2nd Buffalo Day *for* 5G and Wireless Internet of Things

EE701: The Internet of Things: From Technology to Applications

INTRA-BODY COMMUNICATION SYSTEMS AND NETWORKING

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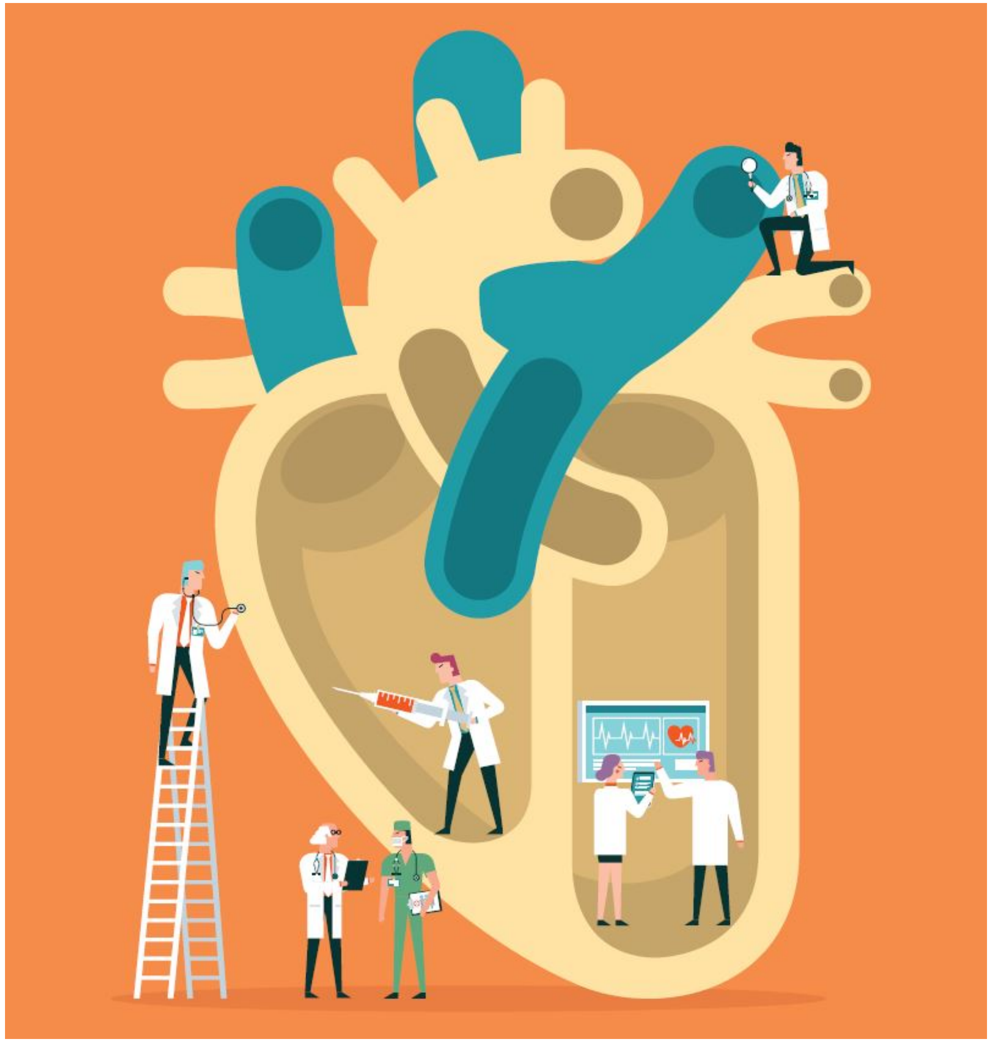
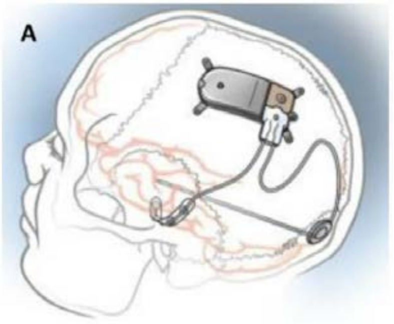
OUTLINE

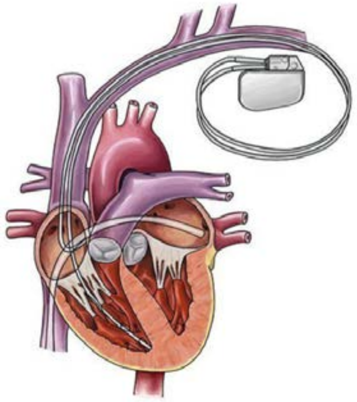
- Overview and definitions
- State of the art
- The Internet of Medical Things (IoMT)
- Challenges and requirements
- Classifications and communication technologies
- Networking aspects
- Discussion & Conclusion



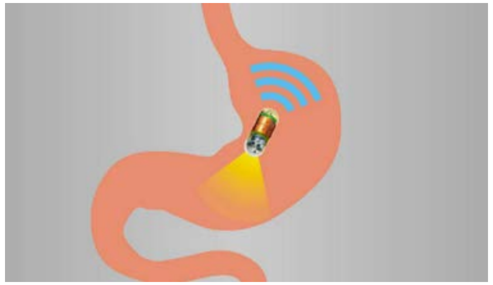
MAIN APPLICATIONS



- Neurostimulators

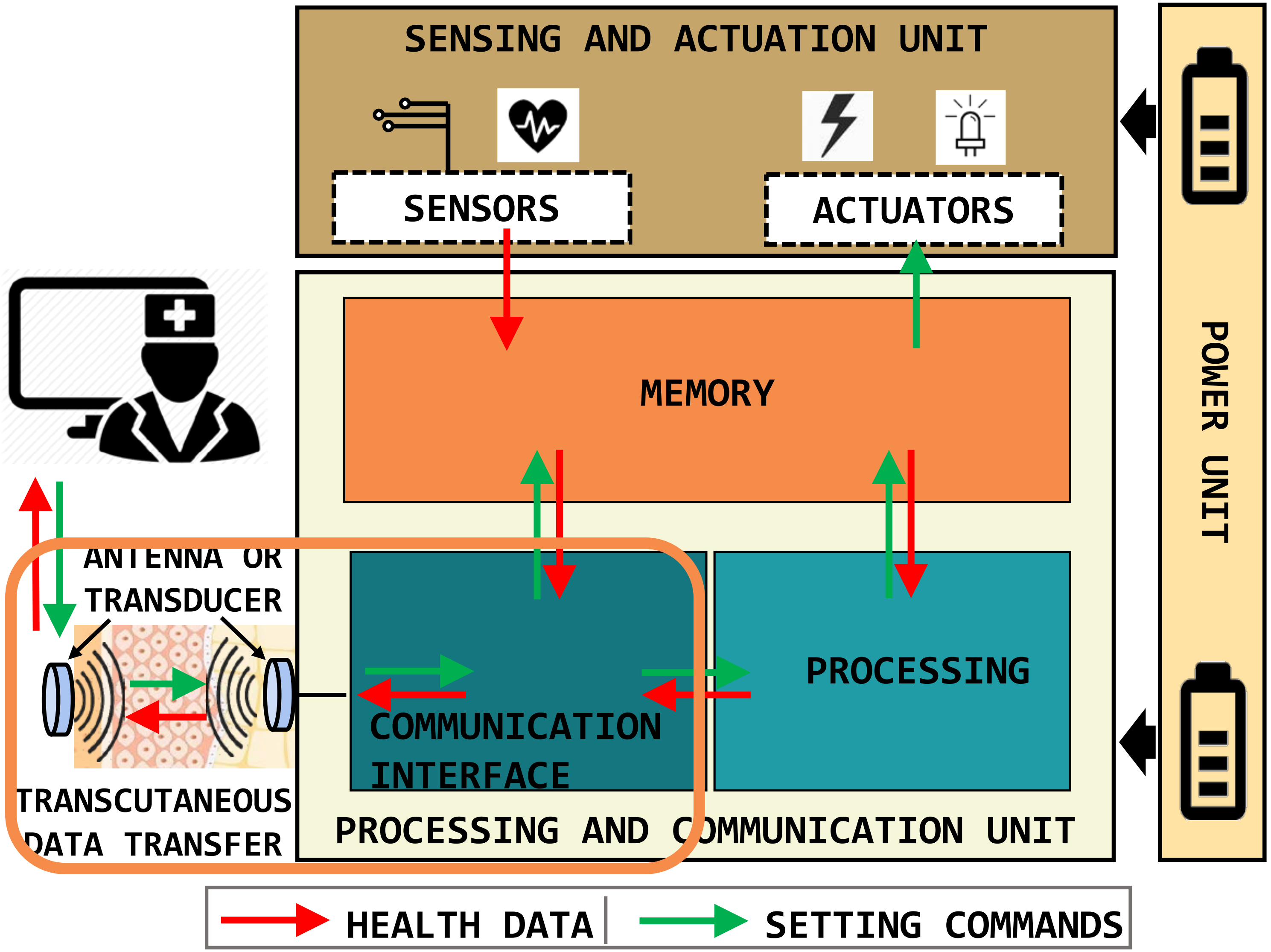


- Pacemakers



- Endoscopic capsules

ARCHITECTURE OF AN IMPLANTABLE MEDICAL DEVICE (IMD)



Medical applications QoS requirements

Application	Bit rate	Delay	BER
Deep brain stimulation	< 320 kbps	< 250 ms	$< 10^{-10}$
Drug delivery	< 16 kbps	< 250 ms	$< 10^{-10}$
Capsule endoscope	1 Mbps	< 250 ms	$< 10^{-10}$
ECG	192 kbps	< 250 ms	$< 10^{-10}$
EEG	86.4 kbps	< 250 ms	$< 10^{-10}$
EMG	1.536 Mbps	< 250 ms	$< 10^{-10}$
Glucose level monitor	< 1 kbps	< 250 ms	$< 10^{-10}$

Medical devices (wearables and implants*) communication data rates

Device	In-body location	Data rate	Data flow direction
Temperature	Forehead	48 bps	Uplink
Heart Beat Rate	Finger tip	48 bps	Uplink
Pulse Oximetry	Finger tip, at injured site	48 bps	Uplink
pH Sensor*	Implanted in oral cavity	48 bps	Uplink
CardioMEMS	Pulmonary artery	1.44 kbps	Uplink
Fall detection	Waist band	1 kbps	Uplink
Barostim Sensor*	Carotid artery of neck	48 bps	Uplink/downlink
Barostim stimulator*	Carotid artery at collar bone	48 bps	Uplink/downlink
Bladder volume sensor*	Bladder	48 bps	Uplink
Bladder control*	Under abdomen skin	48 bps	Uplink
pstim* - pain reliever	Ears (battery behind ears)	48 bps	Uplink/downlink
Artificial Retina*	Behind ear	36 kbps	Uplink/downlink
Pacemaker*	Chest implant	0.5 kbps	Uplink/downlink
Hearing Aid	middle-ear or cochlear	10 kbps	Uplink/downlink
1 point ECG	On chest	4 kbps	Uplink
Glucose monitor	Beneath skin at abdomen	32 bps	Uplink/downlink
Insulin Pump*	Inside abdomen	32 bps	Downlink
Plethysmogram*	Vein implant	48 bps	Uplink
e-AR gait sensor	Ear canal	200 bps	Uplink

How the IoMT will transform the healthcare landscape

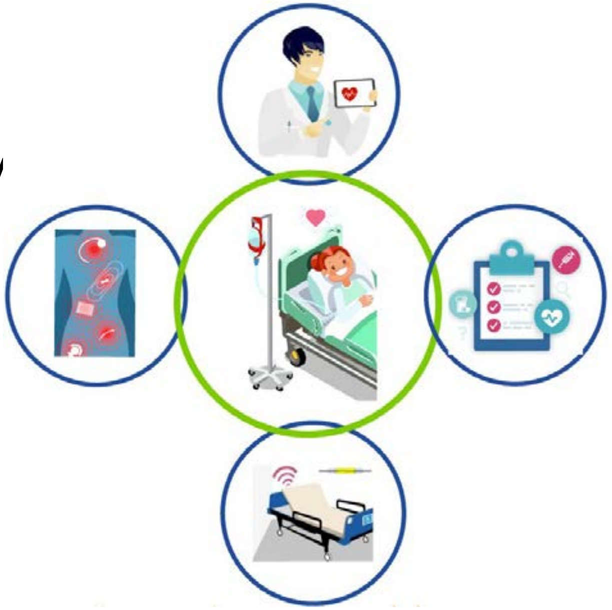
"The Internet of Medical Things (IoMT) designates the interconnection of communication-enabled medical-grade devices and their integration to wider-scale health networks in order
to improve patients' health*"* *

- **Bring together** physicians, caregivers, patients, data analytics, and "things" (implantable medical devices (IM smart pills, smart beds, etc.)

