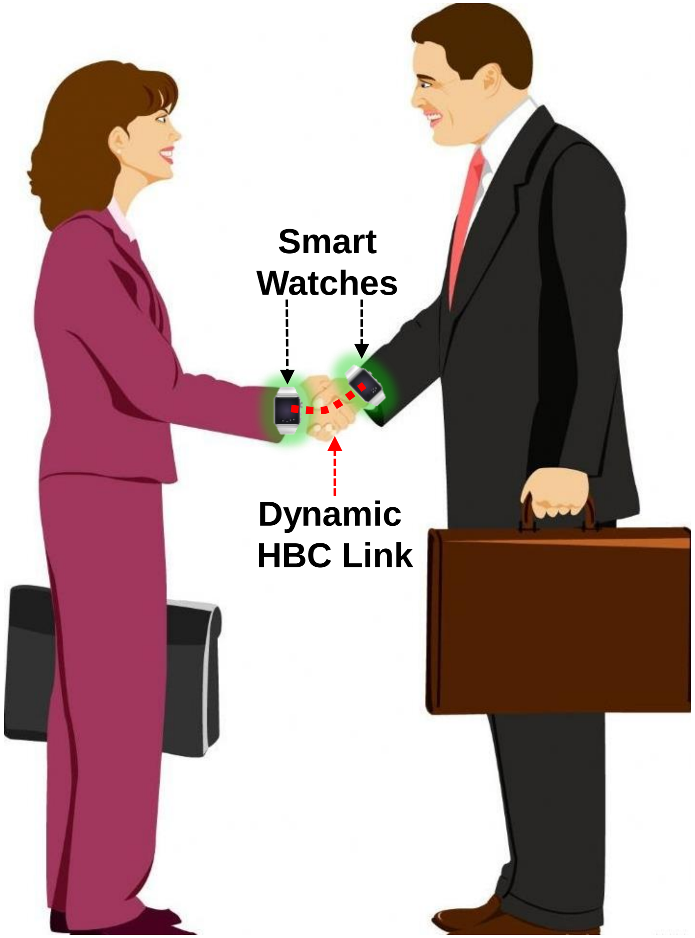
Accomplishments

- MIT TR35 India Award, CNBC TV18
- 19 publications total, TBME, NSR, JSSC
- Patents: 2 (filed), 2 (submitted to PU)
- Presentations (2019): 7/0 (invited/contributed)

Vision: Human Body as a Comm Medium

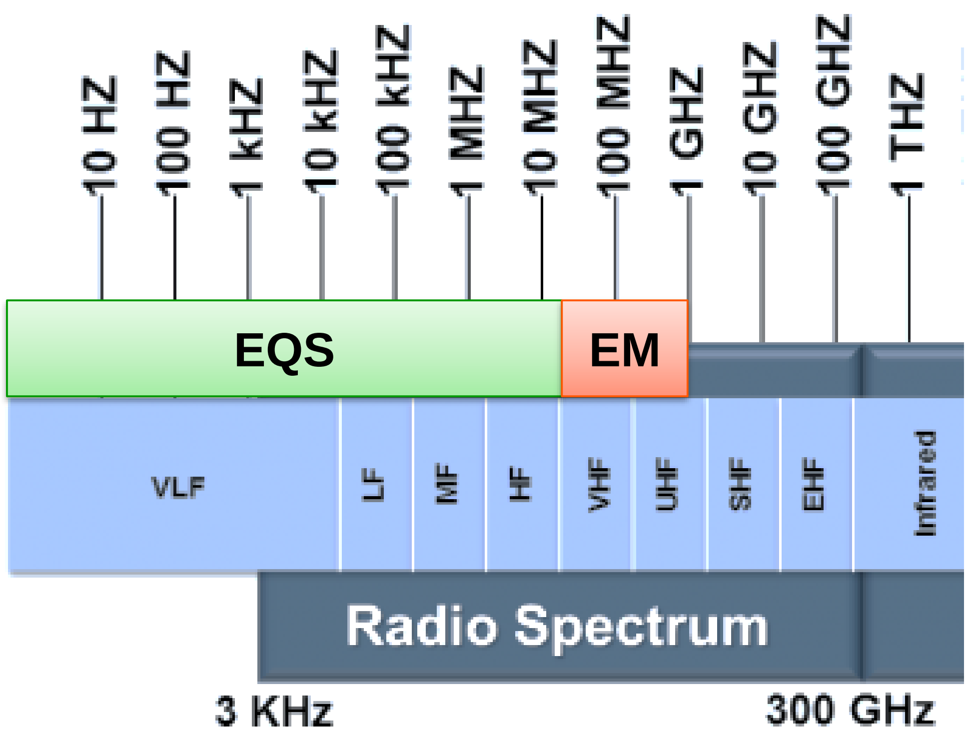


Human-Intranet



Human-Internet

Project 1st Half: EQS-HBC



- Measure in **KHz-GHz** range of **Human Body** properties:
  - Conduction
  - Security (Leakage)
  - Interference

Maxwell and Haus

Electric Fields

$$\oint_S \epsilon_0 \overline{E} \cdot d\overline{A} = \int_V \rho dV$$

EQS

$$\int_C \overline{E} \cdot d\overline{l} = 0$$

Magnetic Fields

$$\oint_S \overline{B} \cdot d\overline{A} = 0$$

MQS

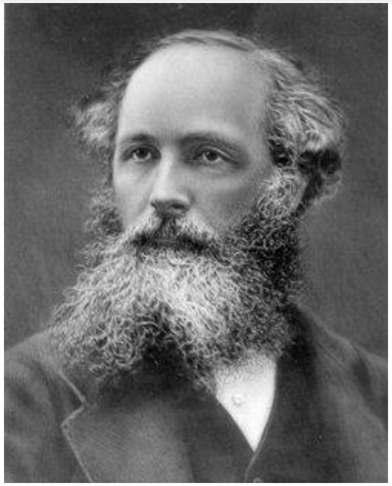
$$\oint_C \overline{H} \cdot d\overline{l} = \int_S \overline{J} \cdot d\overline{A} + \frac{d}{dt}\int_S \epsilon \overline{E} \cdot d\overline{A}$$

For **Statics systems** both time derivatives are unimportant, and Maxwell's Equations split into decoupled electrostatic and magnetostatic equations.

Electro-quasistatic and **Magneto-quasitatic** systems arise when one (but not both) time derivative becomes important.

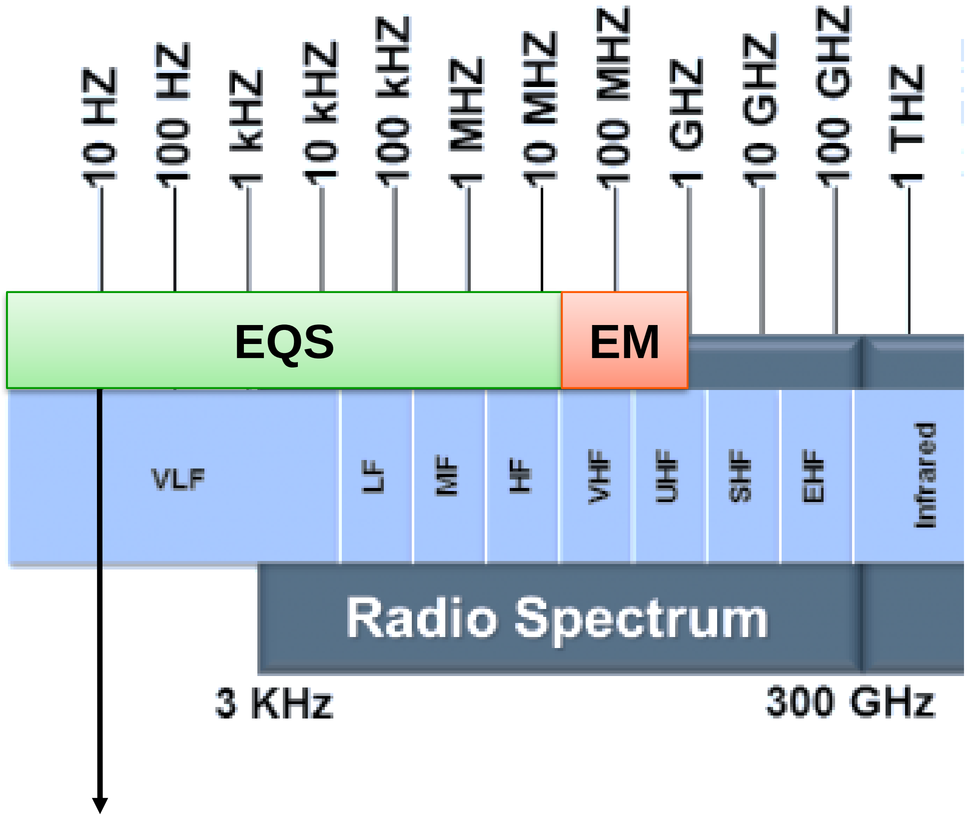
INTRODUCTION TO ELECTROQUASISTATICS AND MAGNETOQUASISTATICS

Limits to Statics and Quasistatics, MIT OCW

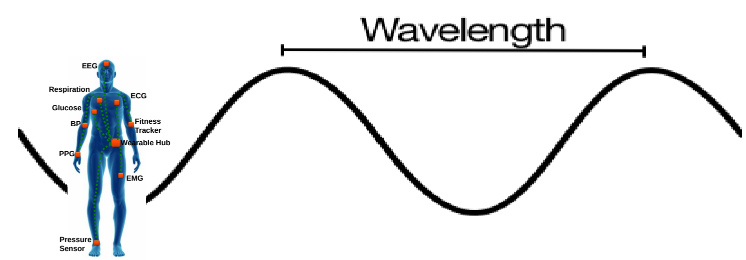


Hermann A. Haus

Project 1st Half: EQS-HBC



- Measure in **KHz-GHz** range of **Human Body** properties:
  - Conduction
  - Security (Leakage)
  - Interference
- **Hz-MHz Range**
  - **→ Electro-Quasistatic HBC**
    - **EQS-HBC**
- **Higher Freq → EM effects**



$$E = E_{EQS} + E_{error} \approx E_{EQS}$$

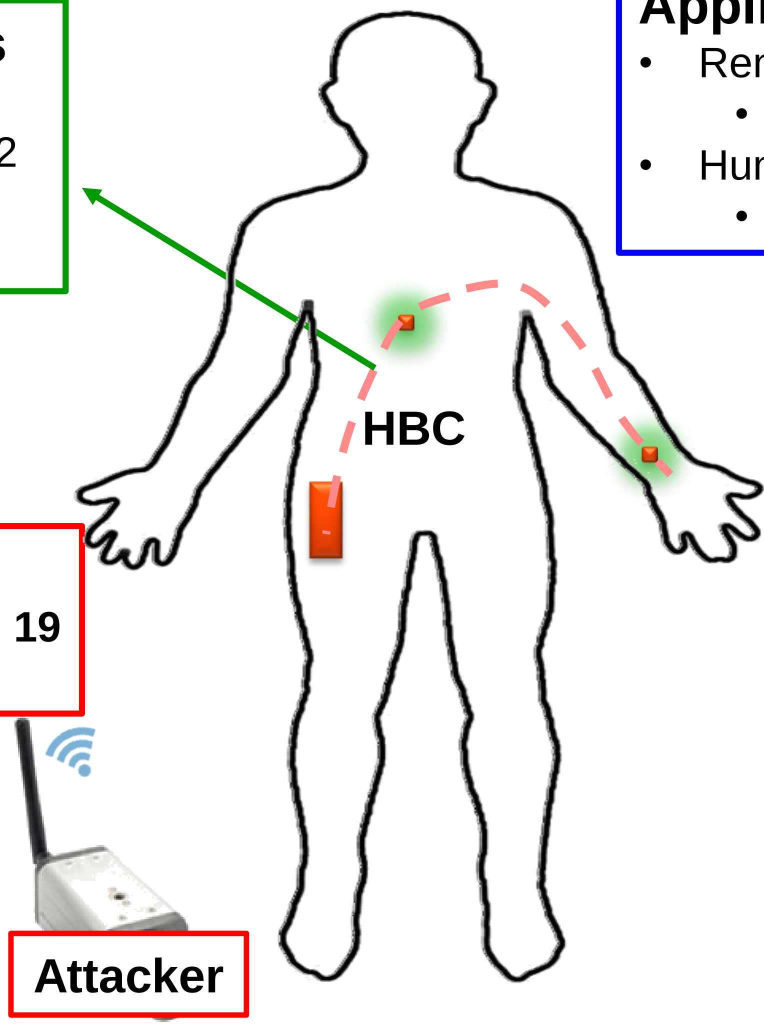
$$\frac{E_{error}}{E} = \omega^2 \mu_{tissue}\, \epsilon_{tissue}\, r^2 = 0.014$$

$$r = 2m, f = 1MHz \qquad \epsilon_{tissue} = 8\epsilon_{air} \quad \mu_{tissue} = \mu_{air}$$

Outline: EQS-HBC

Conduction Properties
- MWCL 18, **TBME 18**
- EMBC 18, **JSSC19,** TCAS2 19, TBioCAS 19(x2)
- *ToCHI*, *IMWUT*

Applications:
- Remote Health Monitoring
  - EMBC 17, CICC 18
- Human-Computer Interaction
  - ISLPED 17, EMBC 18



Security Properties
- **Nature Scientific Reports 19**
- *NSR Inter-Human*

Submitted are in italics

This Year (Oct 18 – Sep 19)

1. Theoretical Model for Return Capacitance
2. MHz-GHz Measurements and Bio-Physical Modeling

A. Security Property – Inter-Human Coupling

B. Conduction Property – Intra-body Loss

4. Environmental Interference

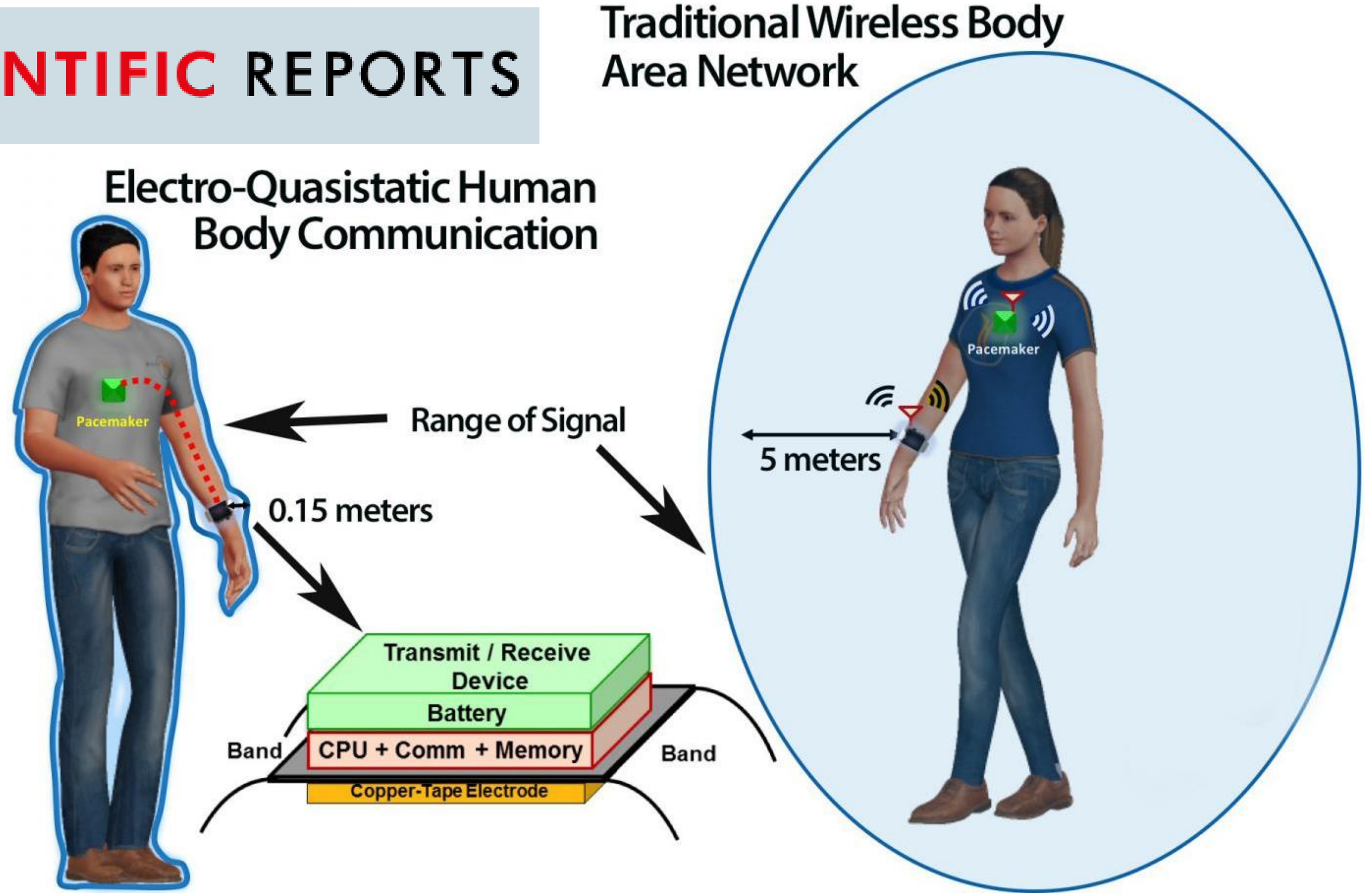
A. Human Body Antenna Properties – Wearable Measurement

5. Safety Analysis
6. Lowest-Power BAN
7. Application Demonstration

Review: Physical Security: EQS HBC

Nature Scientific Reports

SCIENTIFIC REPORTS



D. Das, S. Maity, B. Chatterjee, and S. Sen, "Enabling Covert Body Area Network using Electro-Quasistatic Human Body Communication," *in* ***Scientific Reports (Nature)***, 9, Article number: 4160 (2019) March 2019

EQS-HBC = Physically Secure

Coverage:
80+ News Sites

IEEE SPECTRUM
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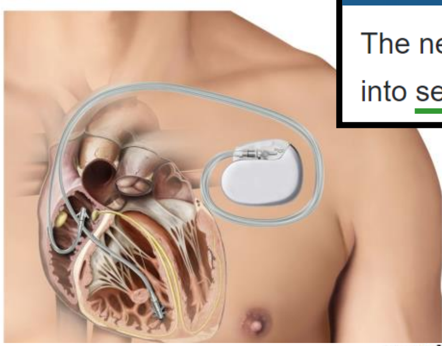
Scientists Design a Network That Lives Inside Your Body

To keep pacemakers and insulin pumps secure.

By David Grossman Mar 13, 2019



ELECTRONICS POINT

> The new device from Purdue University demonstrates a huge leap in medtech data security which could propagate into several other aspects of bioelectronic medicine in years to come.

...vn as an electro-quasistatic field using the ... Signals from a pacemaker can travel from head ... skin. "Unless someone is physically touching ..." Sen says.

...lectro-quasistatic human body communication, ...onth in the journal *Scientific Reports*. In the ... fully confined to the body signals from a ... of

TechXplore — Topics — Week's top

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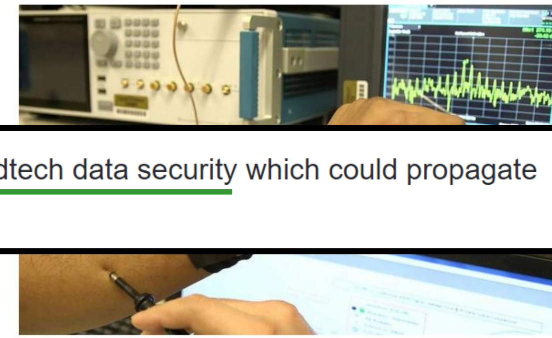
MARCH 12, 2019

Your body has internet—and now it can't be hacked

by Kayla Wiles, Purdue University



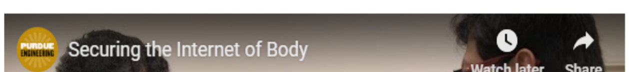
The human body carries electrical signals well. Now these signals can be contained within c...

VB — CHANNELS EVENTS NEWSLETTERS JOB BOARD — Search

MOBILE

Researchers say quasistatic signals will protect wearables and implants from hackers

JEREMY HORWITZ @HORWITZ MARCH 12, 2019 12:58 PM



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Your source for the latest research news

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HOME NEWS RELEASES MULTIMEDIA MEETINGS PORTALS ABOUT

PUBLIC RELEASE: 12-MAR-2019

Your body is your internet -- and now it can't be hacked

Researchers have protected your pacemaker, other medical tech from remote hacks before they happen

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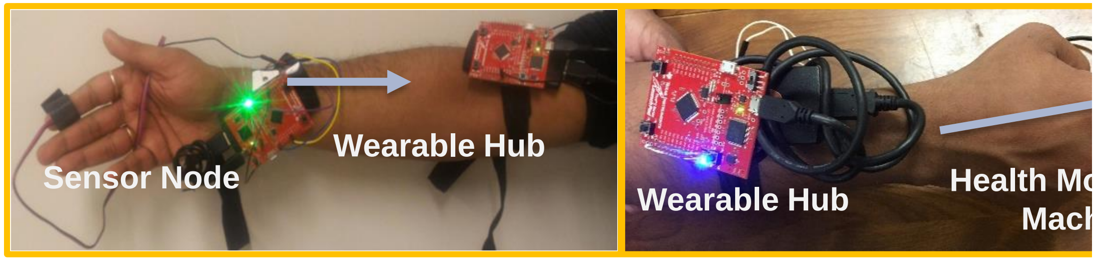
Security of Medical Devices

Wearable Health Monitoring

IEEE SPECTRUM



EMBC 17, 18

U.S. DEPARTMENT OF HOMELAND SECURITY

Medical Advisory (ICSMA-19-080-01)

Medtronic Conexus Radio Frequency Telemetry Protocol

Original release date: March 21, 2019

28 Mar 2019 | 20:00 GMT

Can "Internet-of-Body" Thwart Cyber Attacks on Implanted Medical Devices?

Medtronic discloses medical device vulnerabilities, while Purdue University scientists propose countermeasure to block attacks

By **Emily Waltz**

Photo: Medtronic

The U.S. Department of Homeland Security last week warned that numerous medical devices made by Medtronic are vulnerable to cyber attack. The vulnerabilities affect 17 of the company's implantable cardiac device

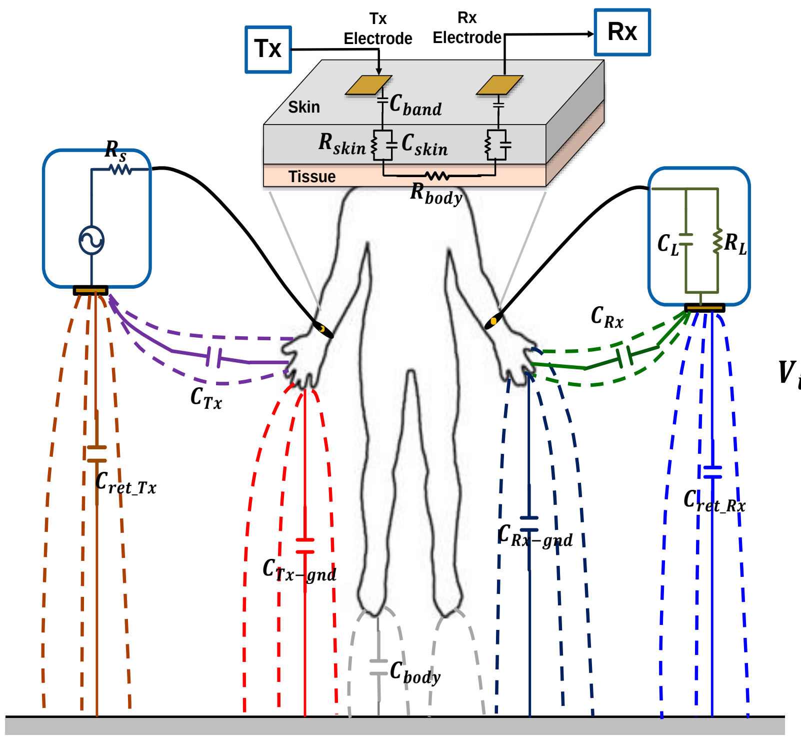
PURDUE UNIVERSITY

SPARC Lab

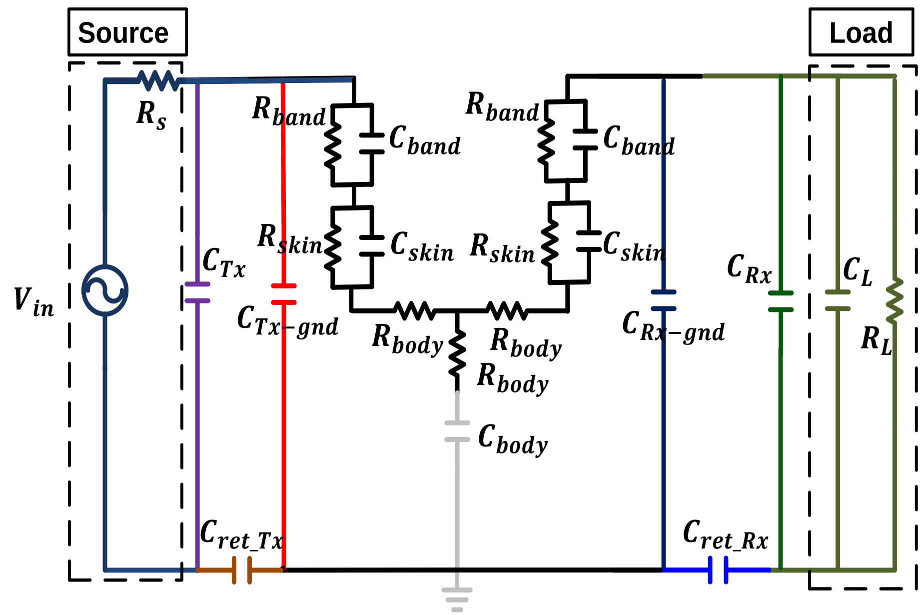
Review: Bio-Physical Model: EQS HBC

Human Body Bio-Physical Circuit Model

Human Body Model showing different Field Lines



Bio-Physical Circuit Model of Human Body



- Bio-physical model to match experimental results
- Forward Path: Body Parameters, source/load impedances
- Return Path: External coupling capacitances

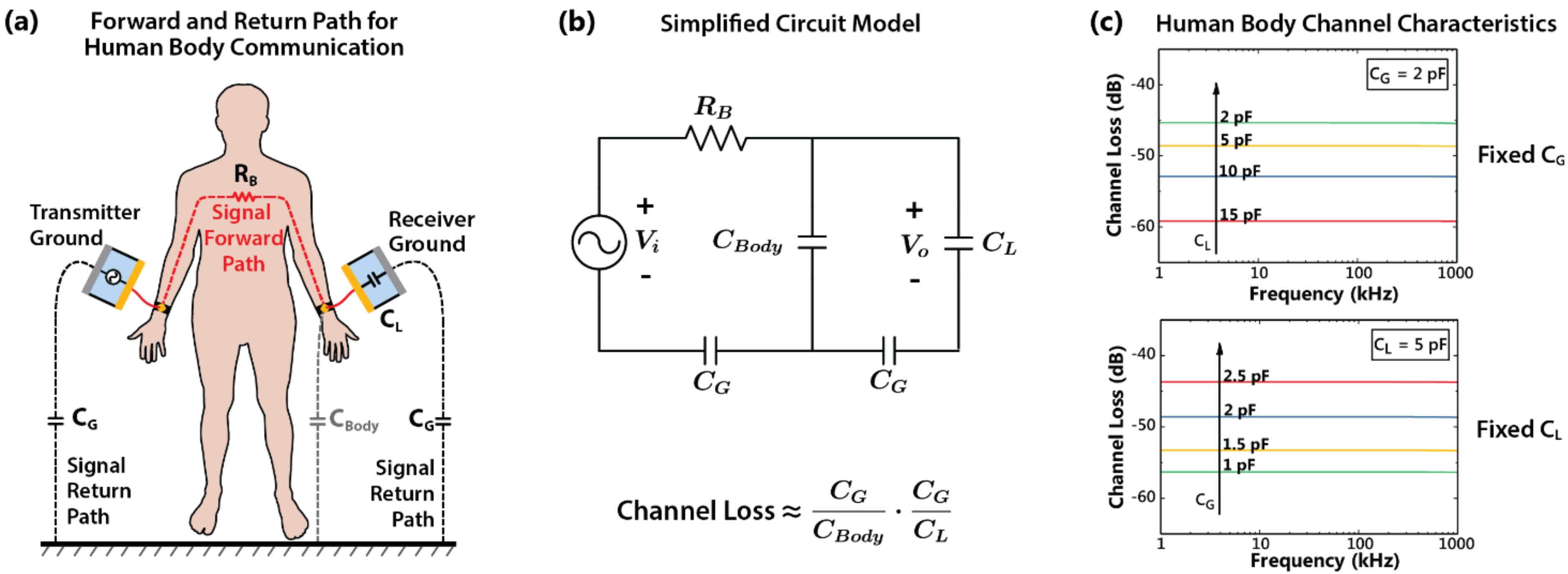
TBME 2018

Experiment 1

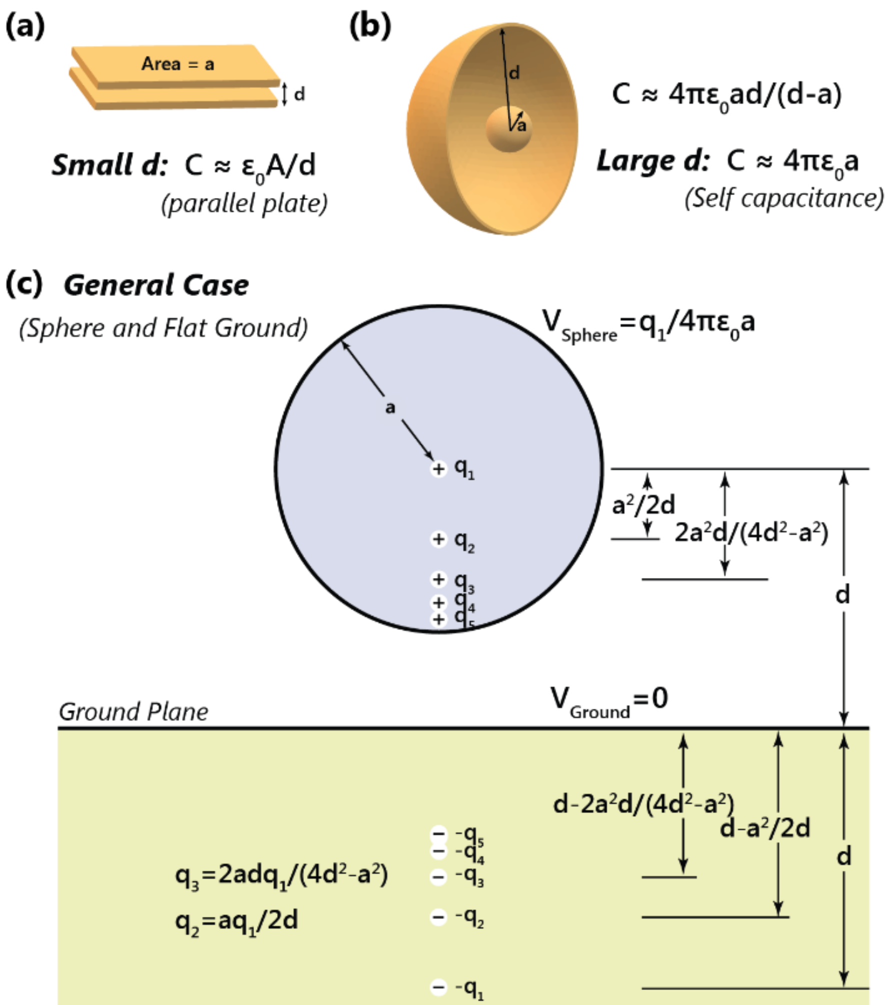
What is the return path Capacitance ?
How does it vary with distance ?