- **Remote monitoring** for early diagnosis and prevention

- **Faster response** to life-threatening events

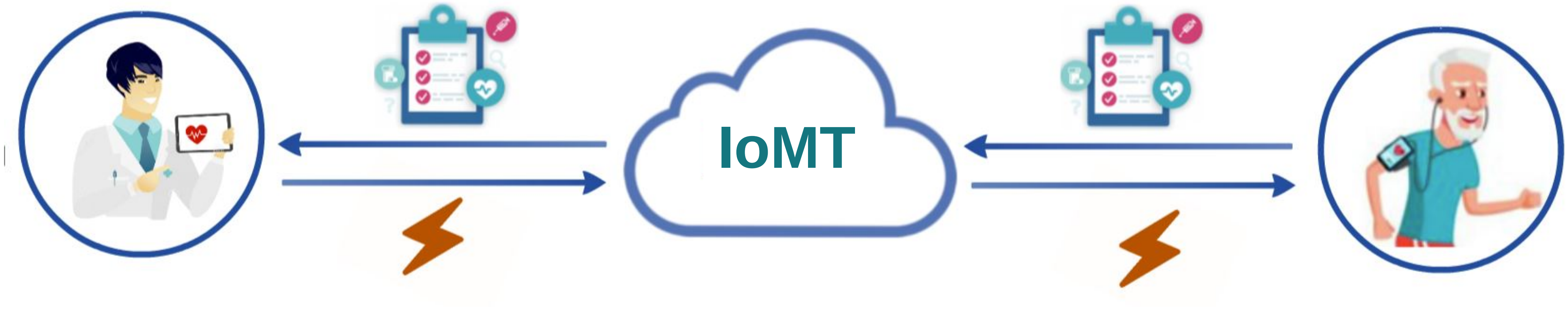
- **New business models**: $534.3B by 2025, CAGR 20.2% per year



The patient is at the center of the IoMT

* https://www.grandviewresearch.com/industry-analysis/internet-of-things-iot-healthcare-market

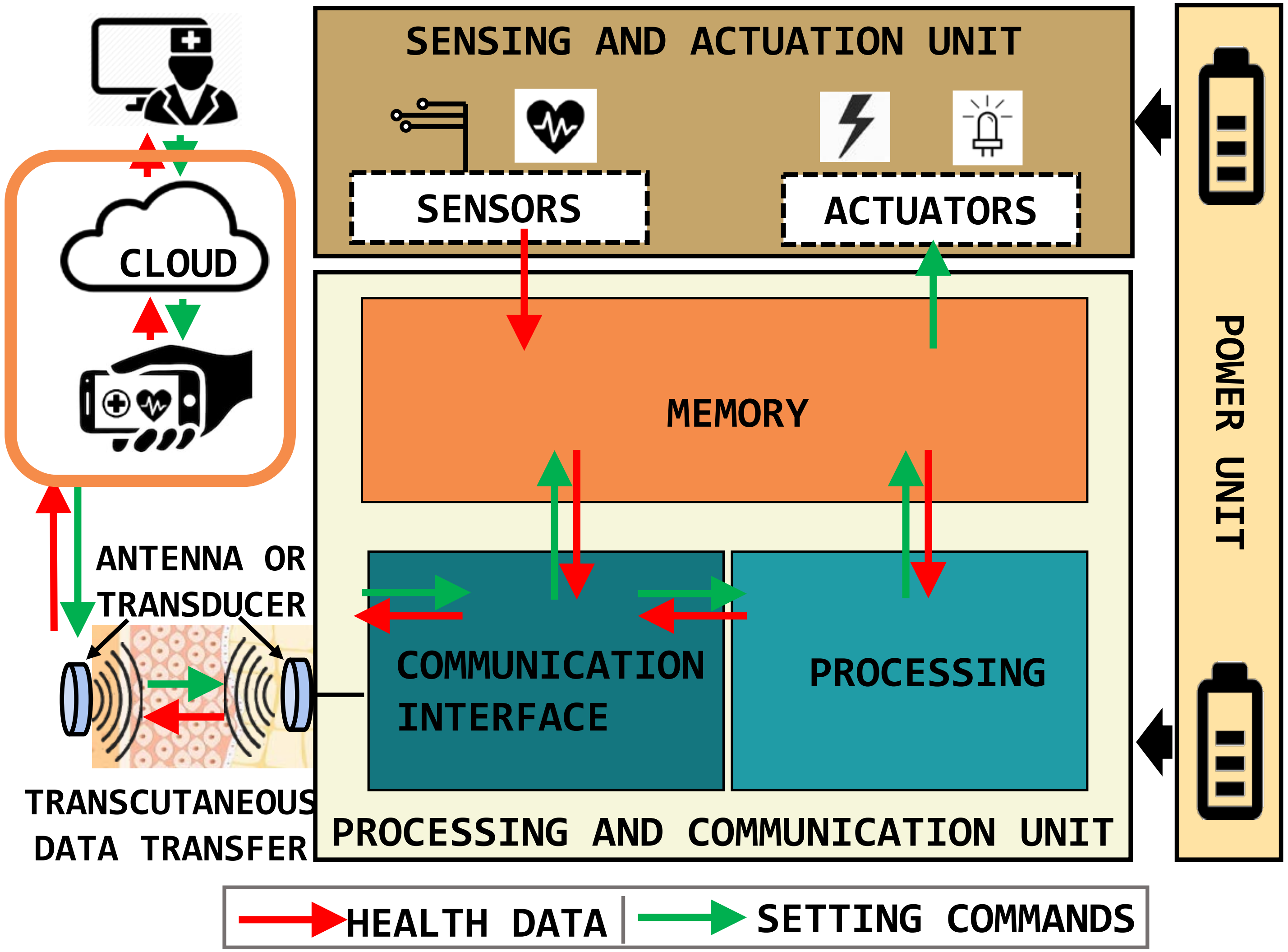
Vision: end-to-end system



Key enabler: **communication technology**

ARCHITECTURE OF A NEXT-GENERATION IMPLANTABLE MEDICAL DEVICE (IMD)

Integration of IMDs in the IoMT



Challenges

CHALLENGING WIRELESS ENVIRONMENT

- Attenuation
- Dynamical
- Heterogeneity and layered structures

FOOD AND DRUG ADMINISTRATION (FDA) REGULATION

- Max exposure limits to waves and radiations

LIMITED ON-BOARD RESOURCES

- Power/energy, computation, communication resources

HIGLY ENERGY-EFFICIENT SYSTEM

- Energy and computational power are limited

Design Requirements

MINIATURIZATION

Micra™ Leadless Pacemaker

- Comfortably implanted
- Modern leadless pacemaker 1cm^3
- Size depends on powering and functions

LONGEVITY

- Energy storage vs. power consumption
  - SNR, energy per bit, application duty-cycle
- Traditional batteries max lifetime 5-10 years
- Futuristic devices will implement new funcionalities (*e.g.*, sensing, communication, actuation, data processing)