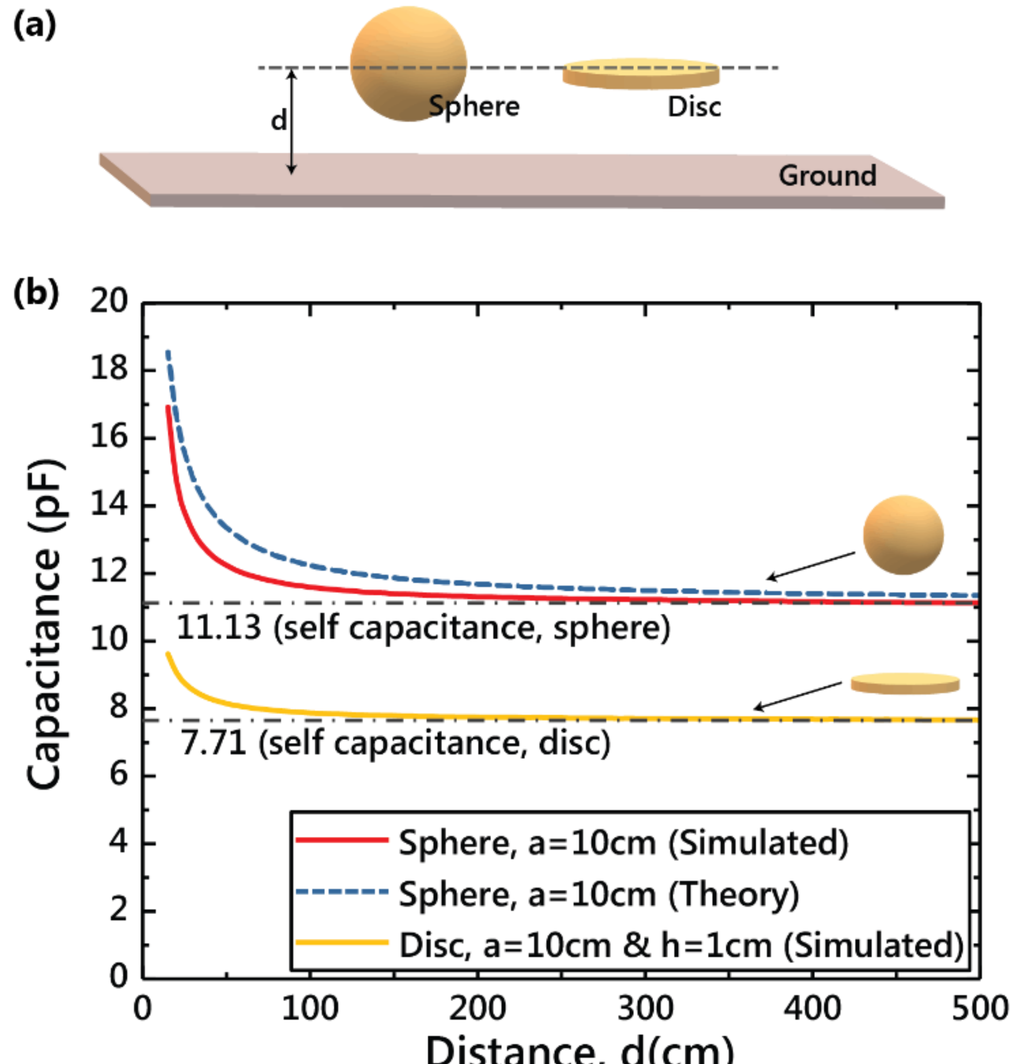
Return Path Capacitance Circuit Model

- **Purpose:** Model and measure return path capacitance to model channel loss



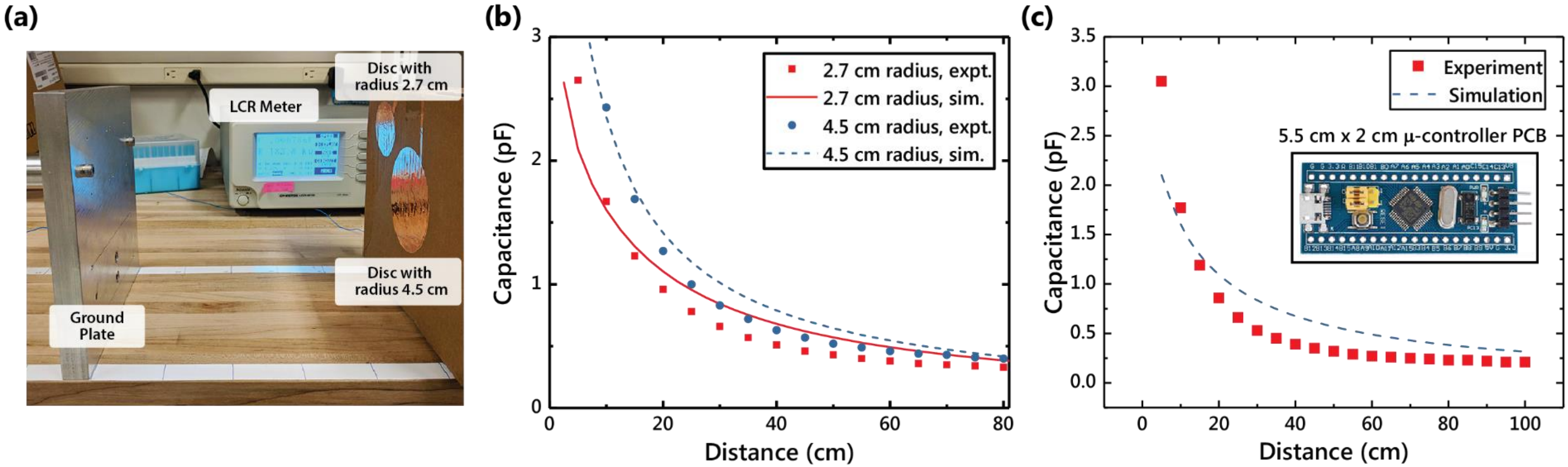
Return Path Capacitance Modeling





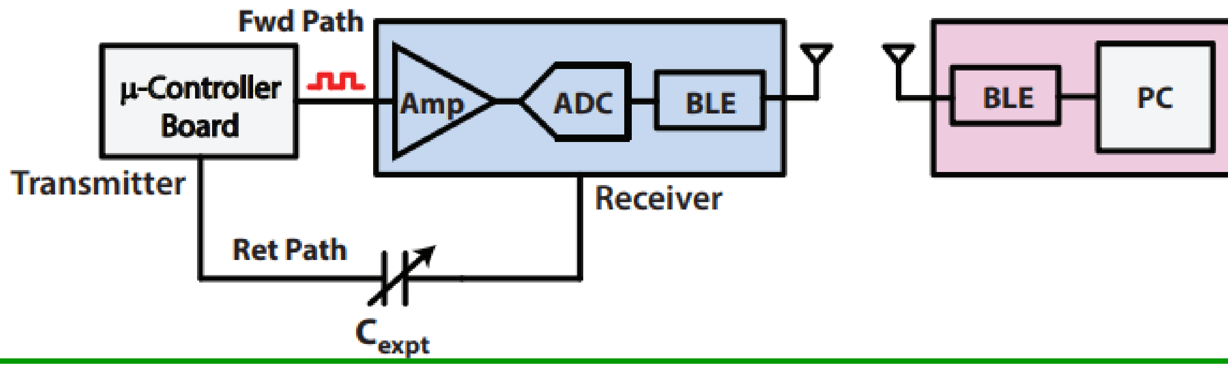
Return Path Cap: Benchtop Measurement

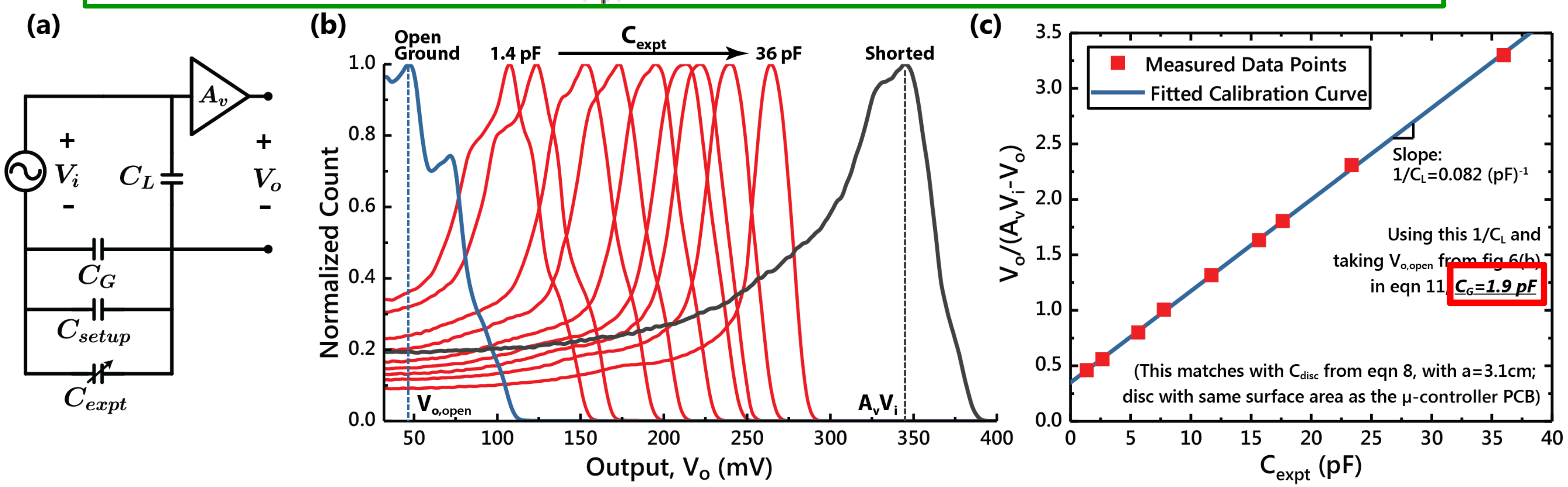
- **Verification of return path capacitance modeling using disc with various radius'**



Return Path Cap: Wearable Measurement

Measurement Setup using a known C_{expt}





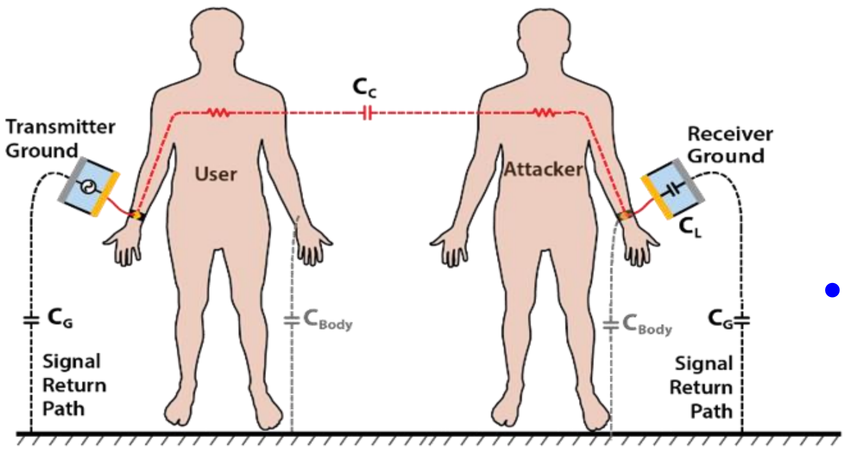
- **Observation:** **Capacitance measured: 1.9pF**

Experiment 2

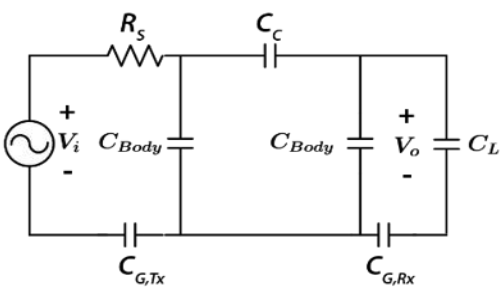
Can other humans pick up my signals ?

Modeling Inter-body Coupling

Capacitive coupling formed between an EQS-HBC user and an attacker: HBC Leakage/ Inter-Body HBC



Simplified Circuit Model for for Leakage/ Inter-body EQS-HBC

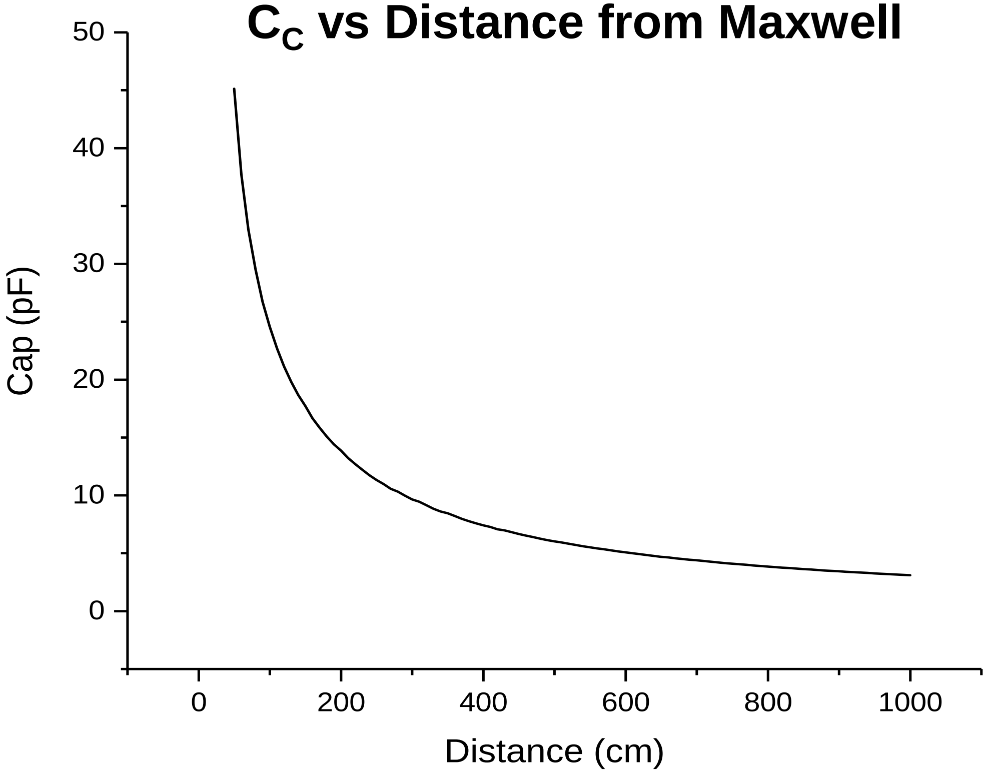


$$\frac{V_o}{V_i} \approx \frac{C_{G,Tx}}{C_{Body}} \times \frac{C_C}{C_{Body}} \times \frac{C_{G,Rx}}{C_{G,Rx} + C_L}$$

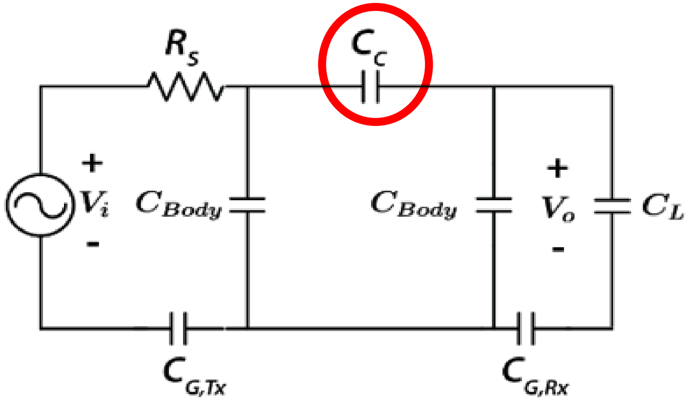
- **Purpose:** Measure capacitive coupling to a nearby human body
- **Observation:** In EQS regime, another capacitive division to another human body

Effect of Inter-body Coupling

C_C vs Distance from Maxwell



Simplified Circuit Model for
for Leakage/ Inter-body EQS-HBC



$$\frac{V_o}{V_i} \approx \frac{C_{G,Tx}}{C_{Body}} \times \frac{C_C}{C_{Body}} \times \frac{C_{G,Rx}}{C_{G,Rx} + C_L}$$

- **Inference:**

Margin between Intra-body signal and Inter-body Signal :

At 1m, C_C ~ 20pF, gives an **17.5 dB** margin

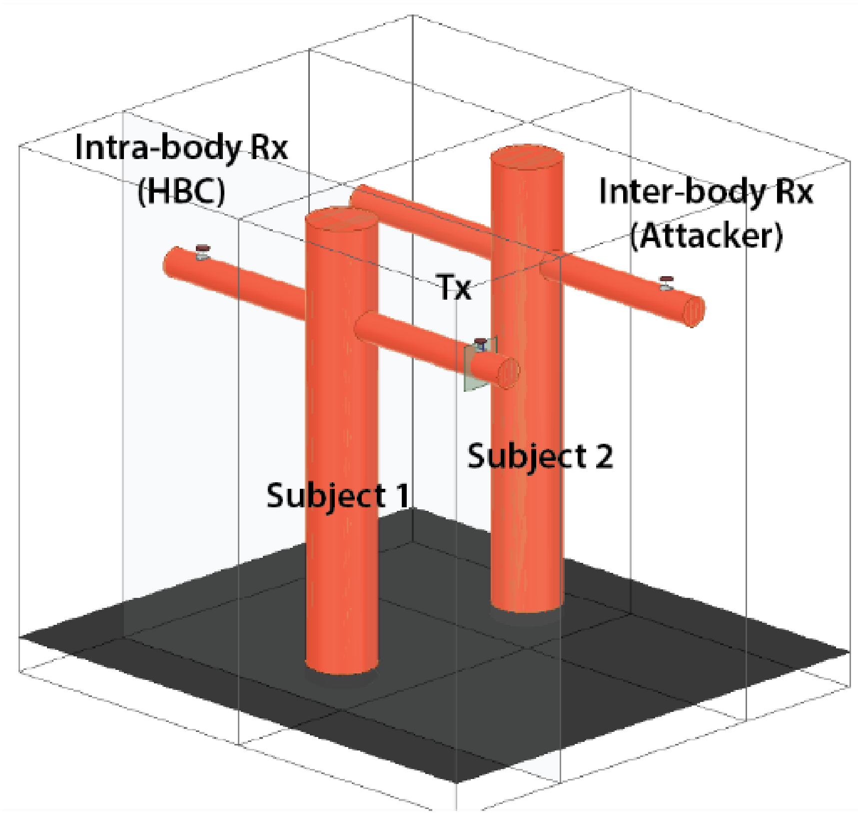
At 5m, C_C ~ 5pF, gives an extra **29.5 dB** margin

Experiment 3

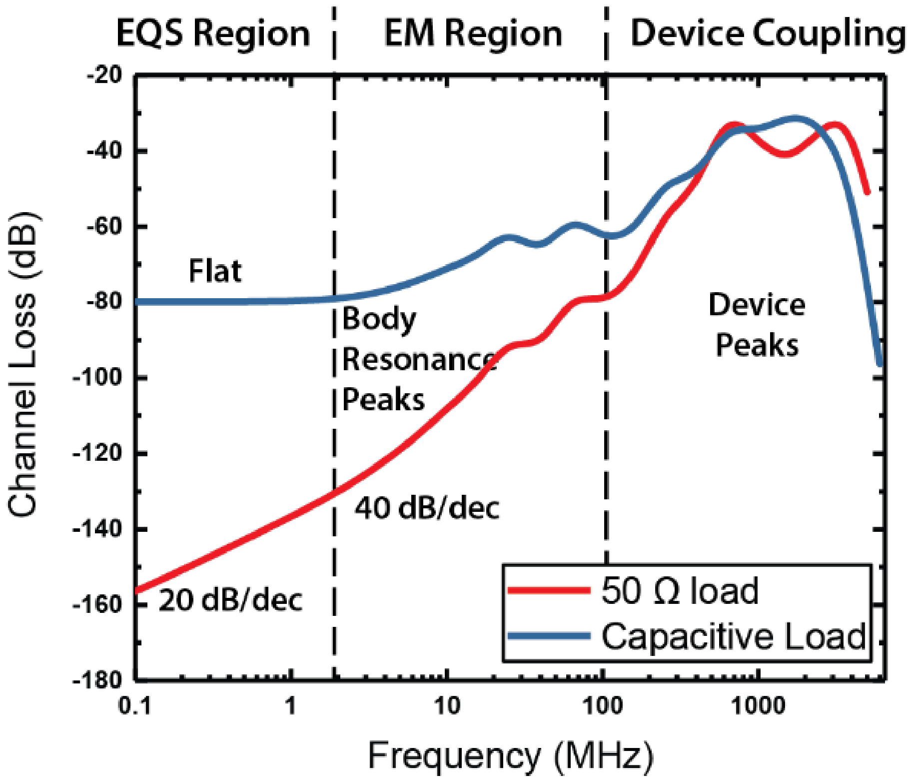
Frequency dependence of Inter-Body Leakage

HFSS modeling

(a) Simulation Setup in HFSS



(b) Different regions in the simulation results



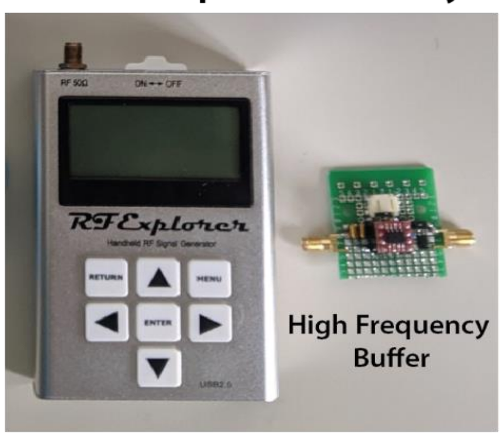
- **Observation:** 20dB/dec slope initially then 40dB/dec for R-term

Wearable Sensitive Measurement Device

(a) Transmitting devices: Handheld Frequency Generators

50 kHz - 1MHz | **1 MHz - 20 MHz** | **24 MHz - 6 GHz**

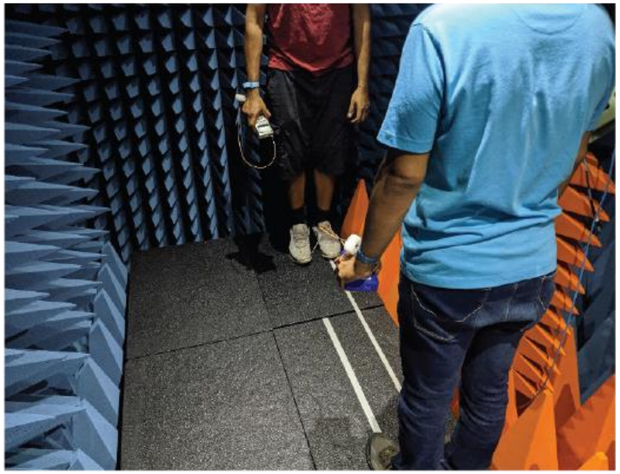
(b) Receiving Device: Handheld Spectrum Analyzer

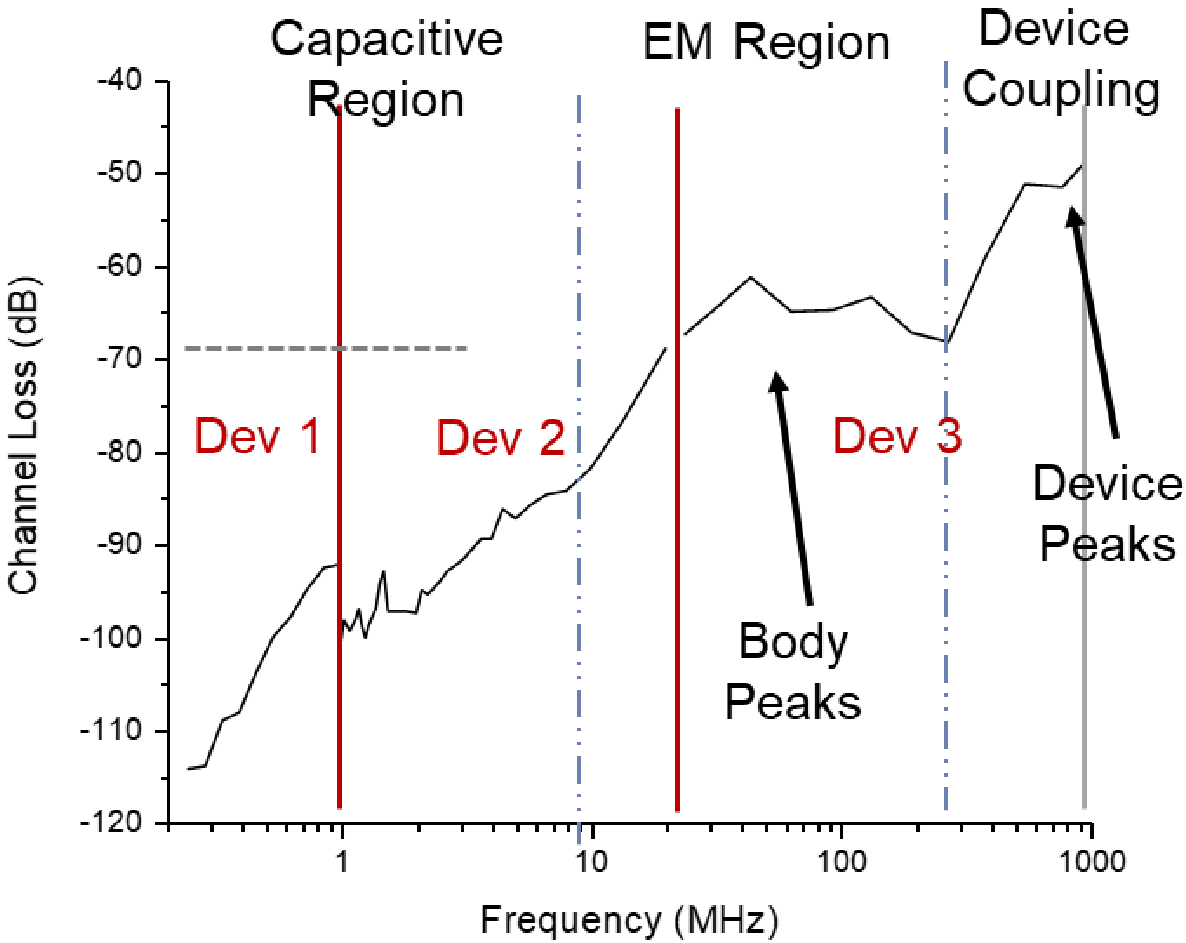


(c) Body to Device Coupler

Inter-body Coupling Measurements

Measurement setup in Anechoic Chamber





Preliminary measurements – *additional meas ongoing*

- **Inference:**
- i) **Capacitive Region:** DC to ~100 kHz (for height = 180 cm, distance = 2m), 20 dB/decade rising slope
- ii) **EM Region:** Above ~100 kHz, rising slope is roughly 40 dB/decade

Experiment 4

MHz-GHz Wearable Channel Model ?

High Frequency Channel Measurements

- **Purpose:** Determine average path loss in HBC channels from MHz to GHz

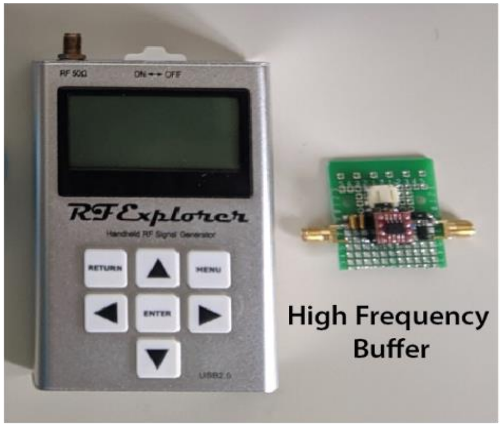
- **Observation:** Channel loss is lower for high impedance termination by 20dB at 10MHz, and equal around 80MHz

- **Inference:**
  - Low-f C-term much better R-term
  - >100MHz gap reduces

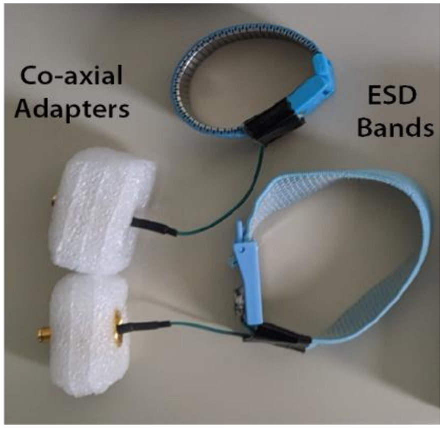
(a) Transmitting devices: Handheld Frequency Generators

1 MHz - 20 MHz   24 MHz - 6 GHz

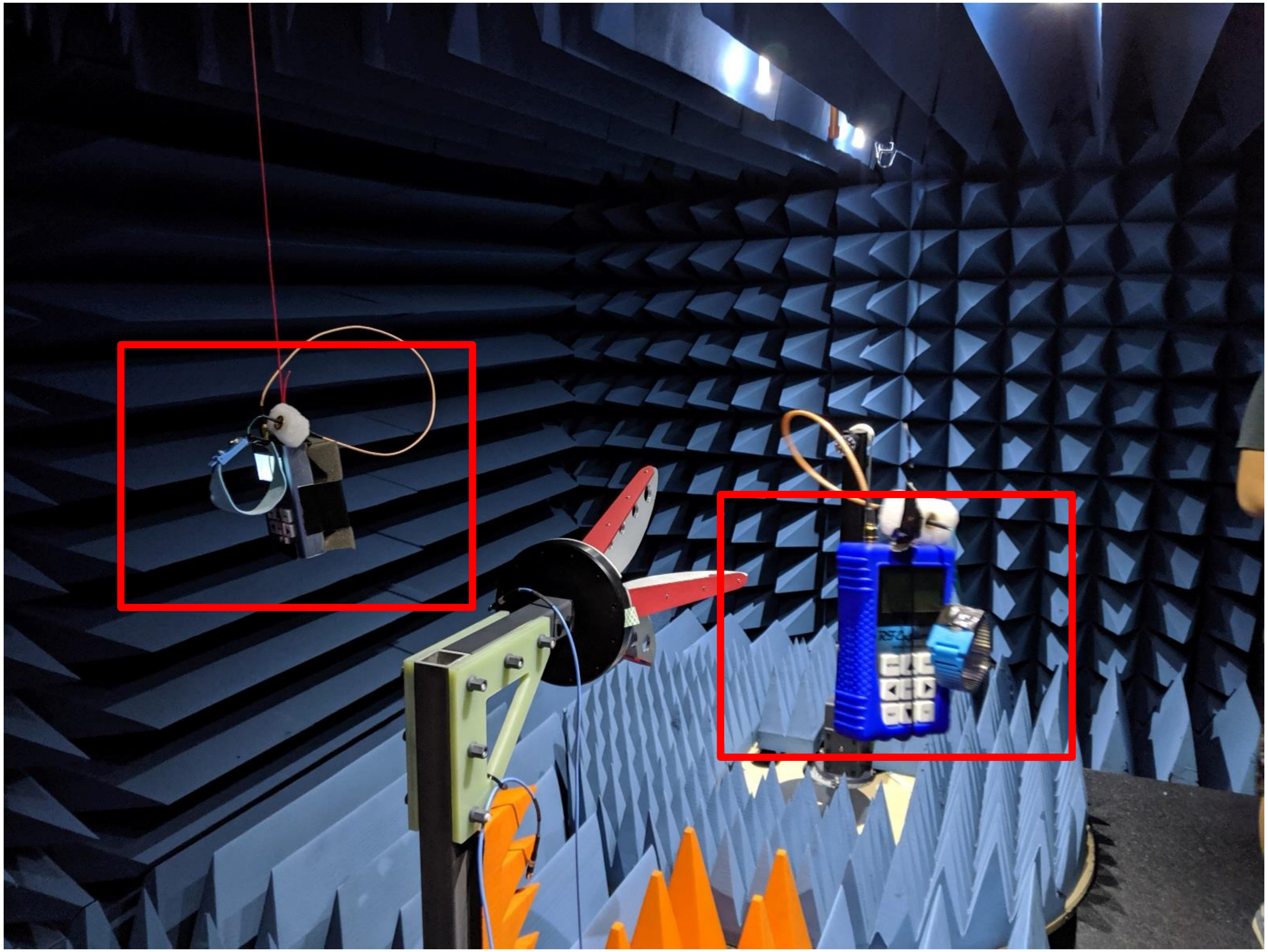
(b) Receiving Device: Handheld Spectrum Analyzer