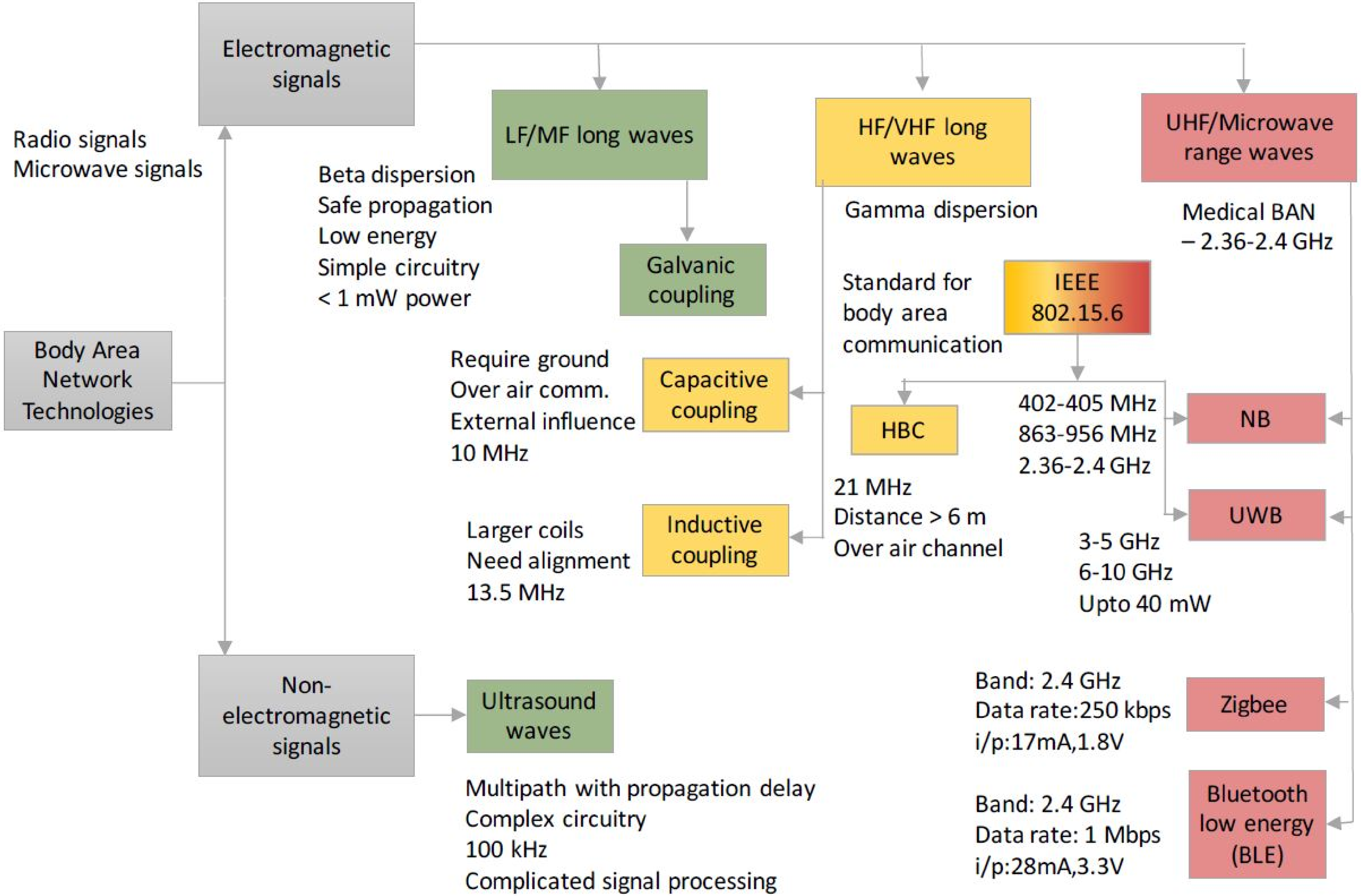
ALTERNATIVE POWERING APPROACH

- Rechargeable systems
- Energy harvesting, wireless power transfer

SAFETY & SECURITY

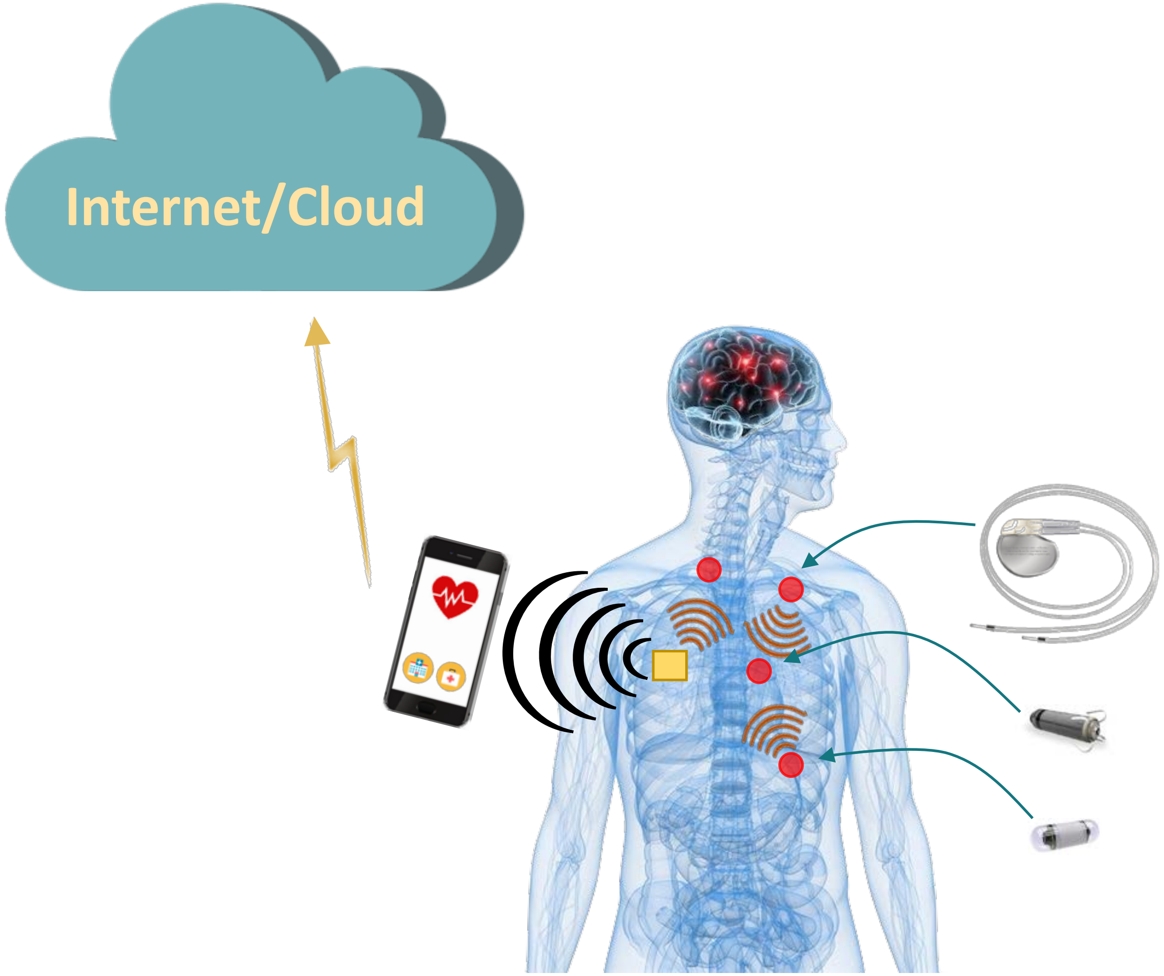
- Energy propagation (waves) through tissues
- Temperature increase
- Bio-compatible materials
- Interference with
  - Vital signals
  - Other IMDs
- Eavesdropping & hacking

COMMUNICATION TECHNOLOGIES FOR IMPLANTABLE SYSTEMS AND NETWORKS



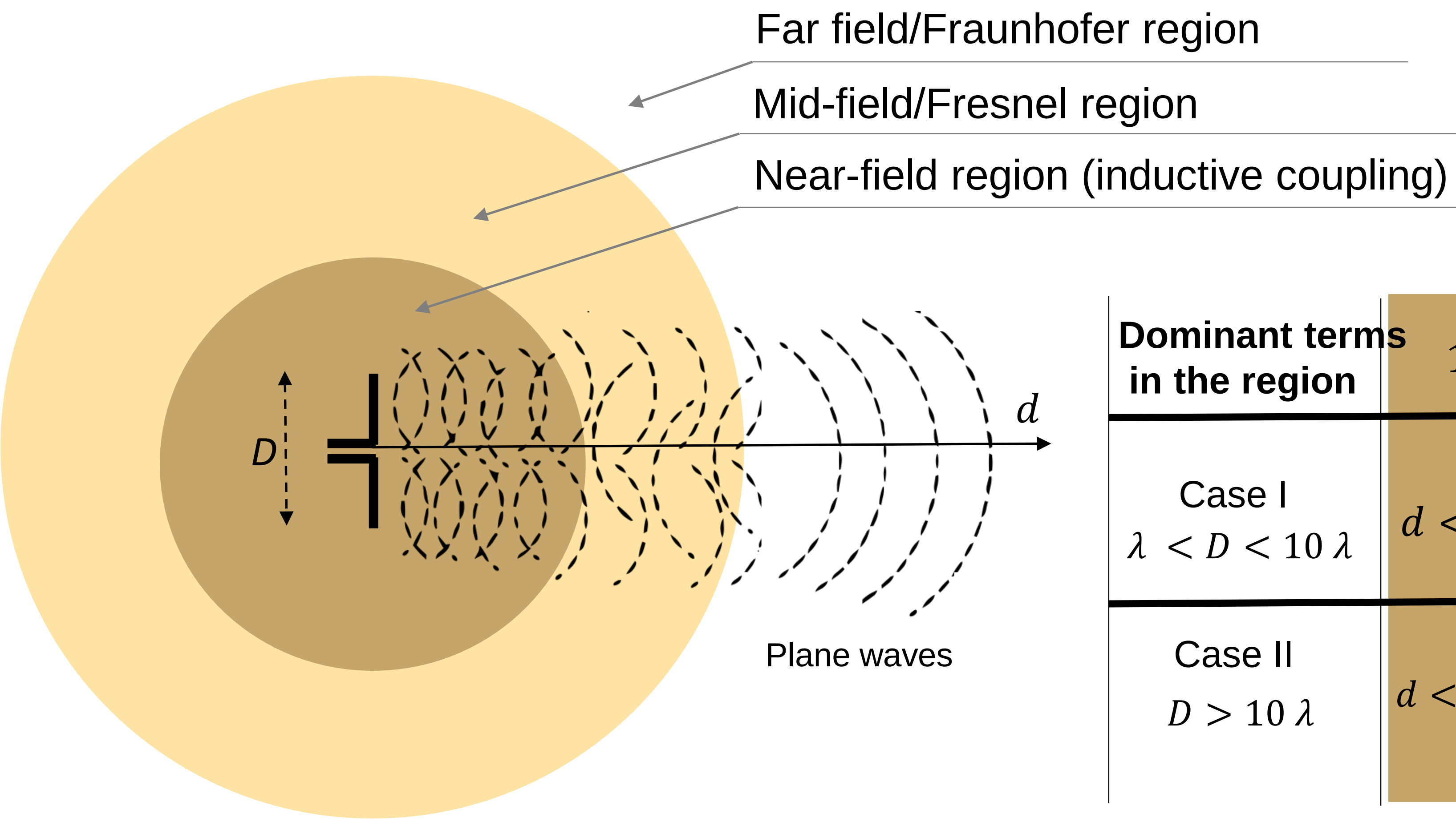
HBC: Human Body Communication
NB: Narrowband
BAN: Body Area Network
UWB: Ultra wideband

Communication Modalities



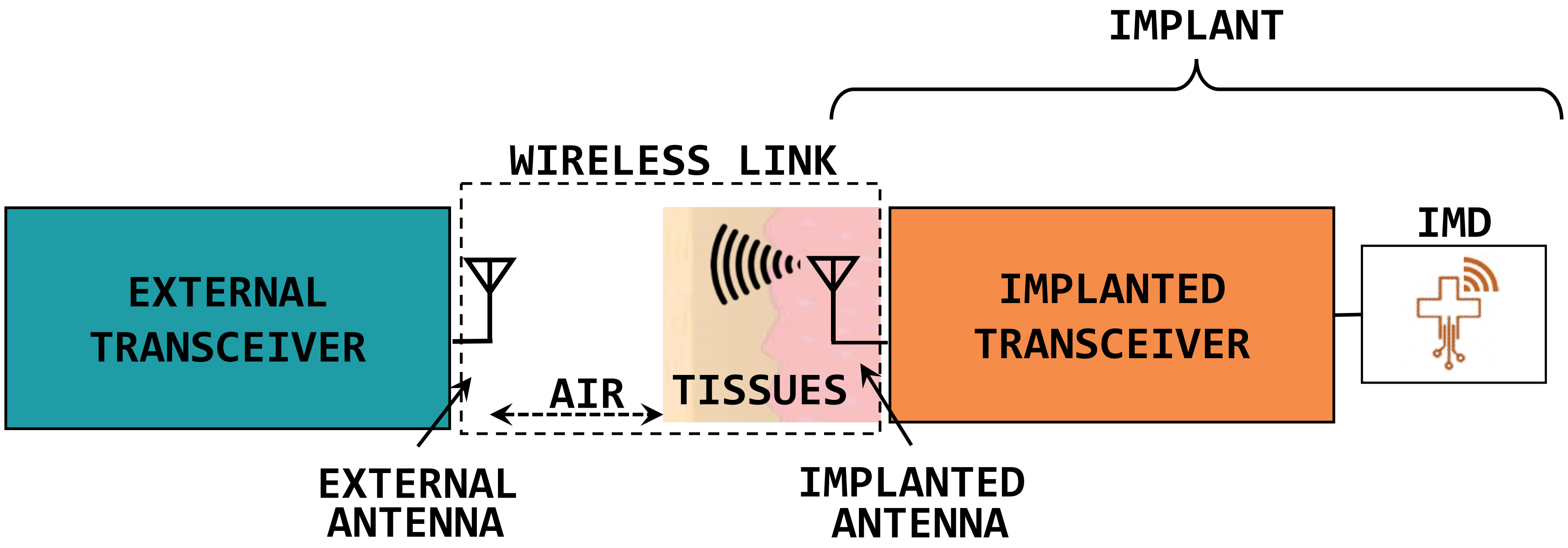
- Wearable-to-wearable
- Wearable-to-implant
- Implant-to-wearable
- Implant-to-implant

Electromagnetic propagation regions



Dominant terms in the region	$1/d^3$	$1/d^2$	$1/d$
Case I $\lambda < D < 10\,\lambda$	$d < 1.2D$	$1.2D < d < 2\frac{D^2}{\lambda}$	$d > 2\frac{D^2}{\lambda}$
Case II $D > 10\,\lambda$	$d < \frac{1}{2}\sqrt[3]{\frac{D^4}{\lambda}}$	$\frac{1}{2}\sqrt[3]{\frac{D^4}{\lambda}} < d < 2\frac{D^2}{\lambda}$	$d > 2\frac{D^2}{\lambda}$