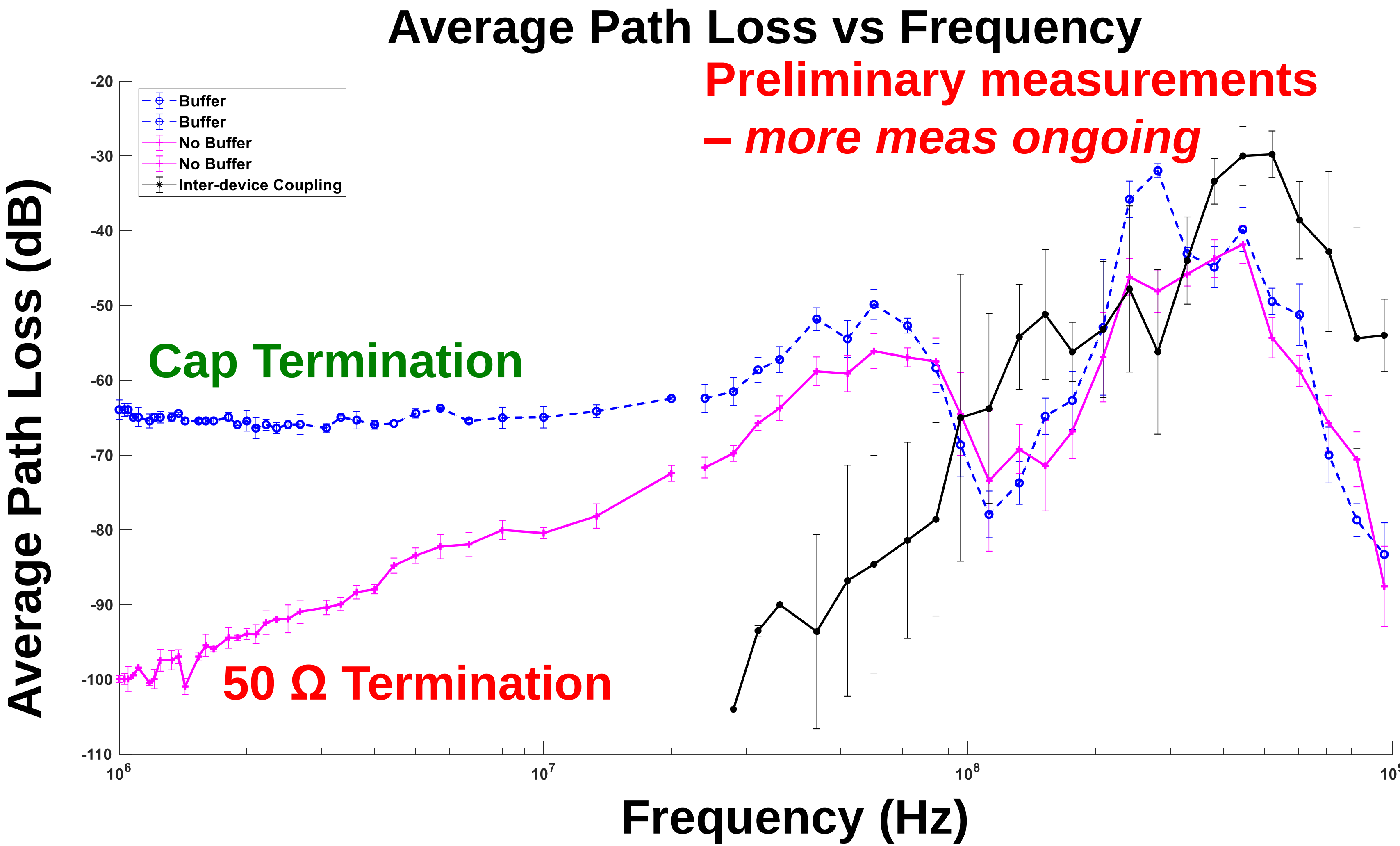
(c) Body to Device Coupler



Hanging setup for Inter-Device



High Frequency Channel Measurements

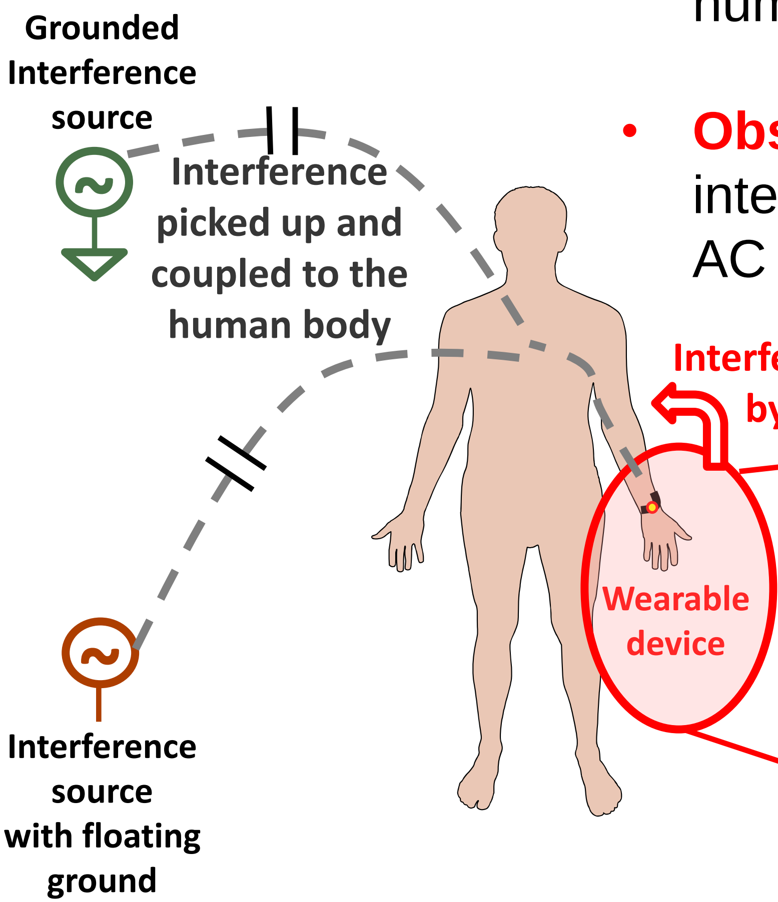


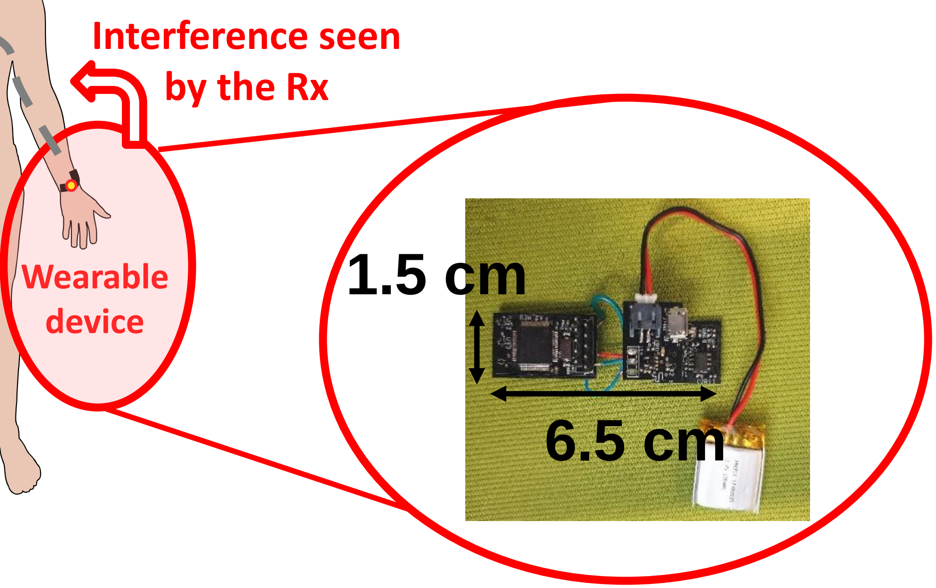
Experiment 5

What about Interference on Human Body ?

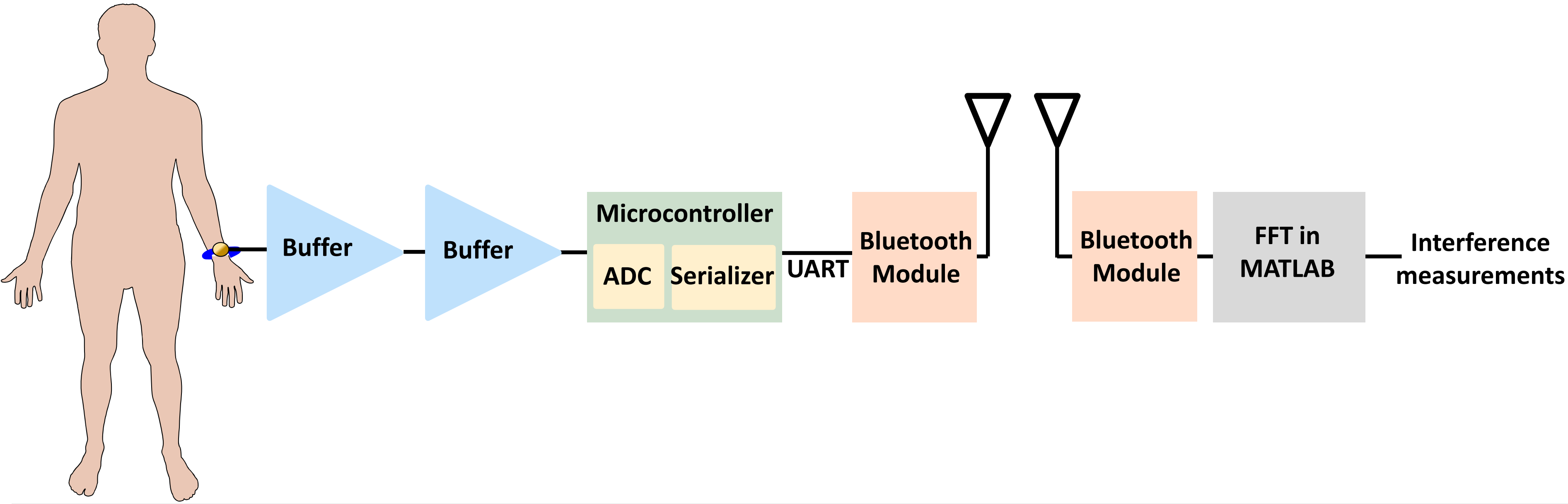
Interference Measurement Setup

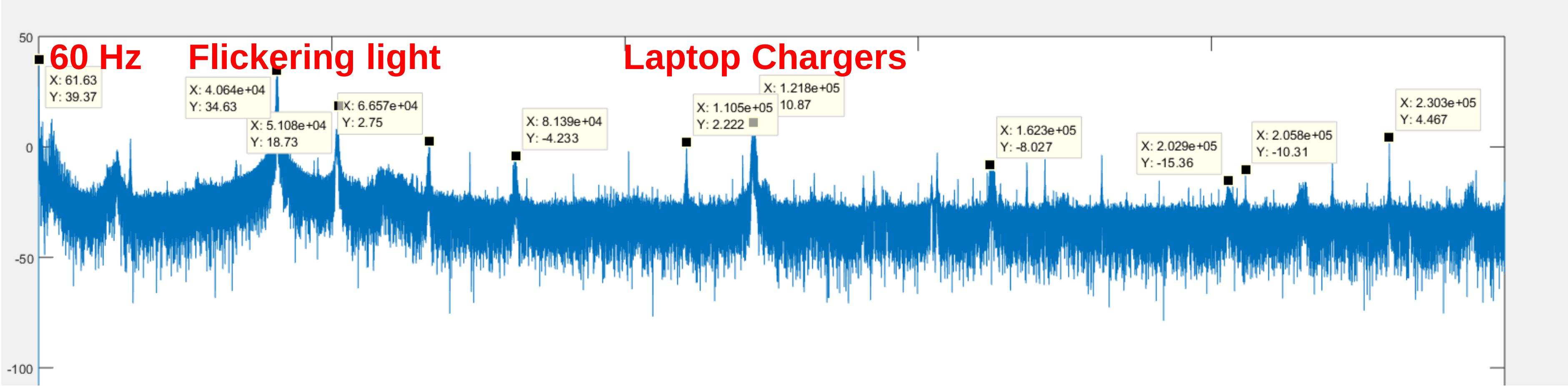
- **Purpose:** Characterization interferences on the human body in a variety of environments
- **Observation:** Common low frequency interferences: 60Hz, 40-50kHz building lighting, AC charging adapters 100kHz,200kHz





Interference on Body (< 250kHz)

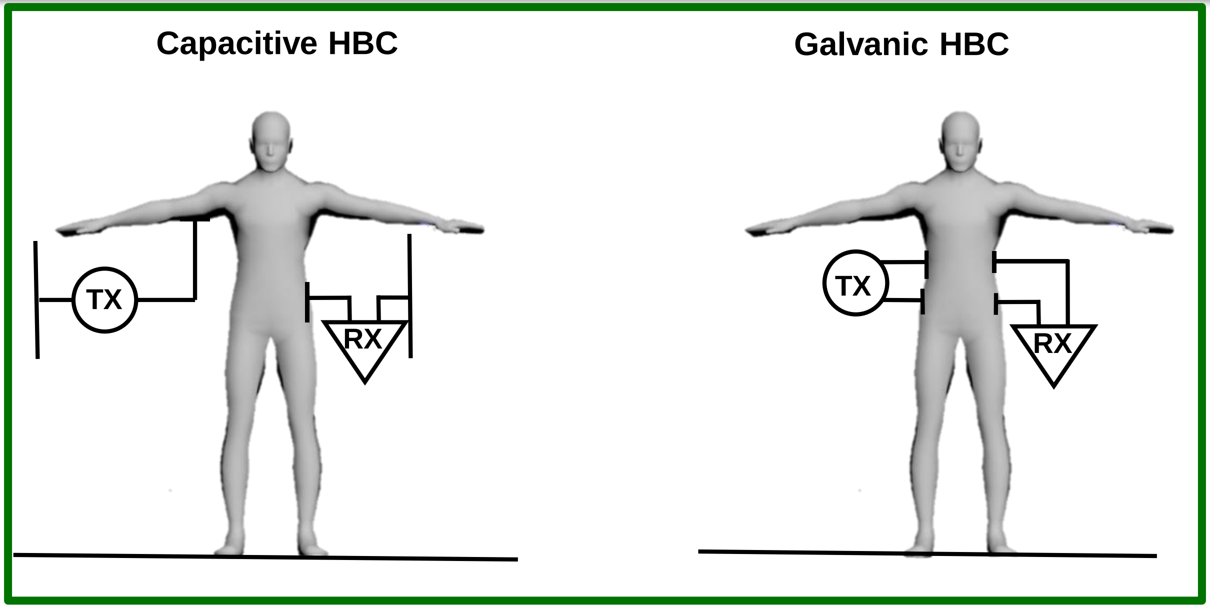




Experiment 6

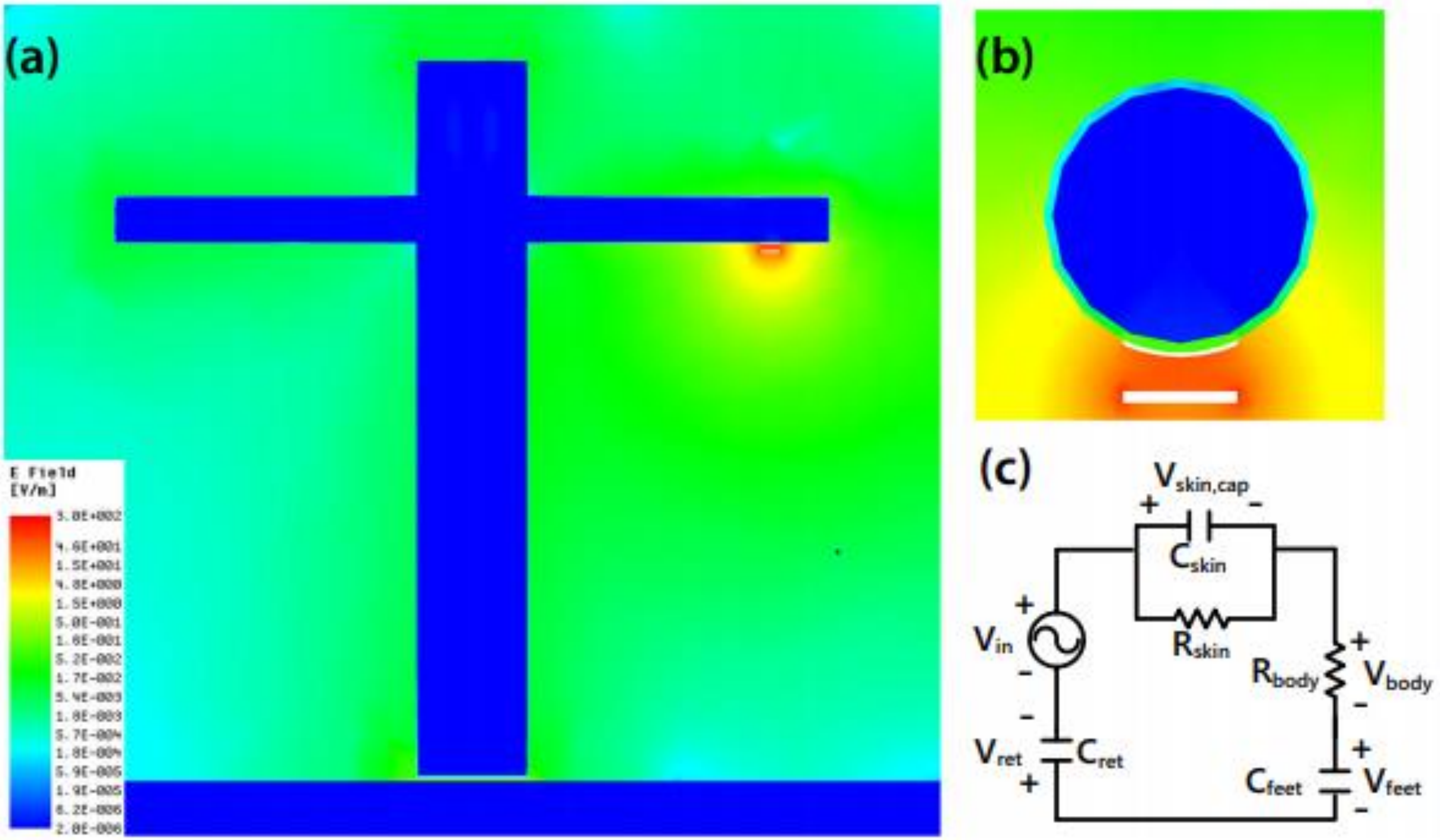
Is EQS-HBC safe for Humans?

HBC Safety Study



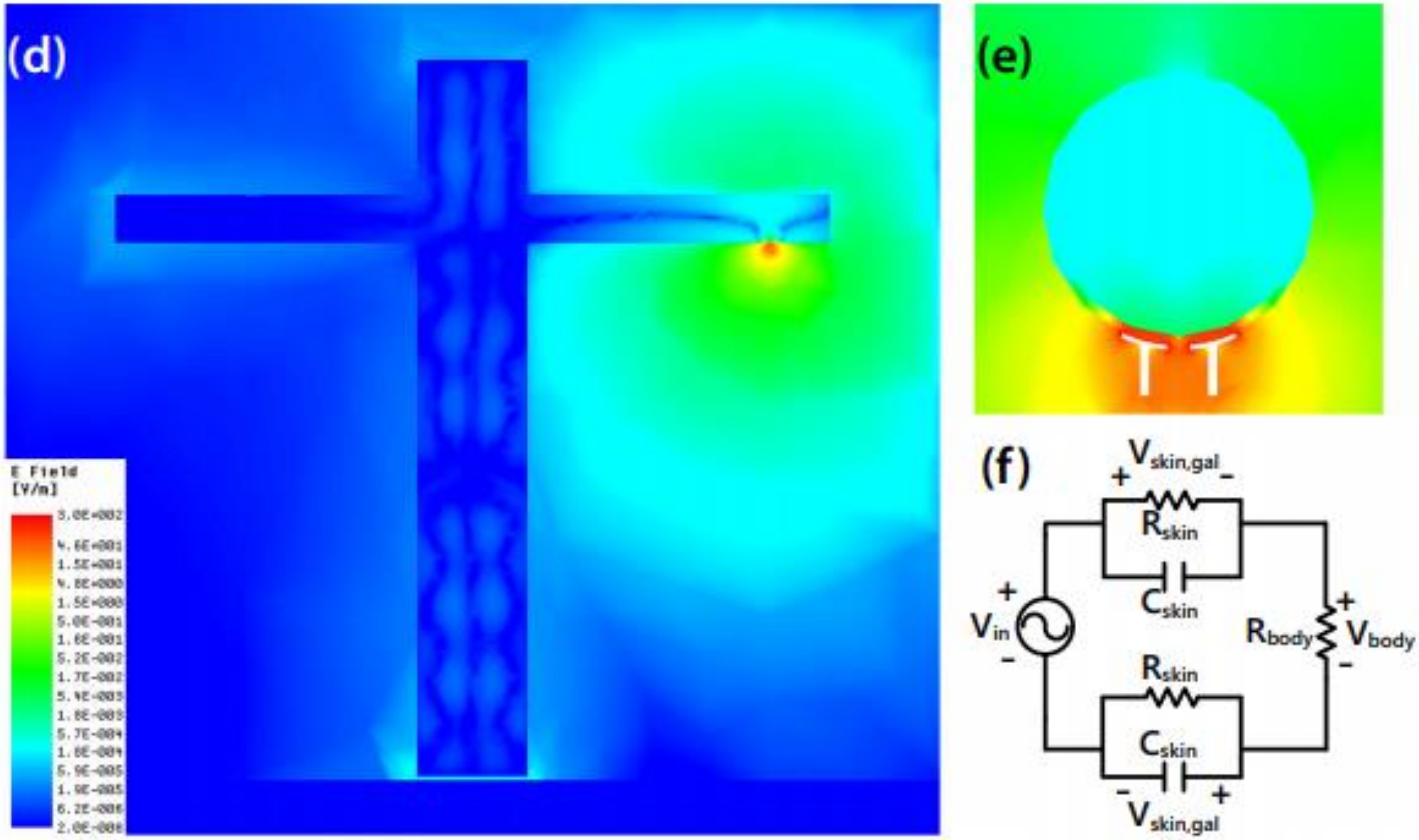
- **Purpose:** Determine safety of EQS-HBC and compliance with standards such as ICNIRP, IEEE, NIOSH
- **Observation:** Field Limits ~100x lower in EQS range, no change in vitals on small safety study subjects.
- **Inference:** Depends on excitation/termination, galvanic excitation may require current limiting circuitry to be compliant with safety

E-Field Distribution: Capacitive HBC



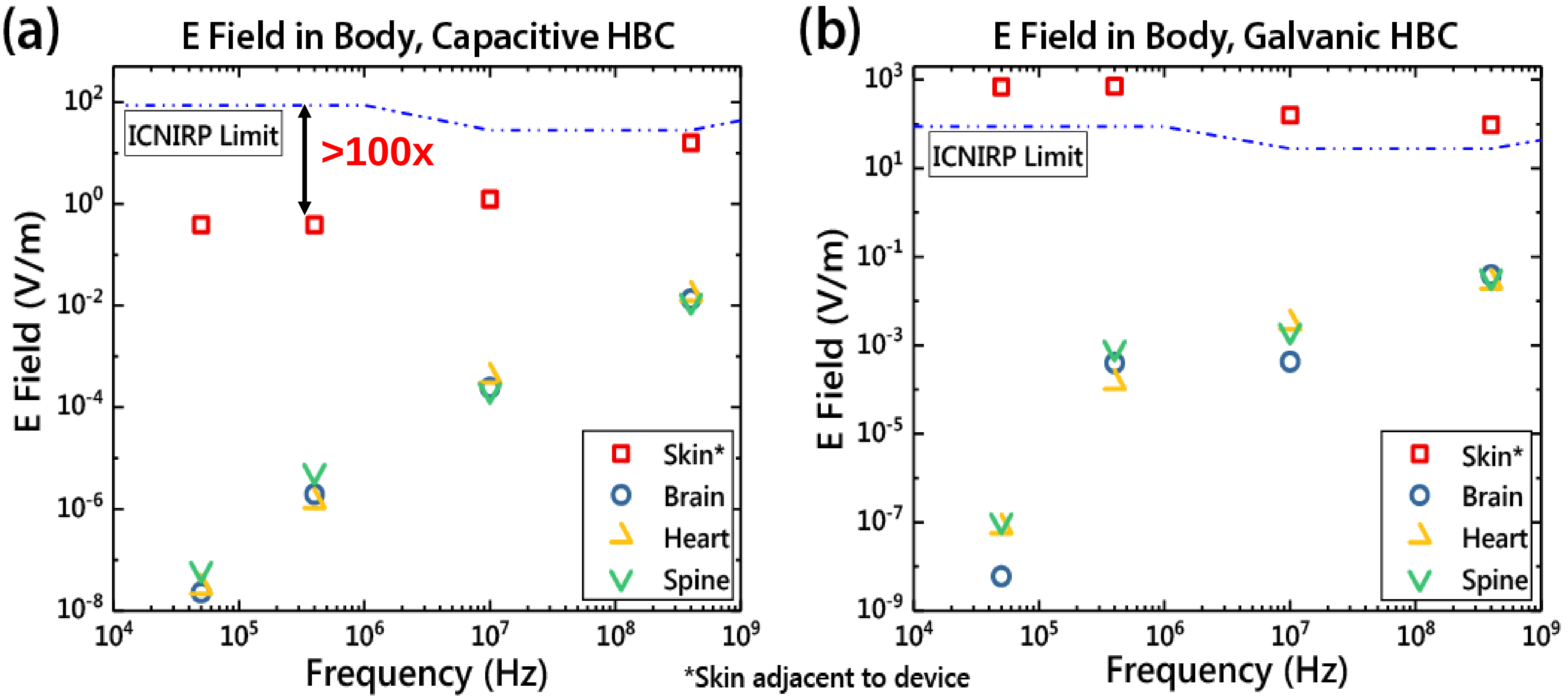
Low field intensity on the skin

E-Field Distribution: Galvanic HBC



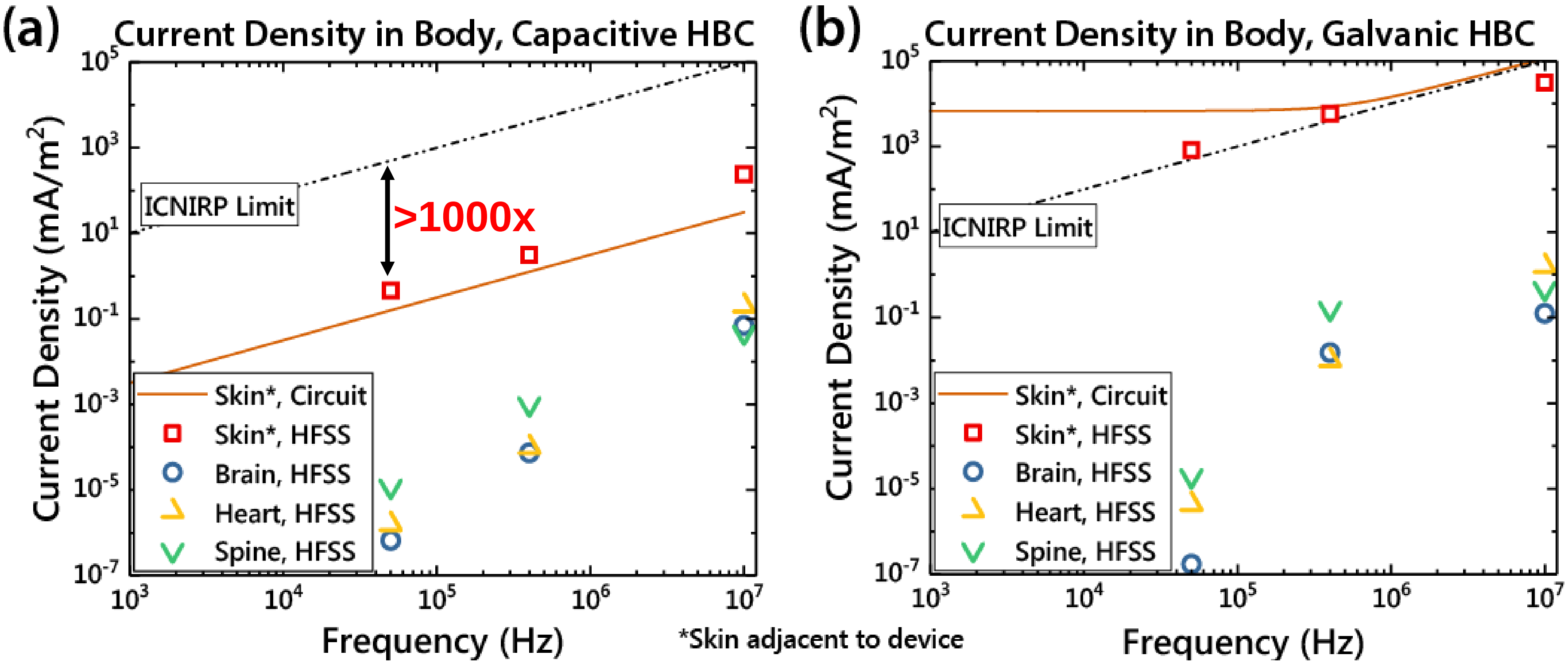
Higher field intensity close to the skin surface