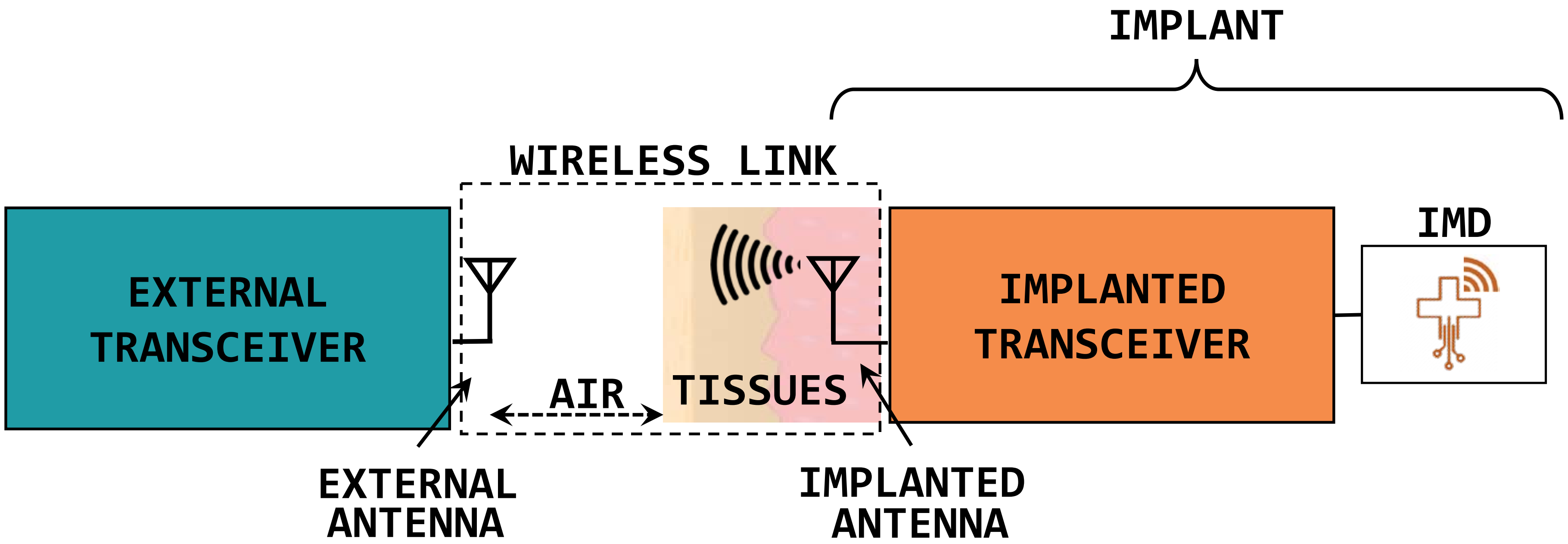
Radio-frequency (RF) - far field



Far field region $d > 2\frac{D^2}{\lambda}$

Maxwell's equation for wave propagation in human tissues

Radio-frequency: design

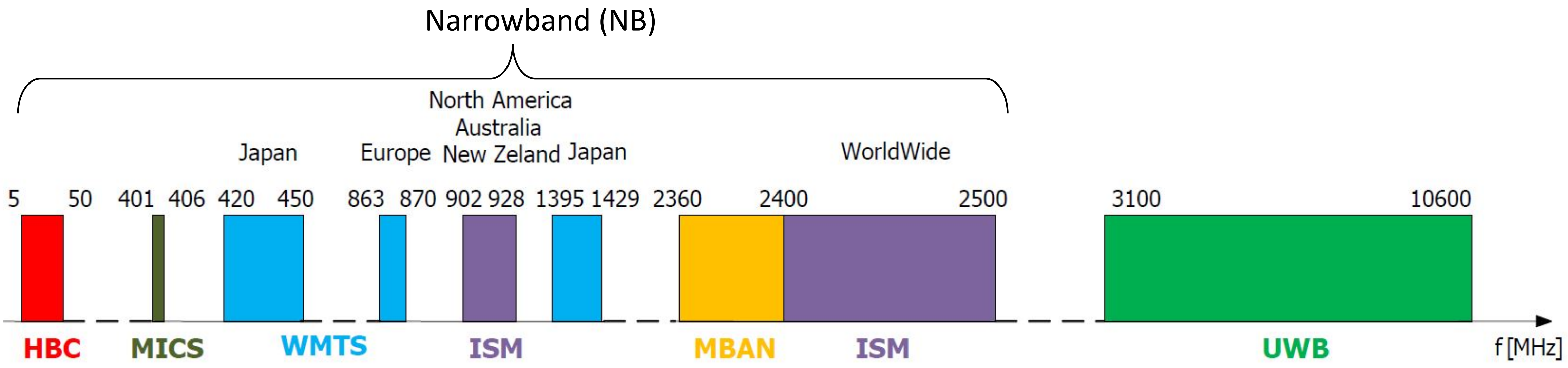


Friis equation (extended version)

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 (1 - |S_{11}|^2)(1 - |S_{22}|^2)\boldsymbol{e^{-2\alpha d}}$$

Attenuation in human body

Bands available for WBANs based on electromagnetics waves



- Human Body Communication (HBC)
- Medical Implant Communications Service (MICS), aka MedRadio
- Wireless Medical Telemetry System (WMTS)
- Industrial Scientific and Medical (ISM)
- Medical Body Area Network (MBAN)
- Ultra Wideband (UWB)

Radio-frequency: bandwidths and standards

RF-NARROWAND (NB)

RF-NB utilizes bands known as the Wireless Medical Telemetry Service (WMTS) and the Medical Implant Communications Service (MICS) regulated by the Federal Communications Commission

EX: MICS

Up to 400 kbps
Communication range around 2m

RF-ULTRA WIDEBAND (UWB)

- Definitions:
  (a) signal bandwidth ≥ 500MHz

  (b) fractional bandwidth $\frac{BW}{f_c} \geq 20\%$

  f_c = band center

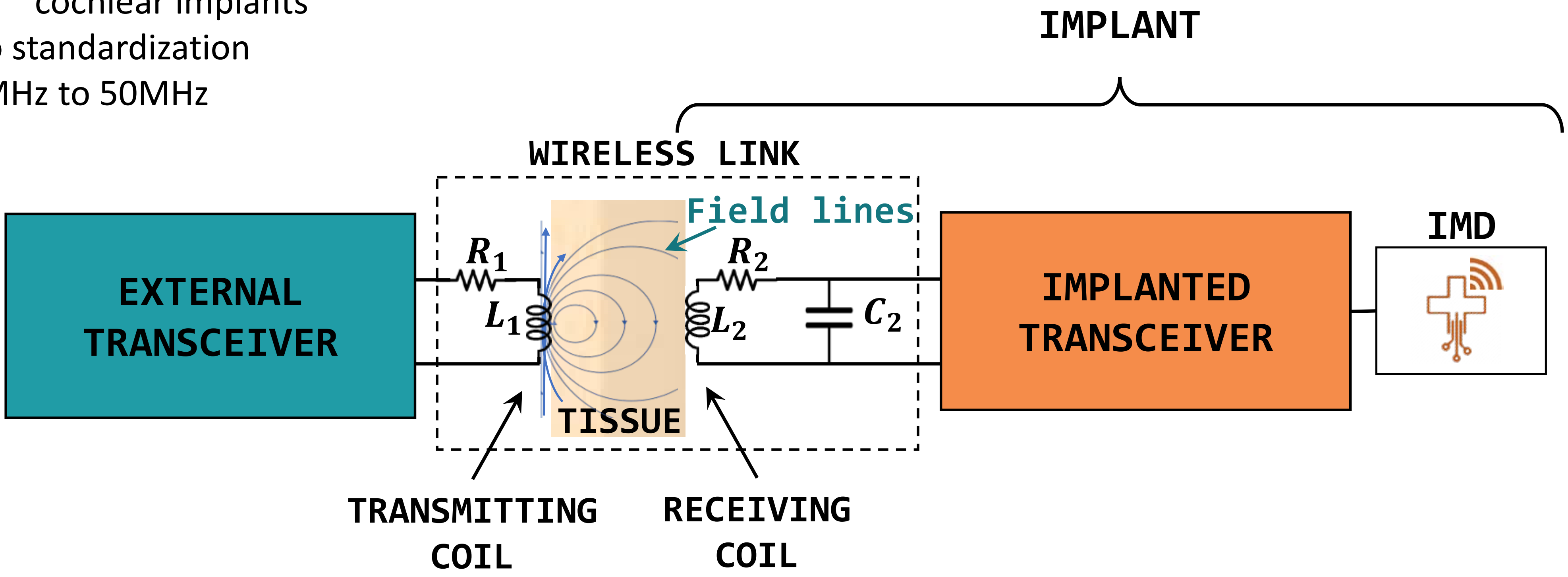
- Up to 1 Mbps
- Communication range 12cm

STANDARDS

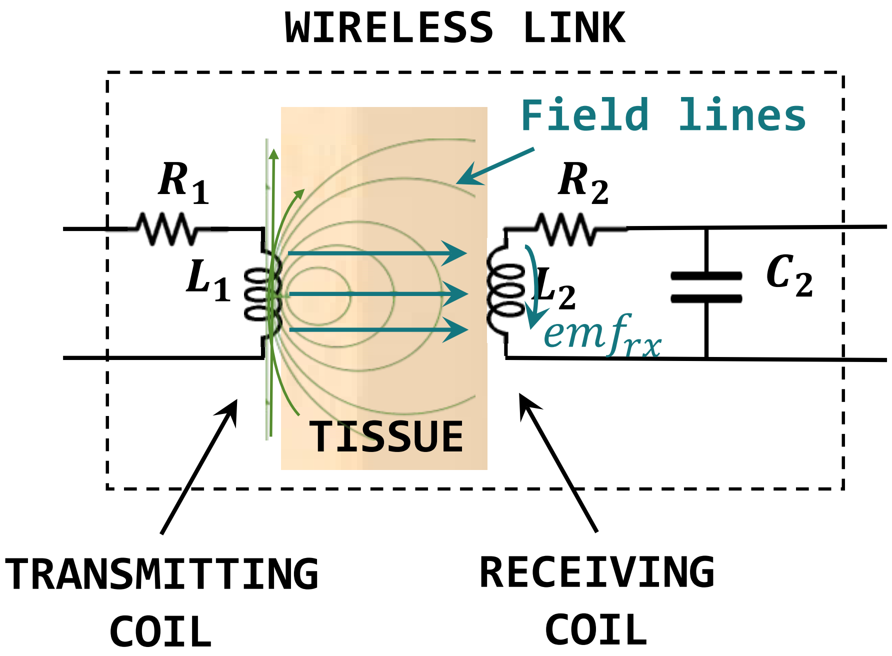
IEEE 802.15.4
IEEE 802.15.6 (NB-PHY, UWB-PHY, and MAC)
Bluetooth Low Energy (BLE)

Inductive Coupling - near field

- Extensively used for short range communications
  - muscle stimulators
  - retinal implants
  - cochlear implants
- No standardization
- 1MHz to 50MHz



Principle of electromagnetic induction between two coils



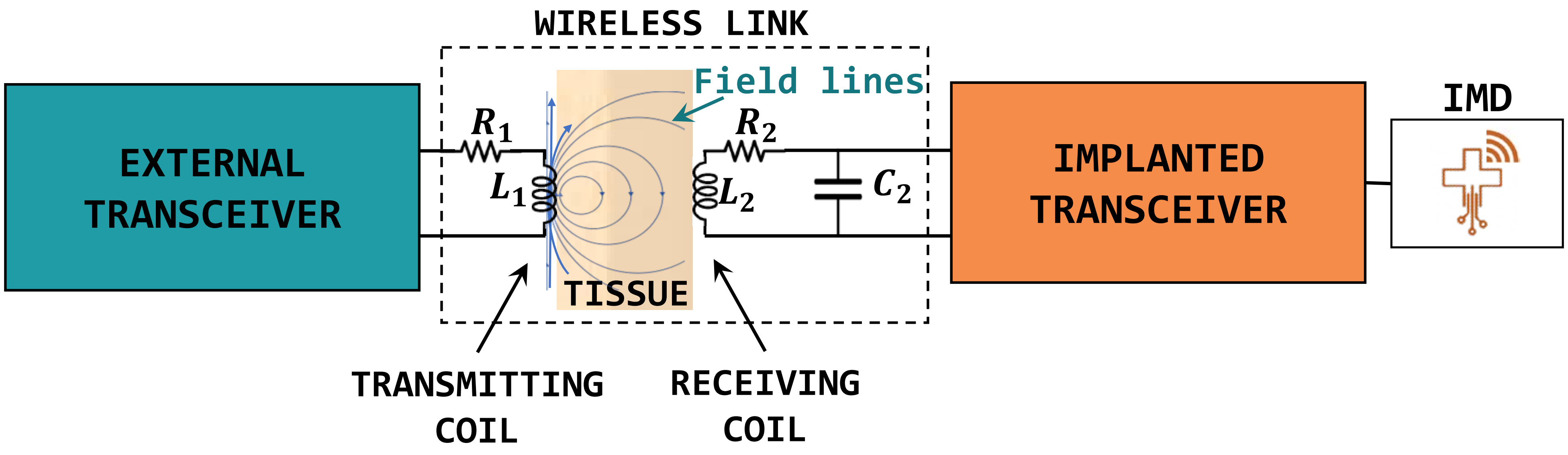
(1) Alternated current

(2) Alternated magnetic field (magnetic flux)

(3) Inducted electromotive force (f.e.m.), *i.e.* voltage

$$emf_{rx} = \oint_{\partial\Sigma} \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\int_{\Sigma} \vec{B} \cdot d\vec{A}$$