Safety Limits: Electric Field



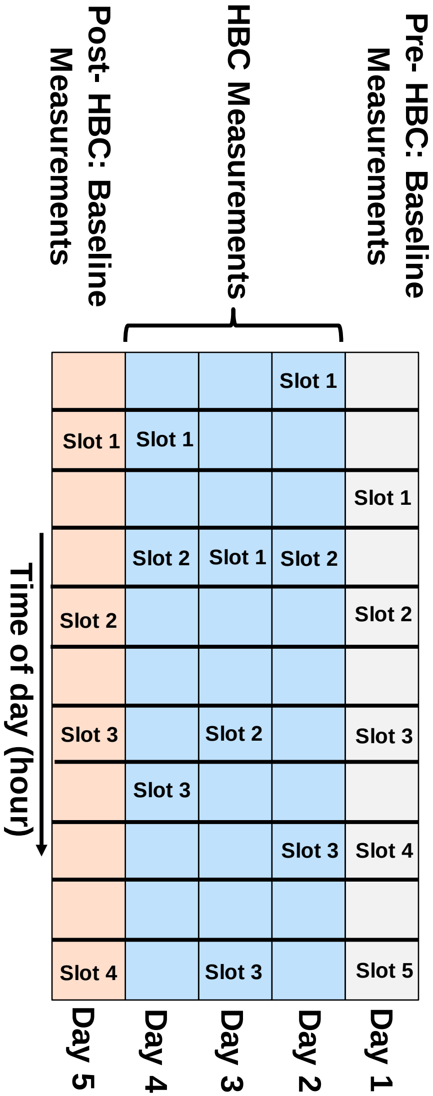
*Skin adjacent to device

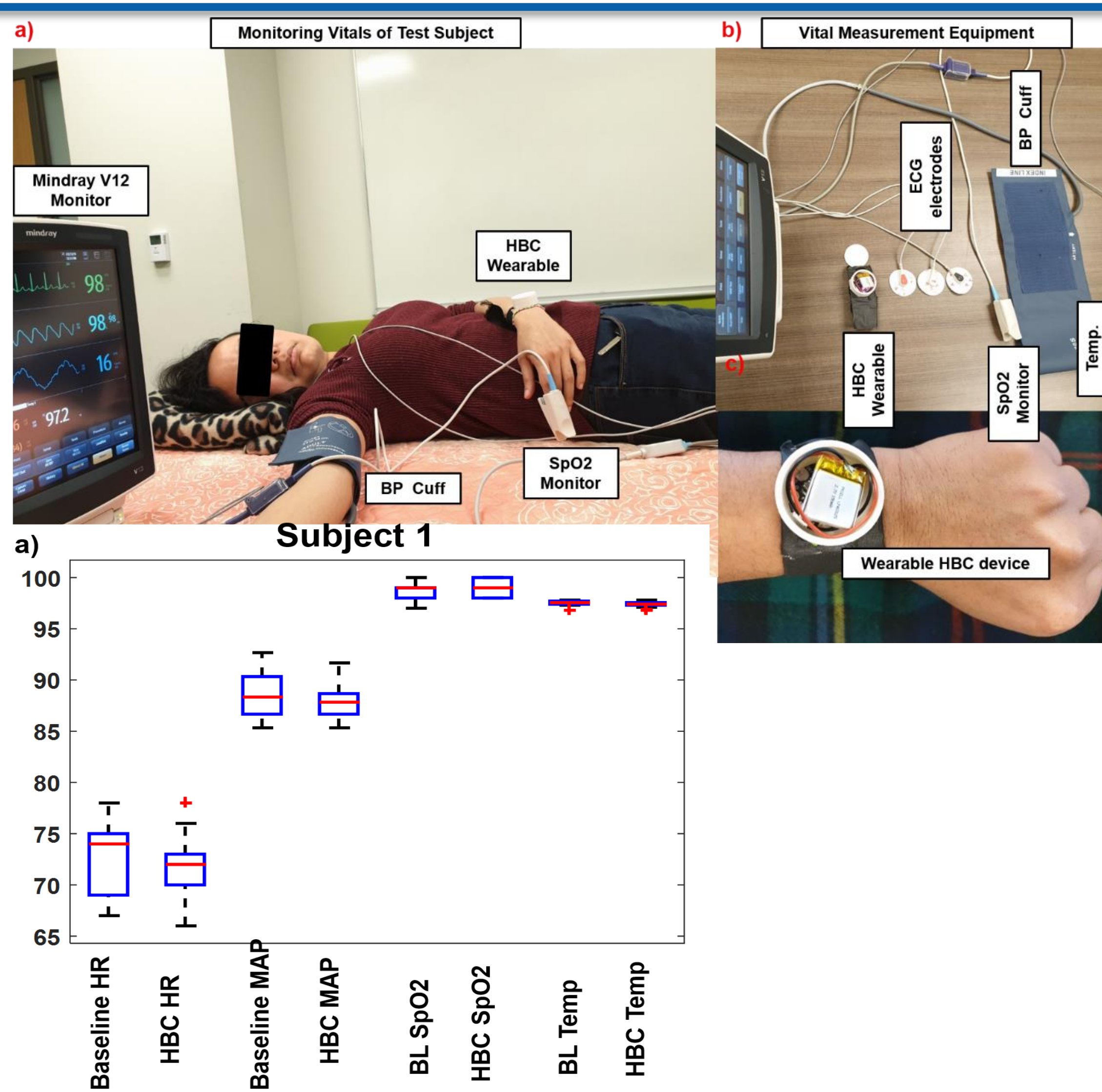
Safety Limits: Current Density



Validation through Circuit/FEM simulations

Safety Study Experiment Setup



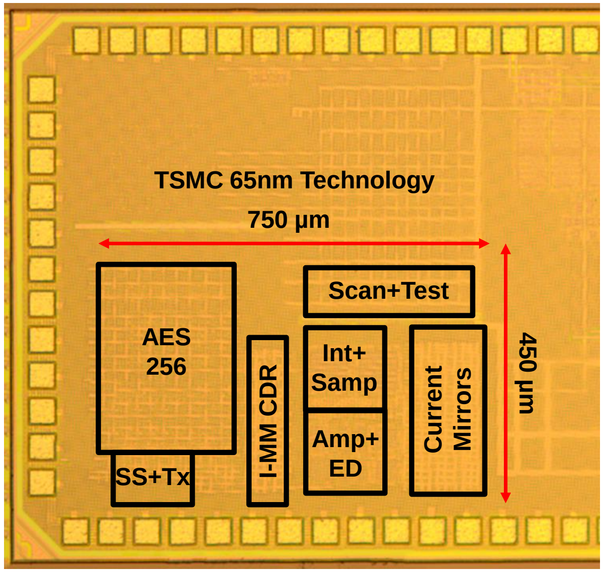


Experiment 7

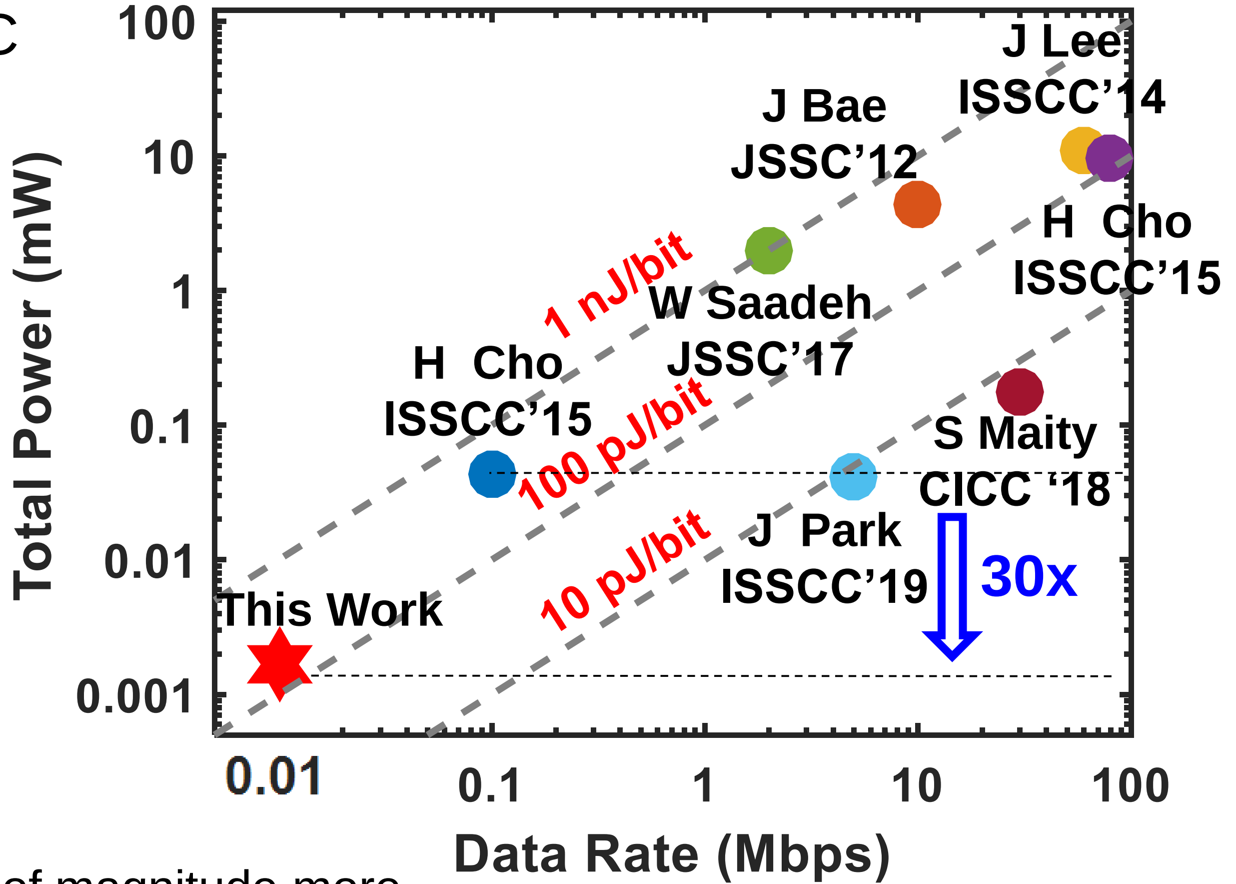
EQS-HBC Power Consumption
→ Lowest energy Body Area Network Possible?

EQS-HBC IC: Energy Requirements

- Developed World's Lowest Power BAN IC
- **~1.5uW @ 10Kbps**
- Low-f, Low-loss



Comparison with State of the Art HBC Transceivers



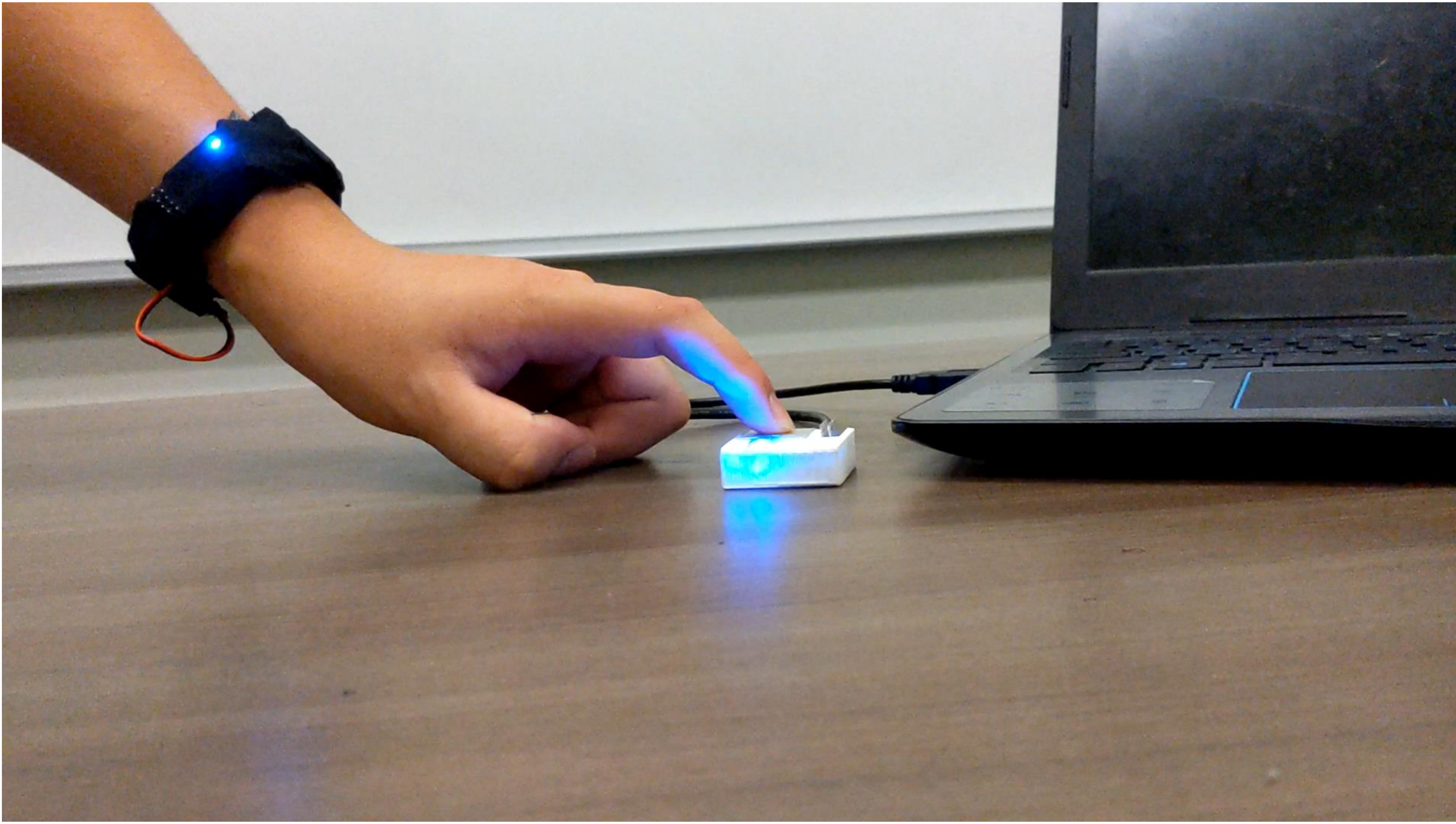
Implication: Opens up order of magnitude more lifetime of wearable connected patch, maybe energy-harvested

Experiment 8

Applications of EQS-HBC

Wearable-Wearable EQS Demo

Miniaturized Wearable-Machine EQS-HBC



This Year (Oct 18 – Sep 19)

1. **Theoretical Model for Return Capacitance**
2. **MHz-GHz Measurements and Bio-Physical Modeling**

A. **Security Property – Inter-Human Coupling**

B. **Conduction Property – Intra-body Loss**

4. **Environmental Interference**

A. **Human Body Antenna Properties – Wearable Measurement**

5. **Safety Analysis**
6. **Lowest-Power BAN**
7. **Application Demonstration**

Next Year

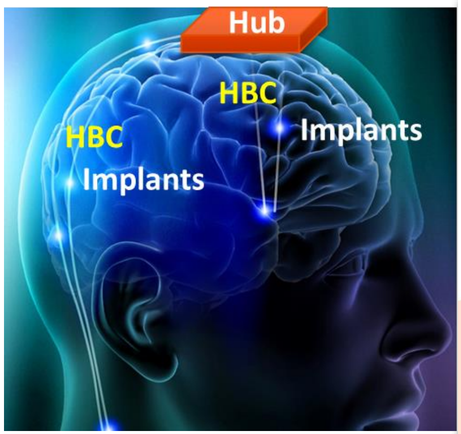
1. **Excitation – Termination Dependence Channel Model**
   A. Galvanic
   B. In-Body to Out of Body

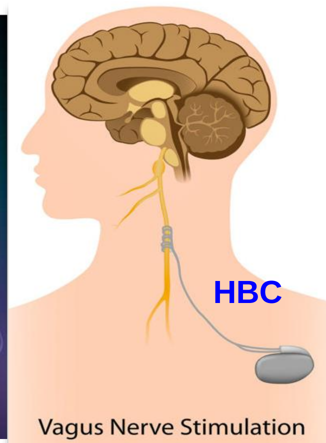
2. **MHz-GHz Measurements and BioPhysical Modeling**
   A. Conduction Property – analysis and channel-loss database
   B. Security Property – Inter Human Coupling 'in-field'

3. **Environmental Interference**
   A. Human Body Interference Database

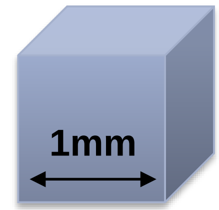
4. **Optimum Coupler**
   A. EM region, Magnetic

Long-Term Societal Needs: Impact of HBC

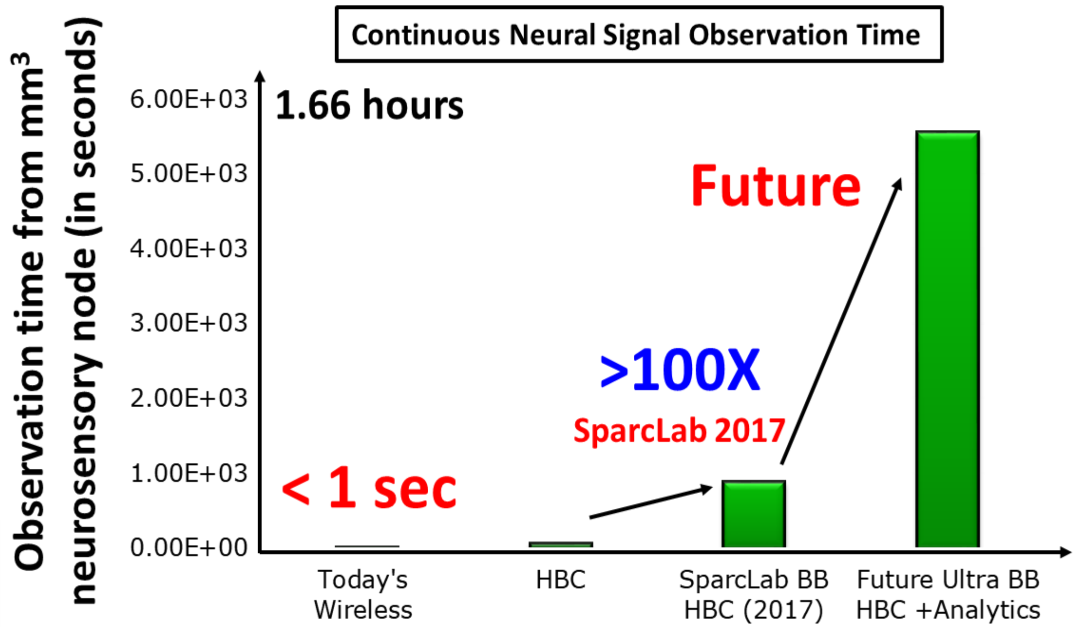




Neuroscience, Healthcare, AR/VR needs
Secure Information Exchange
around the Human Body!



mm^3 neural implant → 2 Joules



HBC is the solution....

Acknowledgement

Dr. Patrick Bradshaw

AFOSR Young Investigator Program (YIP)

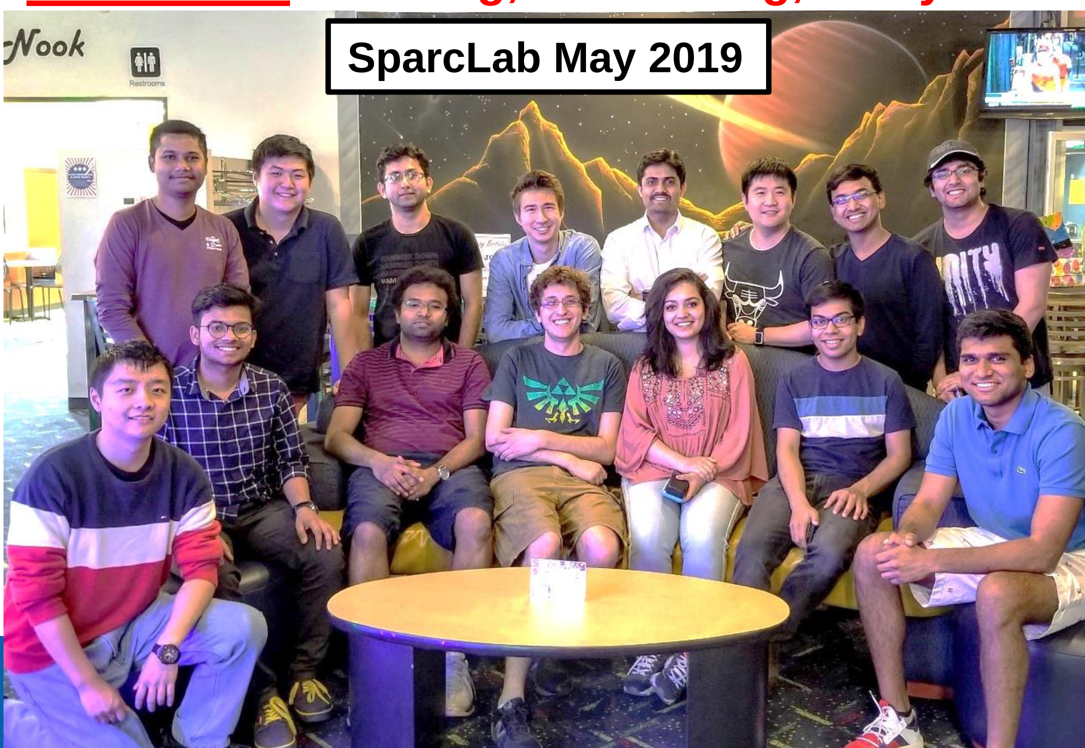
Acknowledgement

PI: Shreyas Sen

Assistant Professor, ECE, Purdue University

13+ years research experience @
Georgia Tech, Intel Labs, Qualcomm, Rambus

SPARC Lab: Sensing, Processing, Analytics & Radio Communication



SparcLab May 2019

THANK YOU

Publications

a) Conduction Properties:

1. S. Maity, K. Mojabe and S. Sen, "Characterization of Human Body Forward Path Loss and Variability Effects in Voltage-Mode HBC," in IEEE Microwave and Wireless Components Letters, vol. PP, no. 99, pp. 1-3.
http://ieeexplore.ieee.org/document/8301525/
The results highlight the **need for** a) **high impedance termination for HBC signaling** and b) future research on investigating return path loss. It reports the variation in **forward path loss** with excitation/termination modalities, electrode area and pressure
2. Maity, S., He, M., Nath, M., Das, D., Chatterjee, B., & Sen, S. (2018). BioPhysical Modeling, Characterization and Optimization of Electro-Quasistatic Human Body Communication. arXiv preprint arXiv:1805.05200.
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Demonstrates the first Bio-Physical Model explaining Electro-Quasistatic HBC Channel characteristics.