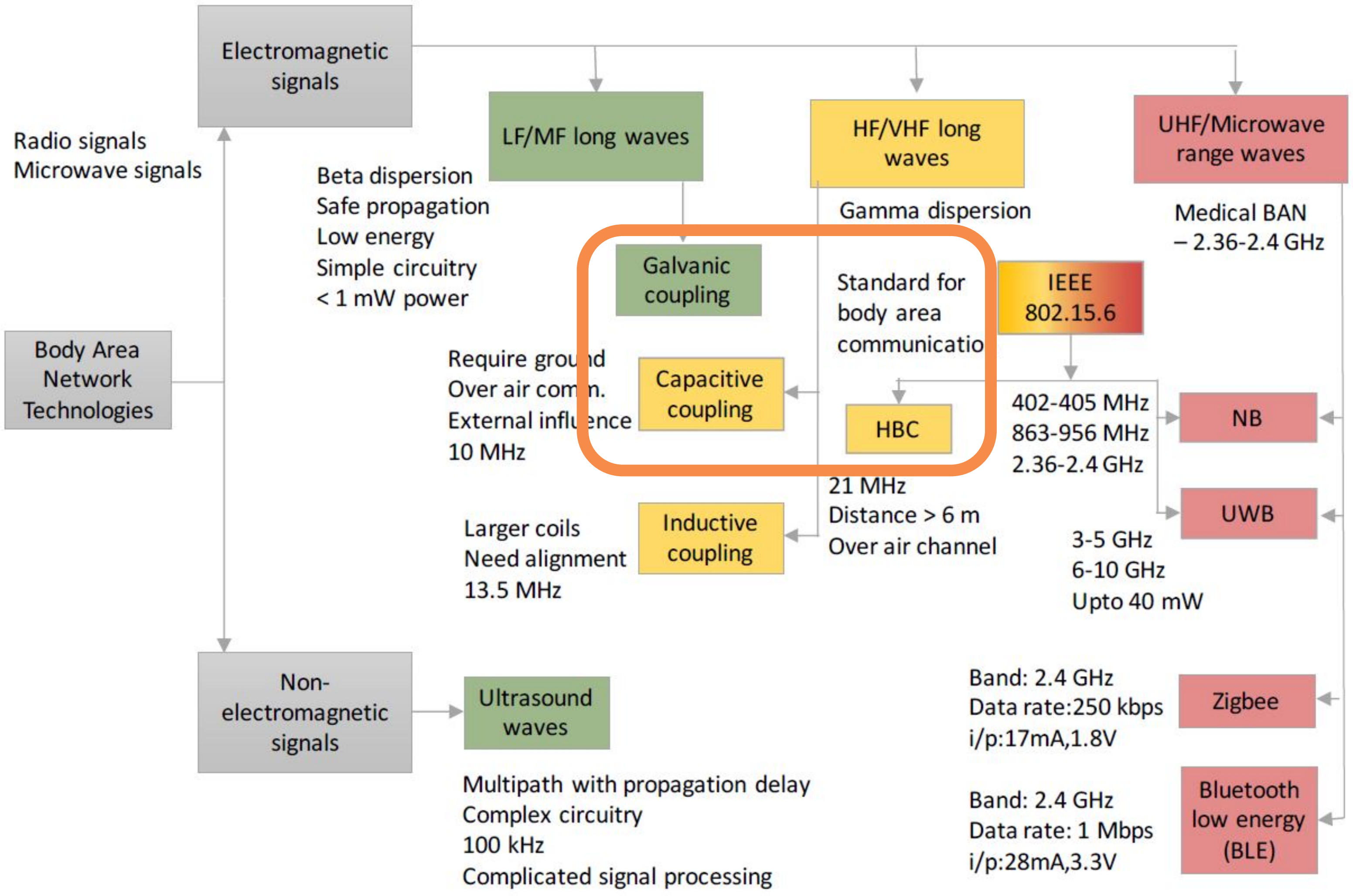
Inductive Coupling: design



DESIGN TRADE-OFF

Higher power transfer efficiency in induction coupled IBN requires larger coils that in turn requires devices with larger surface area

Human Body Communication (HBC)

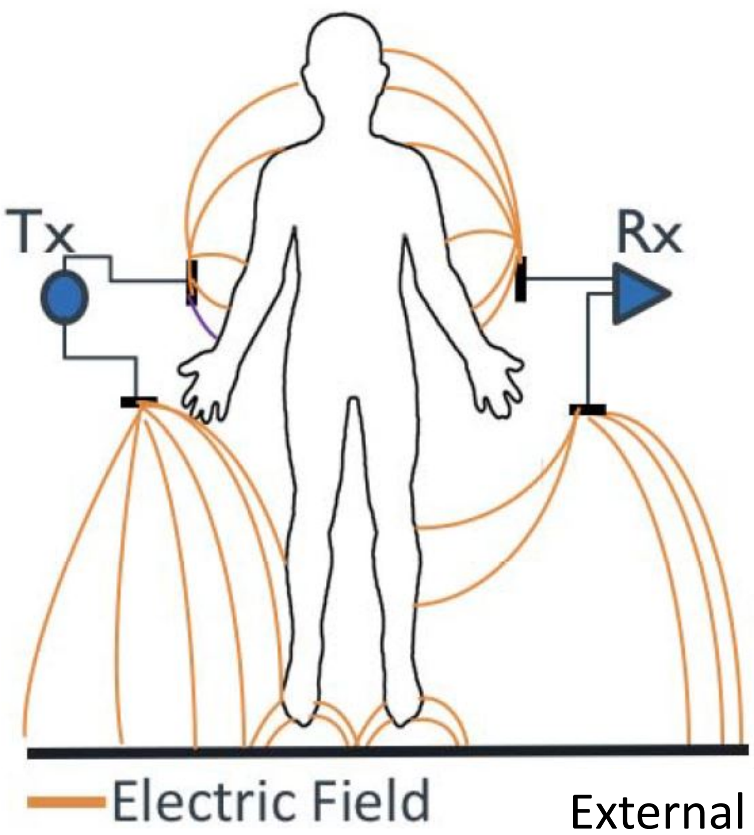


Human Body Communication (HBC)

- Uses the human body as a channel with lossy dielectric properties
- Frequencies ranging from a few hundreds of kilohertz to several megahertz: lower frequencies better penetration in tissues
- Two possible methods: capacitive coupling and galvanic coupling
- The signal is confined to within the human body
- Standard 802.15.6 HBC PHY*:* center frequency 21 MHz, bandwidth of 5.25MHz

Capacitive Coupling. Method 1: using the body as a conductor

WEARABLE-TO-WEARABLE COMMUNICATION



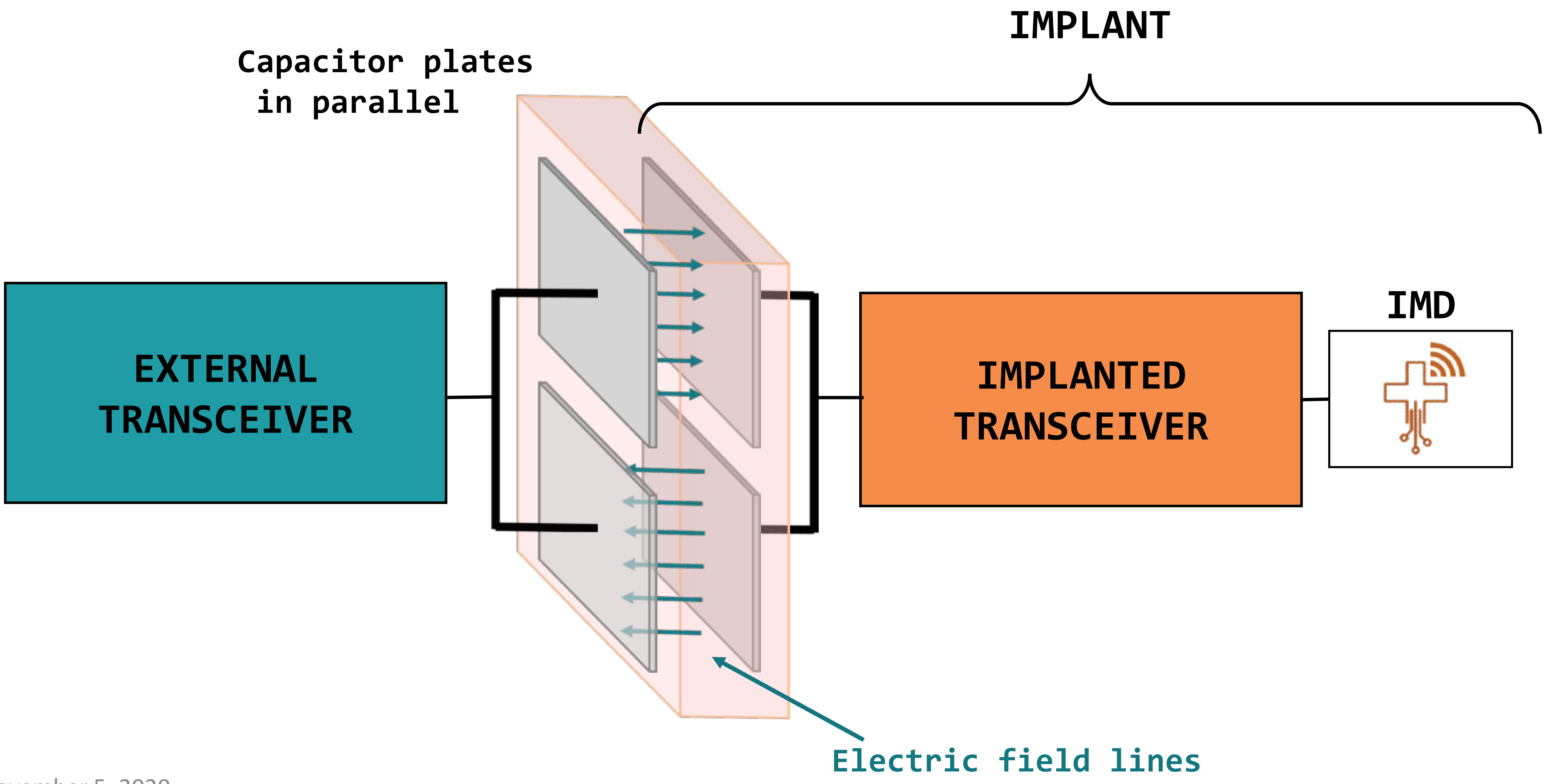
External Ground

WEARABLE-TO-WEARABLE COMMUNICATION

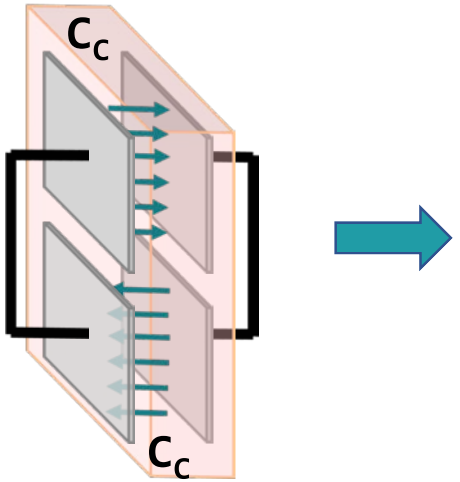
- It exploits the lossy dielectric nature of the conductive tissue Induces a potential distribution from Tx electrode to Rx electrode
- Tx and Rx electrode are attached to the body
- Grounds are floating
- The body acts as a conductor of the electric potential and the
- ground acts as a return path

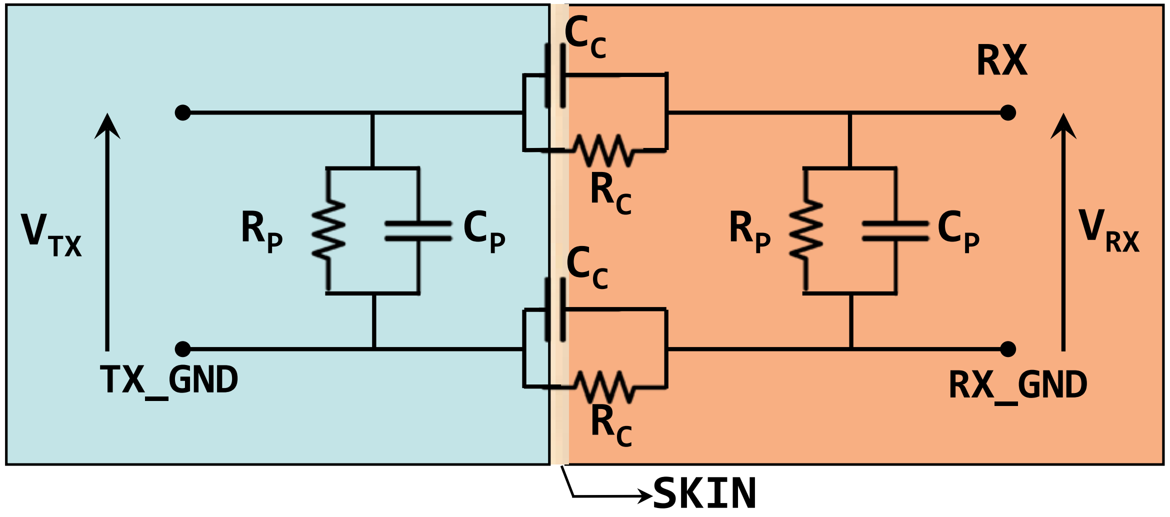
Capacitive Coupling. Method 2: trans-coutaneous data transfer