3. Shovan Maity, Debayan Das, Baibhab Chatterjee, and Shreyas Sen, "Characterization and Classification of Human Body Channel as a function of Excitation and Termination Modalities," in IEEE Engineering in Medicine and Biology Conference (EMBC 2018)
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4. S. Maity, S. Redford, D.Yang, D. Das, B. Chatterjee, S. Sen, " *BodyWire:* Enabling New Interaction Modalities by Communicating Strictly During Touch using Human Body Communication " submitted to CHI 2019
Demonstrates how Electro-Quasistatic HBC enables Communication 'strictly' during Touch.

b) Security Properties:

5. D. Das, S. Maity, B. Chatterjee, and S. Sen, "Enabling Covert Body Area Network using Electro-Quasistatic Human Body Communication" submitted to **Nature Scientific Reports (major revision)**

c) Applications:

6. S. Maity, B. Chatterjee, G. Chang and S. Sen, "A 6.3pJ/b 30Mbps -30dB SIR-tolerant Broadband Interference-Robust Human Body Communication Transceiver using Time Domain Signal-Interference Separation," in IEEE Custom Integrated Circuits Conference (CICC 2018)
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Back-up Slides

Safety Study Experiment Setup

Vital Measurements of subjects without HBC device for establishing baseline parameters

⇩

Vital Measurements of subjects while wearing HBC device multiple times a day over 15 min windows

⇩

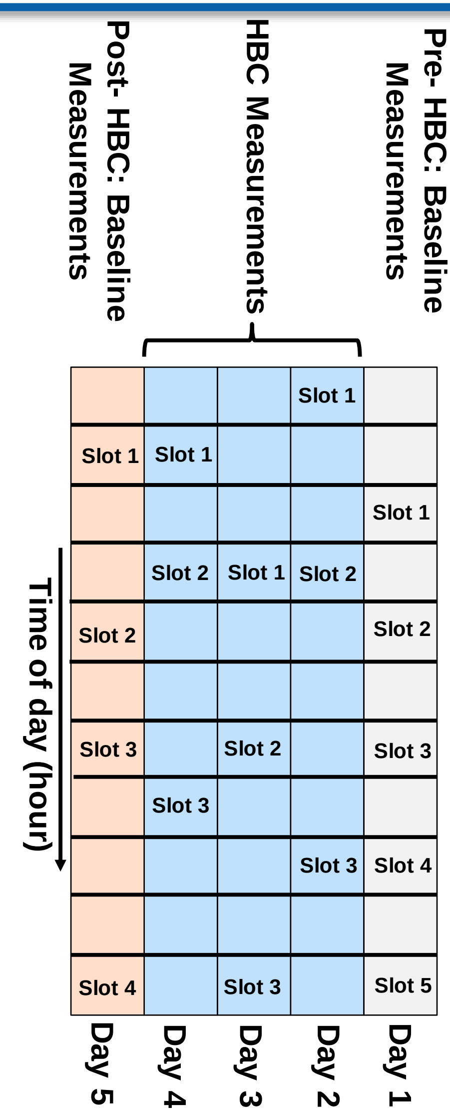
Record multiple readings per day over multiple days: HBC data points

⇩

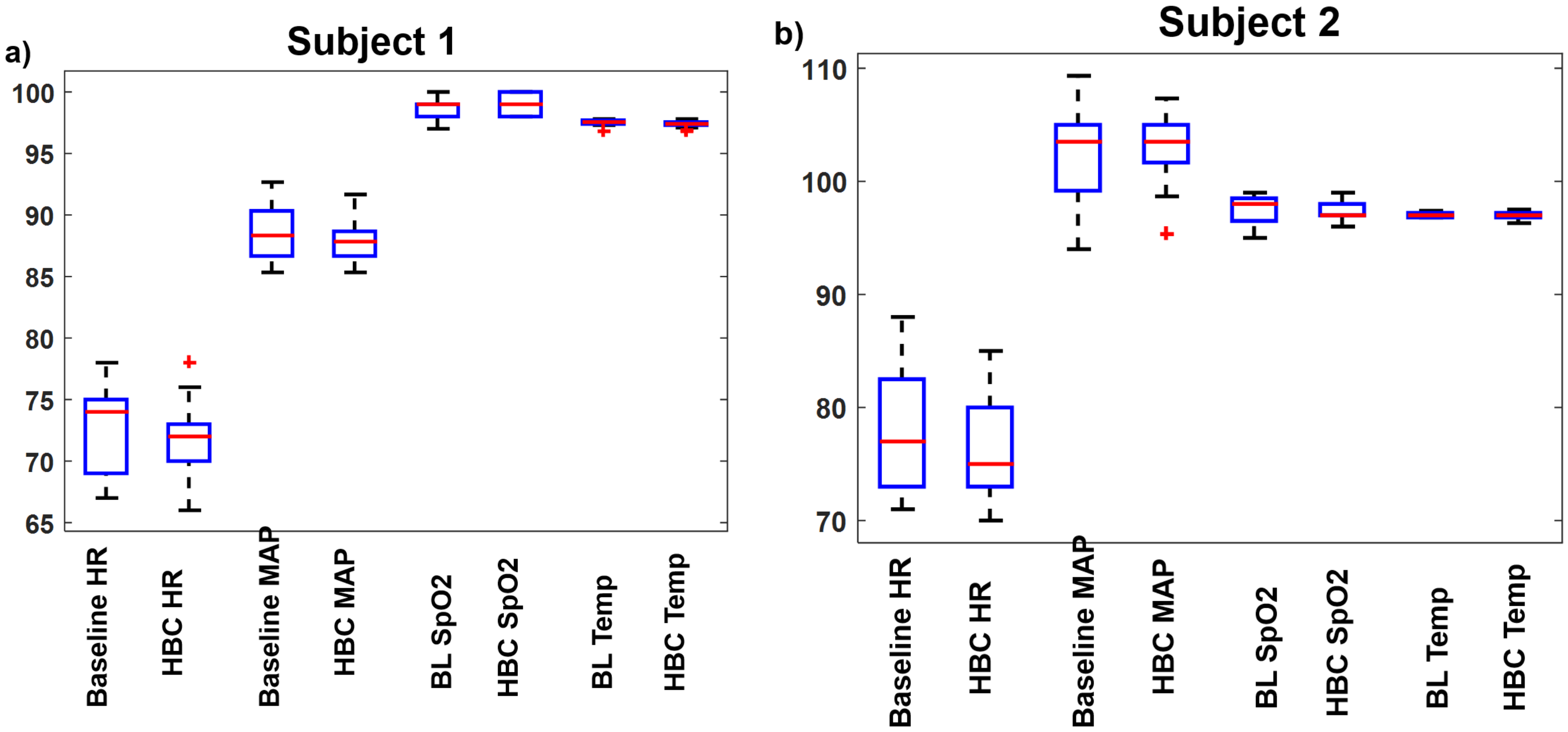
Further measurements of vitals without HBC device for additional baseline data points

⇩

Carry out statistical analysis through paired t-tests on vital data of individual and whole population



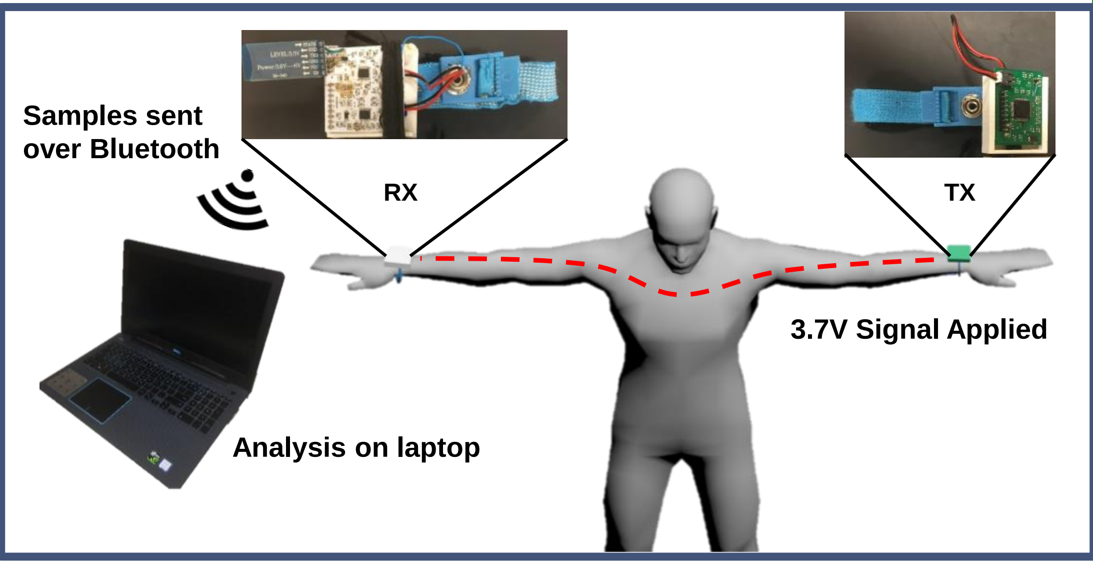
Safety Study

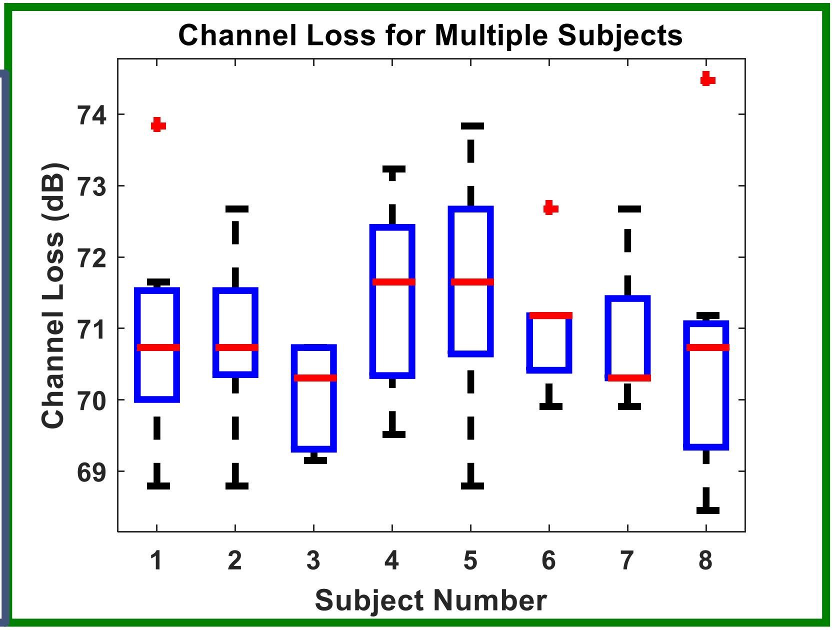


Wearable-Wearable Channel Loss

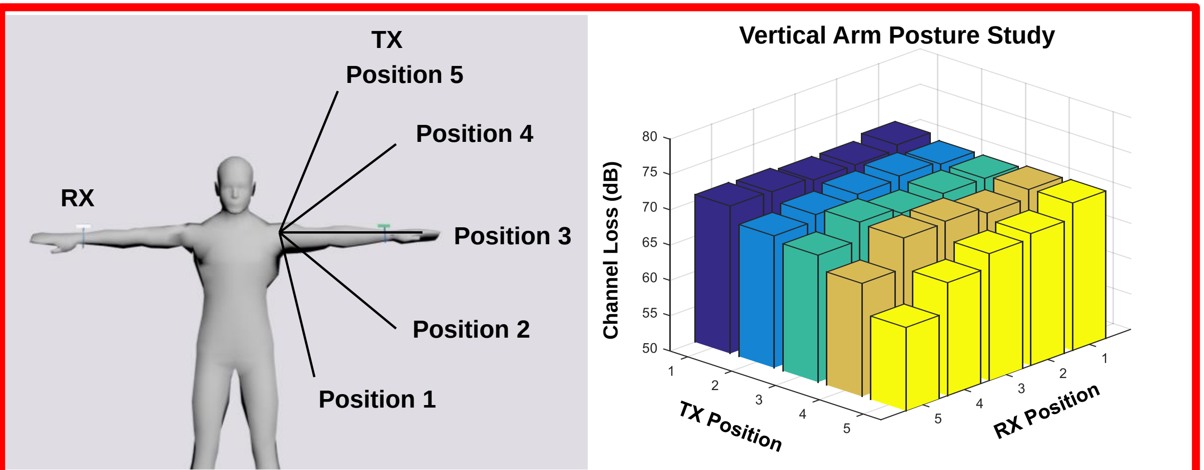
- Channel measurements on multiple subjects at different times of day
- Fully mobile setup enabling new studies

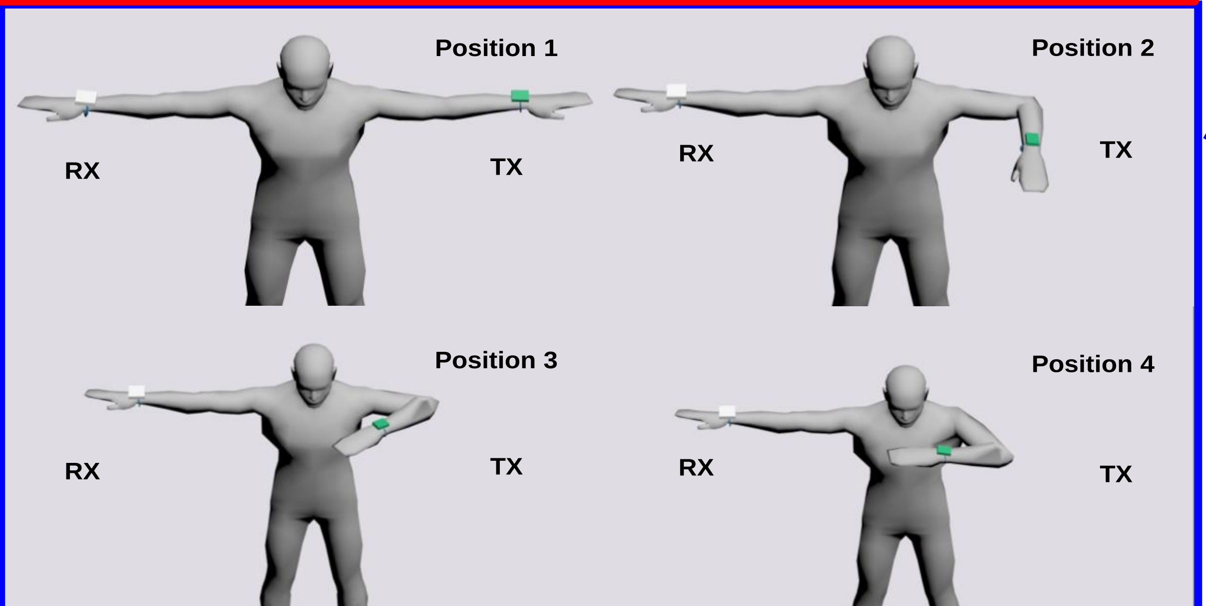
Measurement Setup

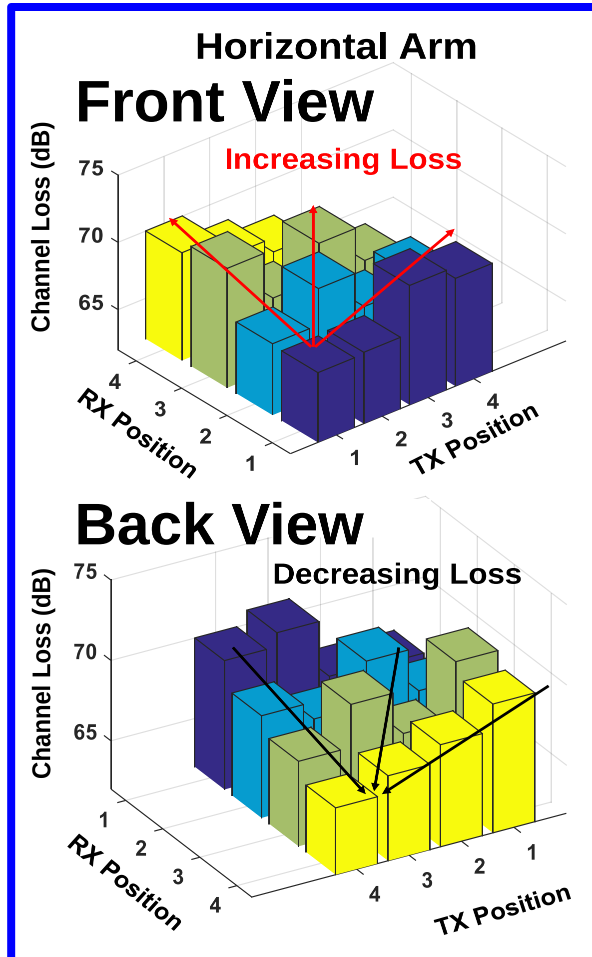




Dependence on Posture







Dependence on Environment