WEARABLE-TO-IMPLANT AND IMPLANT-TO-WEARABLE COMMUNICATION



Equivalent Electrical Circuit





Parasitic resistance R_P
Parasitic capacitance C_P

TRANSFER FUNCTION

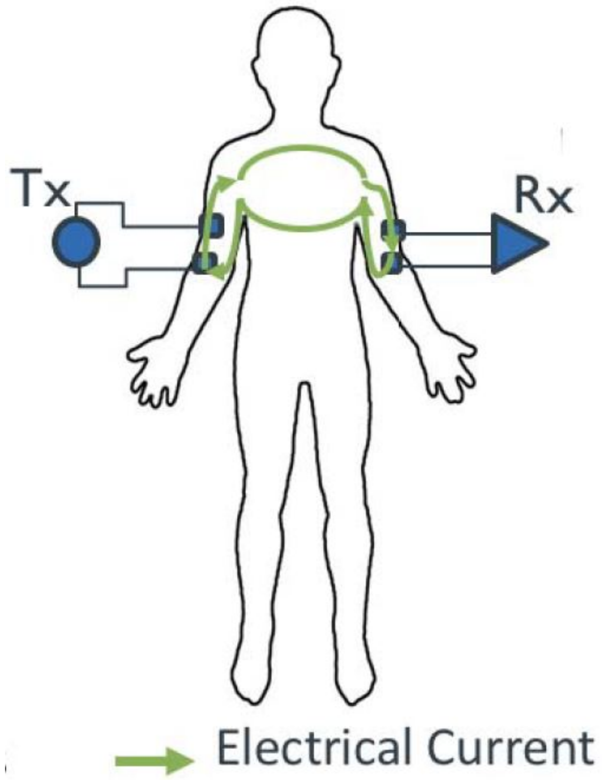
$$\frac{V_{Rx}}{V_{Tx}} = \frac{\frac{R_P}{1+j\omega R_P C_P}}{\frac{2R_C}{1+j\omega R_C C_C} + \frac{R_P}{1+j\omega R_P C_P}}$$

DESIGN TRADE-OFF

Maximize t.f. $\Longrightarrow$ Minimize the parasitic impedence $\Longleftrightarrow$
$\Longleftrightarrow$ Increase coupling $\Longrightarrow$ Increase distance $\Longrightarrow$ Larger area $\Longrightarrow$
$\Longrightarrow$ Invasiveness

Galvanic coupling (GC)

ALL 4 COMMUNICATION MODALITIES



- 10 kHz to 100 MHz
- Uses the human body as a channel to propagate the electrical signal created by a pair of coupled electrodes
- The difference between this method and CC, is that the alternating current is coupled inside the body instead of between the body and the environment
- No need for a floating ground reference or the environment as a return path for the signal GC signal
- Receiver can be on skin or implanted

Galvanic Coupling: modeling

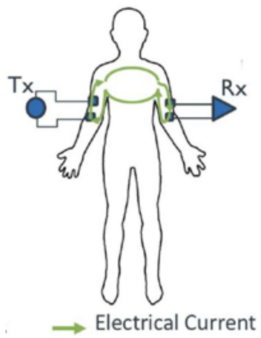
Max frequency few MHz $\Longrightarrow$ quasi-static approximation

$$\nabla \times \boldsymbol{E} = -\frac{\partial B}{\partial t} = 0$$

$$\nabla \times \boldsymbol{B} = \mu J + \mu\epsilon \frac{\partial B}{\partial t} = \mu J$$

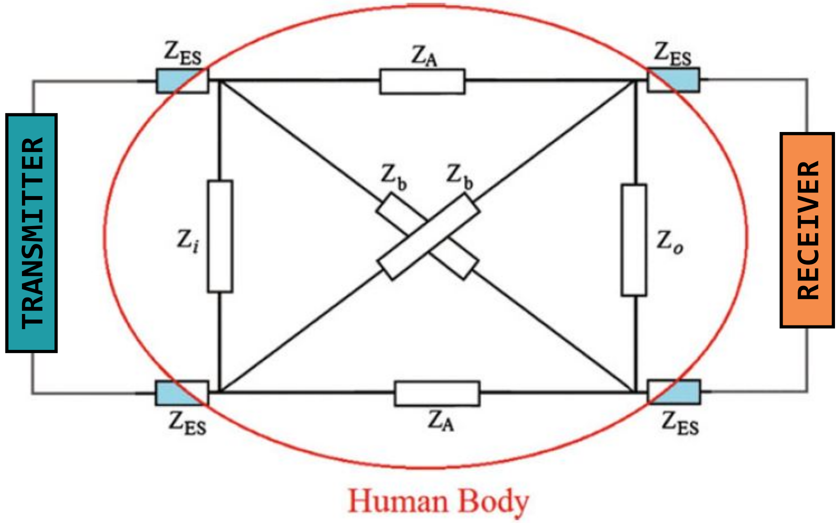
$$\nabla \cdot \boldsymbol{E} = 0$$

$$\nabla \cdot \boldsymbol{B} = 0$$



EQUIVALENT ELECTRICAL CIRCUIT FOR ONE 1 LAYER OF TISS

4 electrode-skin coupling impedances (Z_{ES})



Tissue equivalent circuit of one layer in galvanic coupling

METHODS OF PROPAGATION

Galvanic Coupling: modeling

Max frequency few MHz $\Longrightarrow$ quasi-static approximation

$$\nabla \times \boldsymbol{E} = -\cancel{\frac{\partial B}{\partial t}} = 0$$

$$\nabla \times \boldsymbol{B} = \mu J + \mu\epsilon\cancel{\frac{\partial B}{\partial t}} = \mu J$$

$$\nabla \cdot \boldsymbol{E} = 0$$

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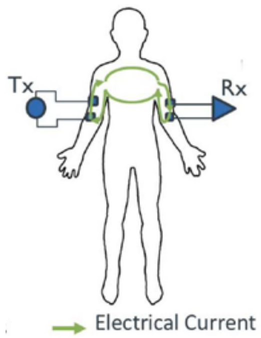
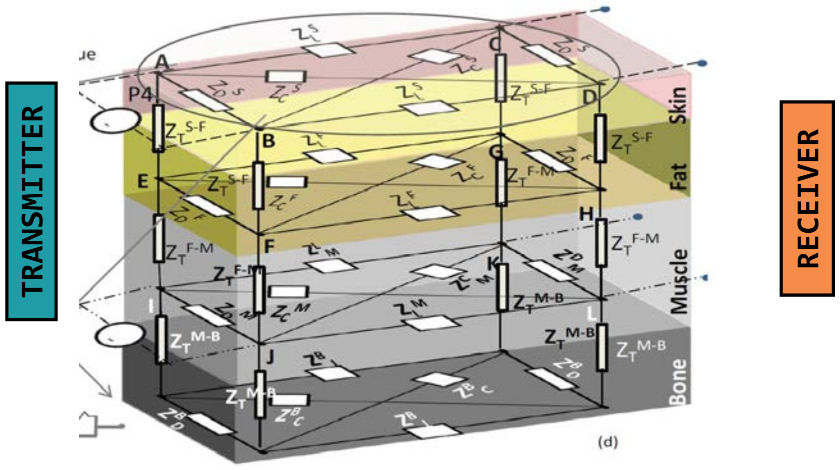


EQUIVALENT ELECTRICAL CIRCUIT FOR MULTIPLE LAYERS OF

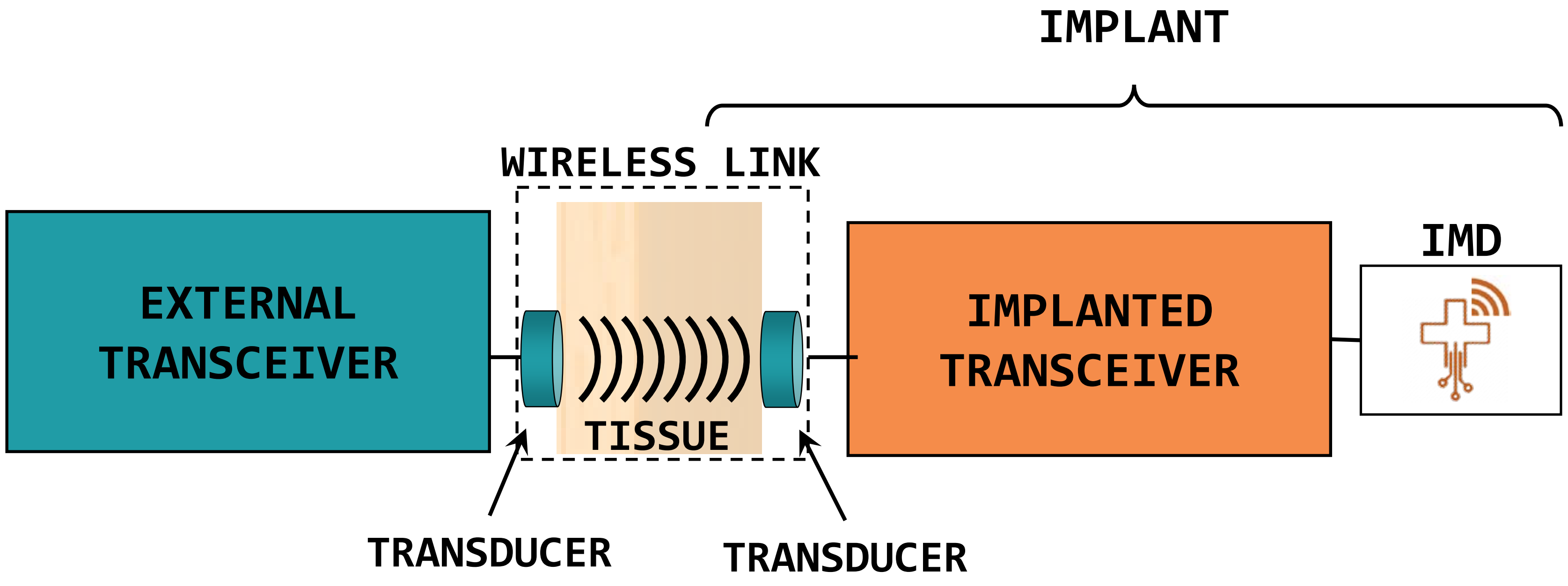
4 electrode-skin coupling impedances (Z_{ES})



Tissue equivalent circuit of multiple layer in galvanic coupling

Ultrasonic waves

Mechanical waves >20kHz

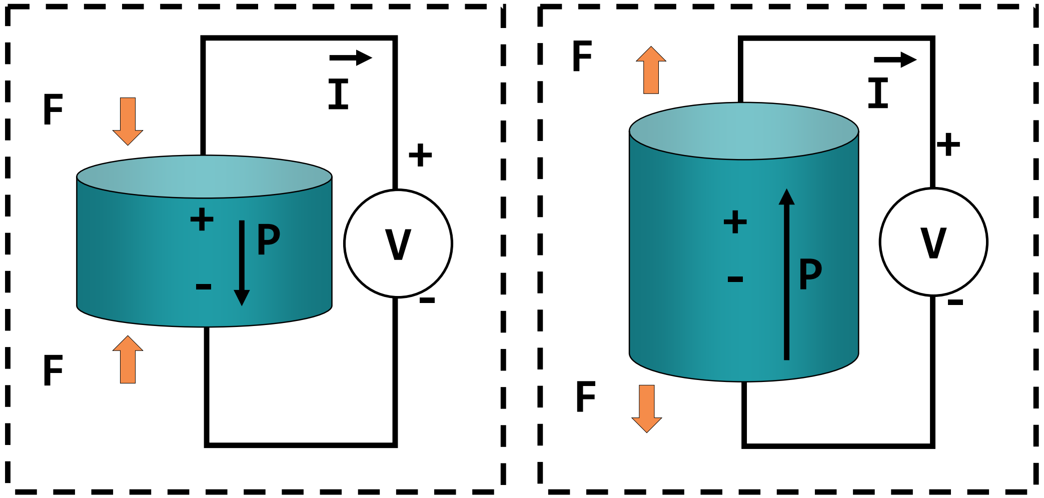


METHODS OF PROPAGATION

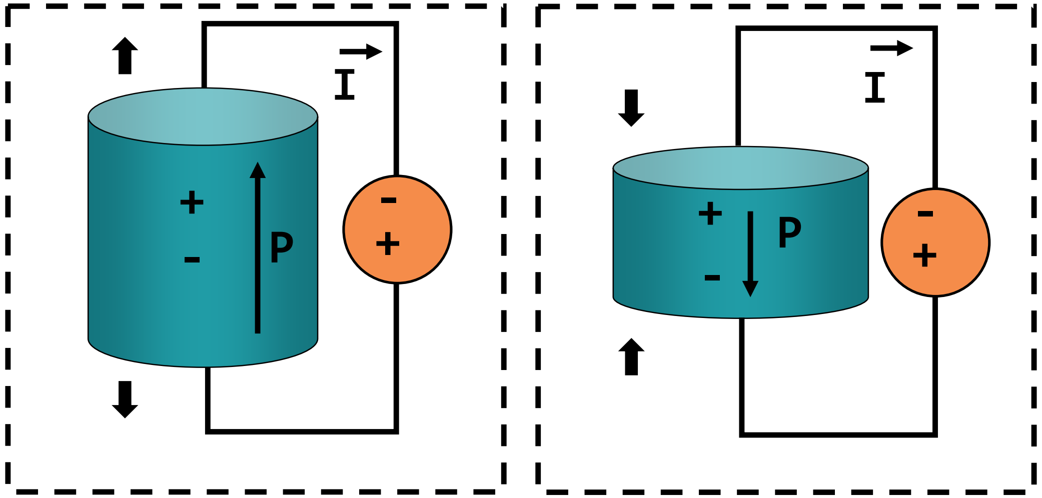
Ultrasonic waves: the piezoelectric effect

The piezoelectric material is initially polarized with a **poling voltage P**.

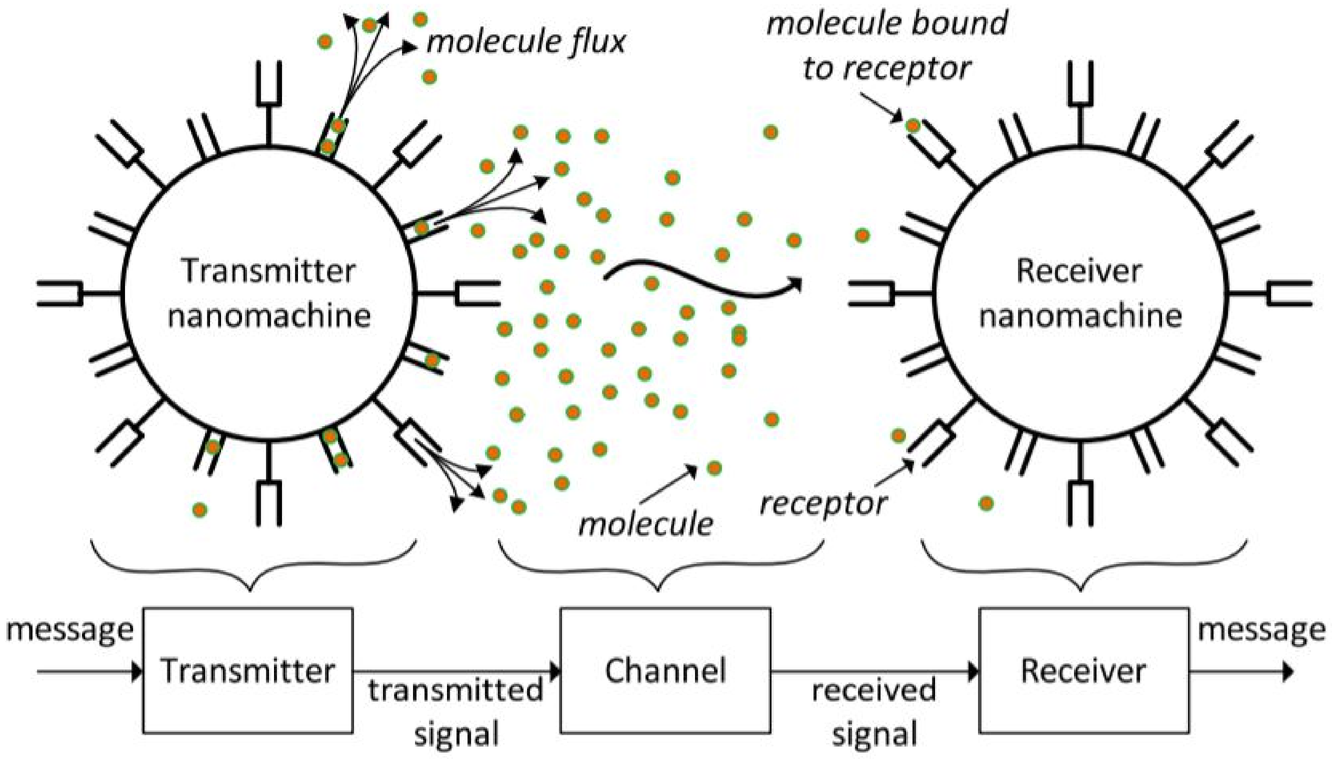
DIRECT PIEZOELECTRIC EFFECT (RECEIVER)



INVERSE PIEZOELECTRIC EFFECT (TRANSMITTER

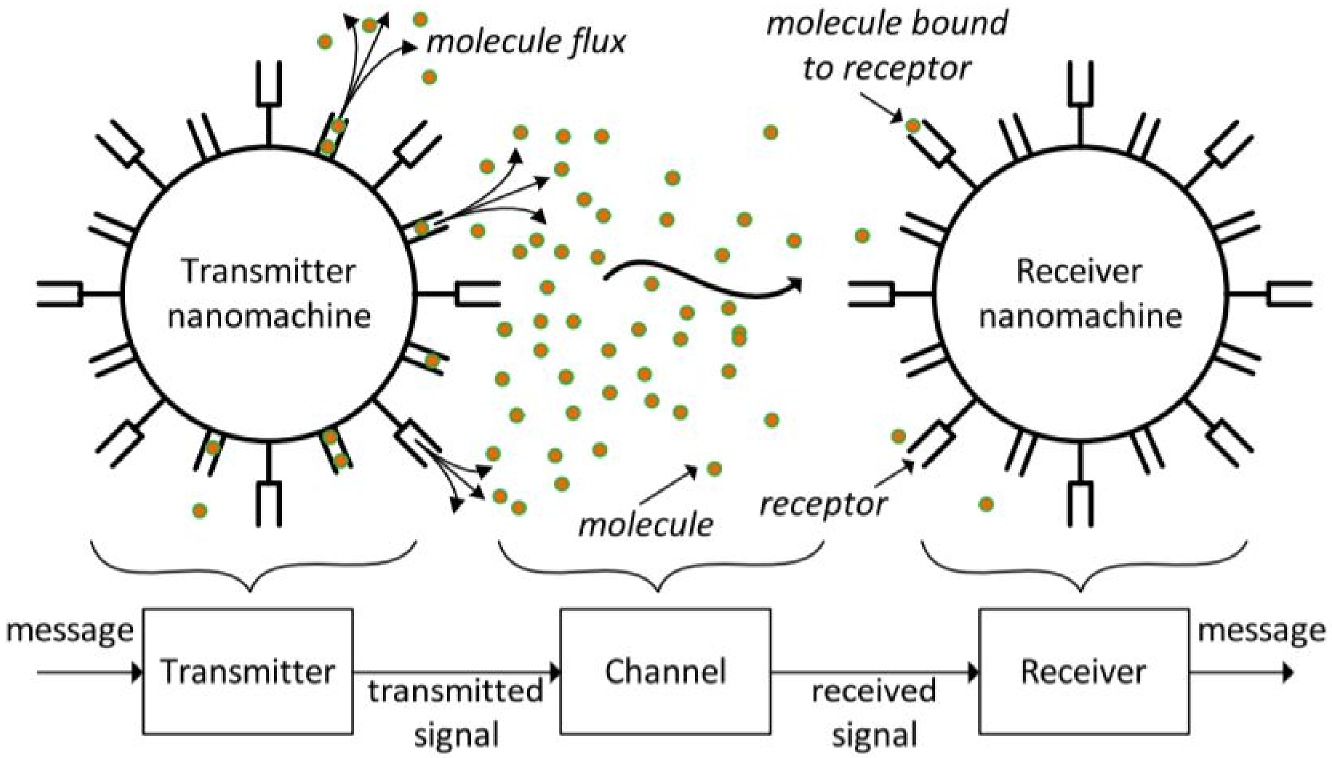


Molecular communication (MC)



- A combination of biochemical reactions and electrical signals through the
- Molecules are used to encode, transmit and receive information
- Only simple tasks such as computing, storing f data, sensing of biological markers and actuation

Molecular communication (MC)



Nanomedicine applications:

- restoration of the glucose feedback loop in diabetic patients
- recognizing and destroying tumors
- intracellular surgery with nanorobots

WHICH ONE IS “THE BEST”?

Technical comparison across intra-body communication methods

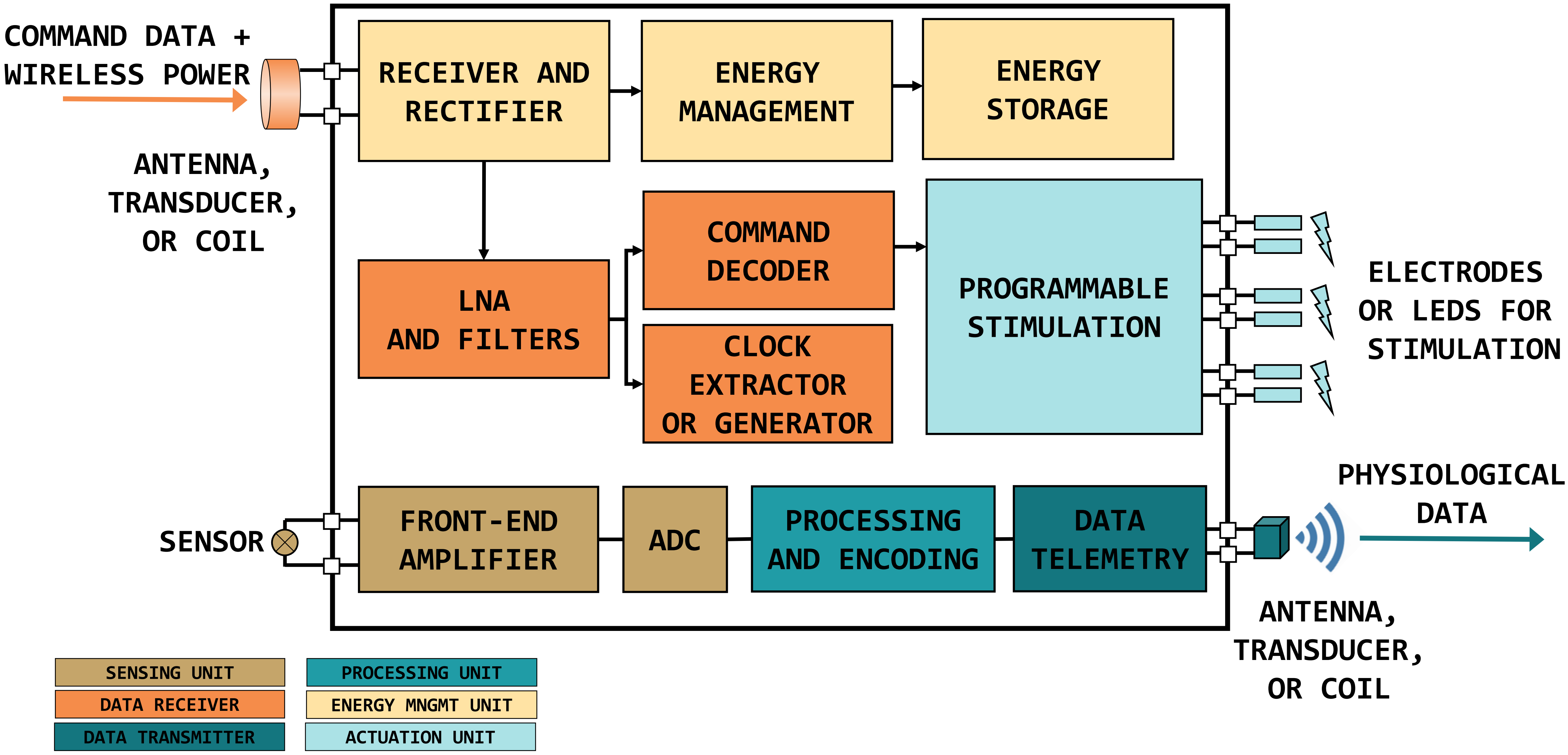
IBC Method	Power Consumption	Energy/bit [nJ/bit]	Supply Voltage [V]	Modulation Scheme	Operating Frequency	Implementation
RF-NB[48]	481 μW	2.60	0.45	OOK/FSK	402-405 MHz	ASIC
RF-UWB[49]	835 μW	1.67	1.20	FSK	3.328-4.608 GHz	ASIC
US[50]	36 mW	70	3.30	PPM	700 kHz	FPGA+MCU
GC[36]	2 mW (Tx only)	1.28	3.30	PPM	65 MHz	FPGA
CC[45]	4.4 mW	0.24	1.00	FSK	40-120 MHz	ASIC

WHICH ONE IS “THE BEST”?

Qualitative comparison across intra-body communication methods

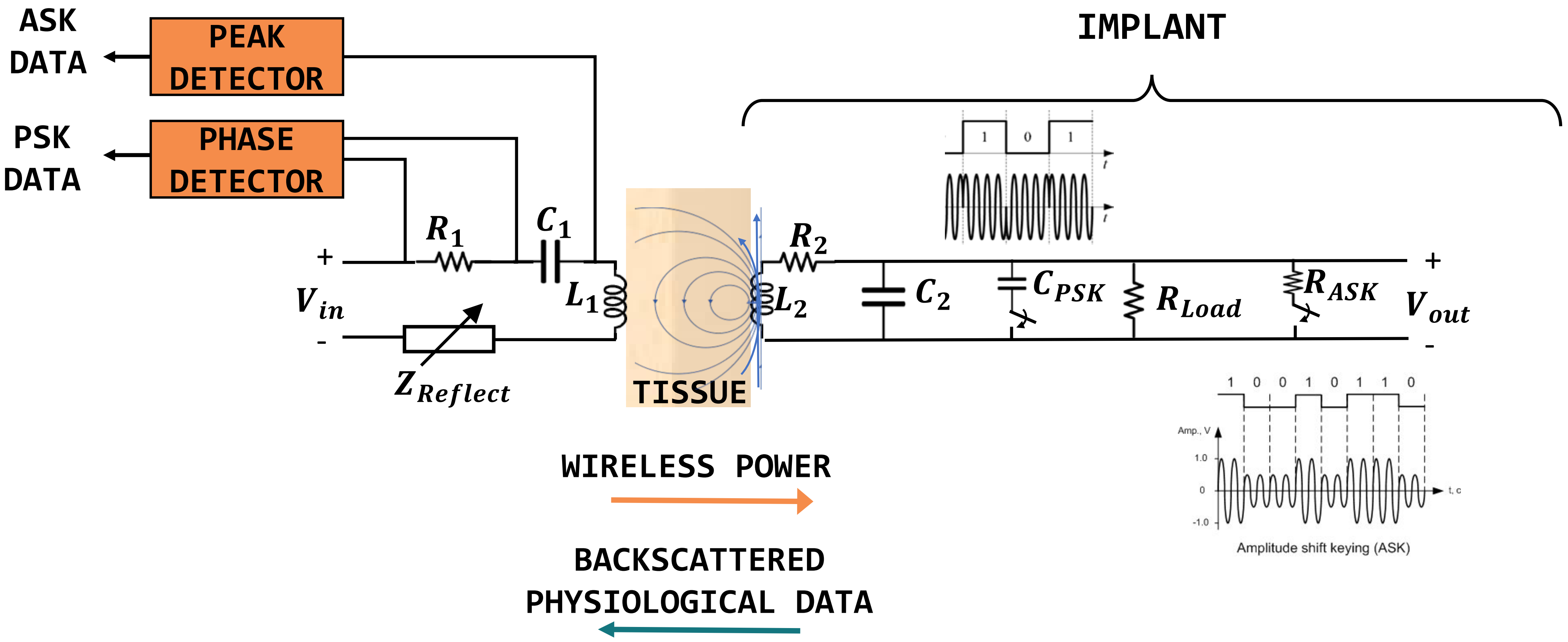
	Power Consumption	Propagation Distance	Transceiver Complexity	Interference Susceptibility	Data Rate	Tissue Safety	Security
RF-NB	●○○	●●○	●●○	●●○	●○○	●○○	●○○
RF-UWB	●○○	●○○	●●○	●●○	●●●	●●○	●●○
US	●●○	●○○	●●○	●○○	●●●	●●●	●●●
GC	●○○	●●○	●○○	●○○	●○○	●●●	●●●
CC	●○○	●●●	●●○	●●●	●●○	●●○	●○○
RC	○○○	●●●	○○○	●●○	○○○	●●●	●○○

FULL SYSTEM ARCHITECTURE



FULL SYSTEM ARCHITECTURE

Example of PASSIVE backscattered data telemetry circuit with inductive coupling



U-Verse: system architecture, functions, and device

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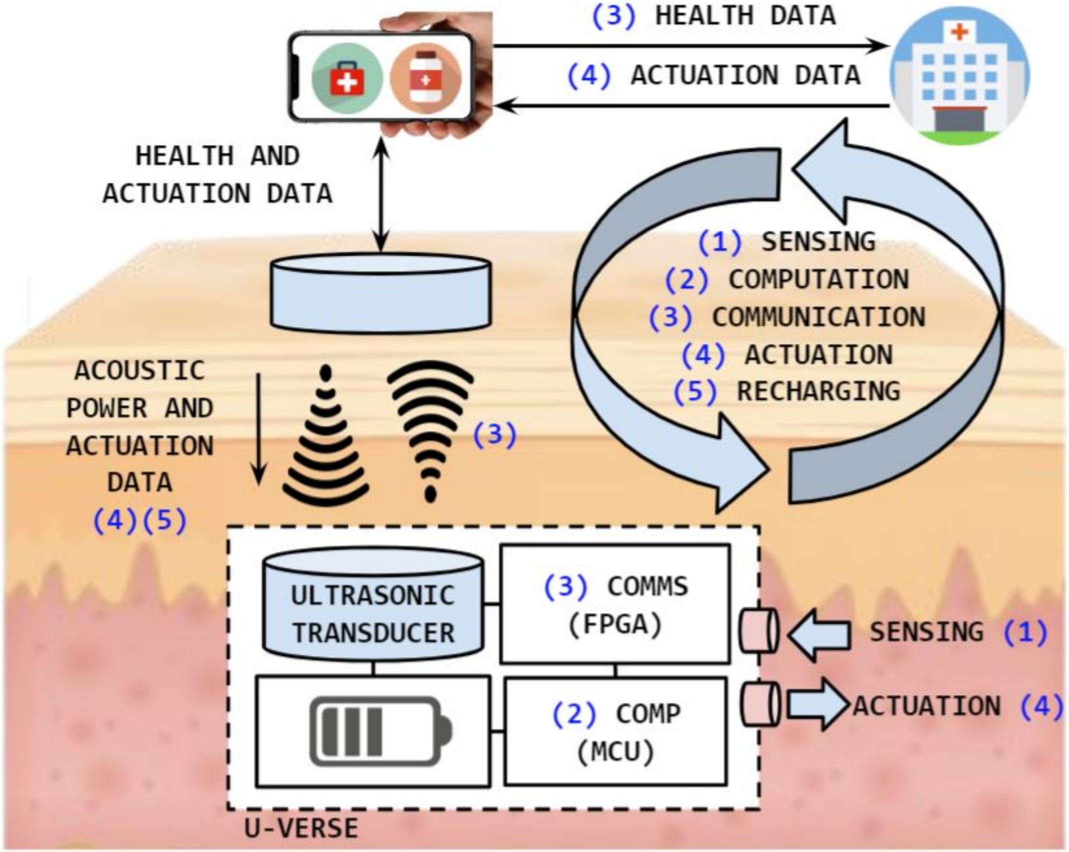

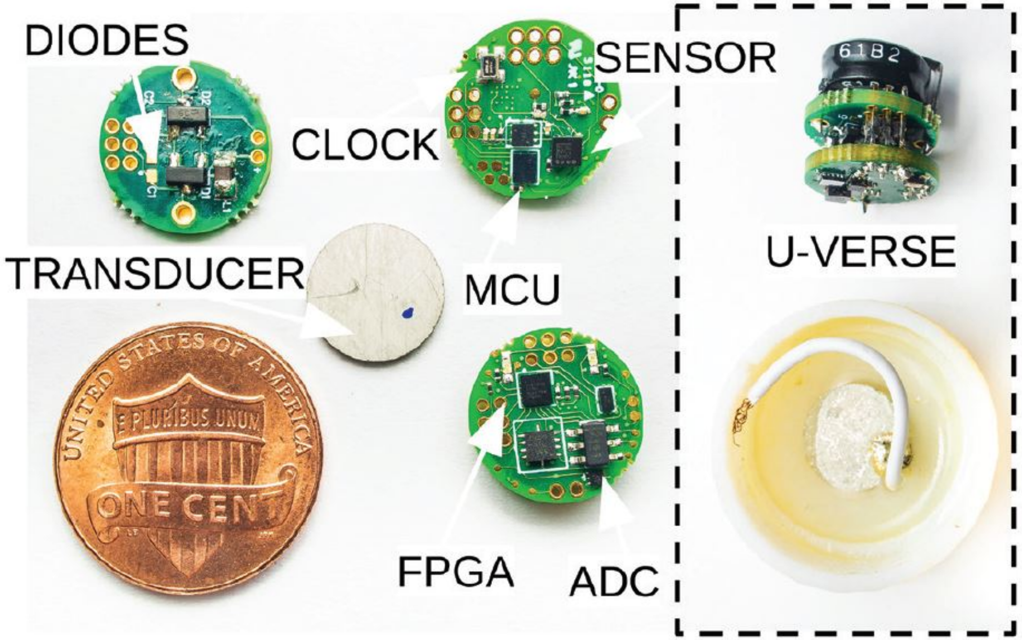

U-Verse is a battery-less rechargeable ultrasonic device that can enable the IoMT 4 core fundamental functions: sensing, computation, communication, actuation

U-Verse: Communication unit

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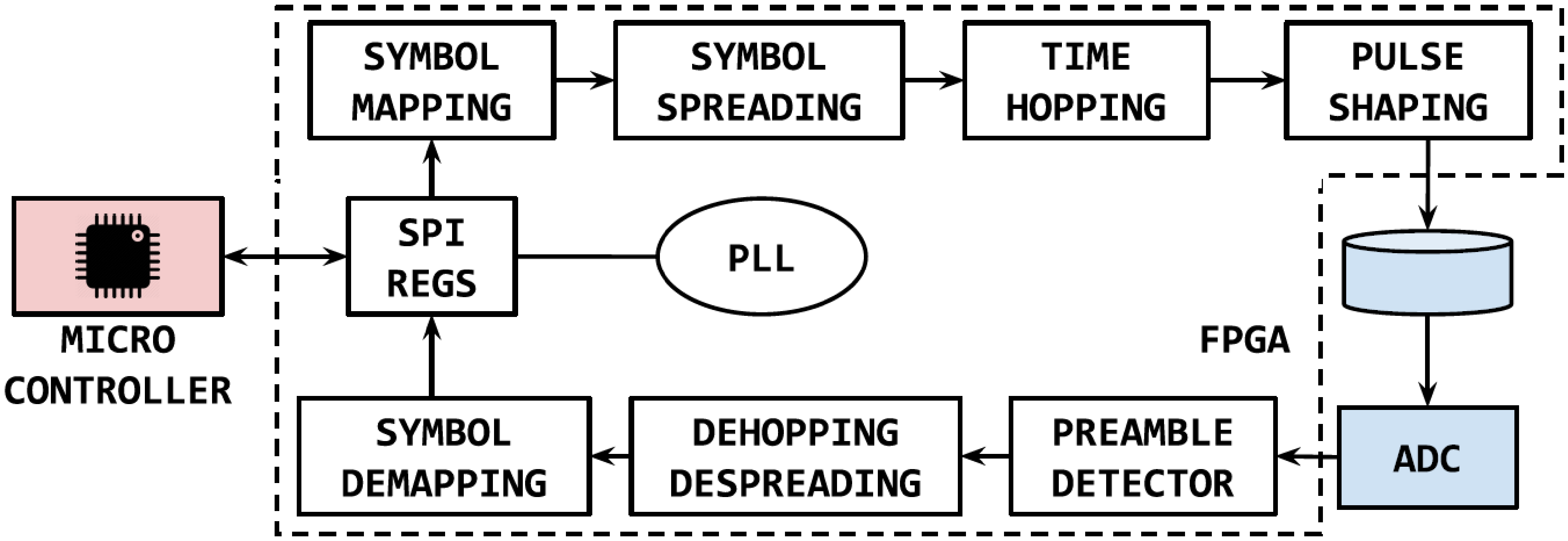

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THANKS!

QUESTIONS?

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