The Fat-Intrabody Communication (Fat-IBC)

Robin Augustine, PhD, Docent
Robin.Augustine@Angstrom.uu.se
Associate Professor
Division of Solid-State Electronics
Department of Electrical Engineering
Uppsala University

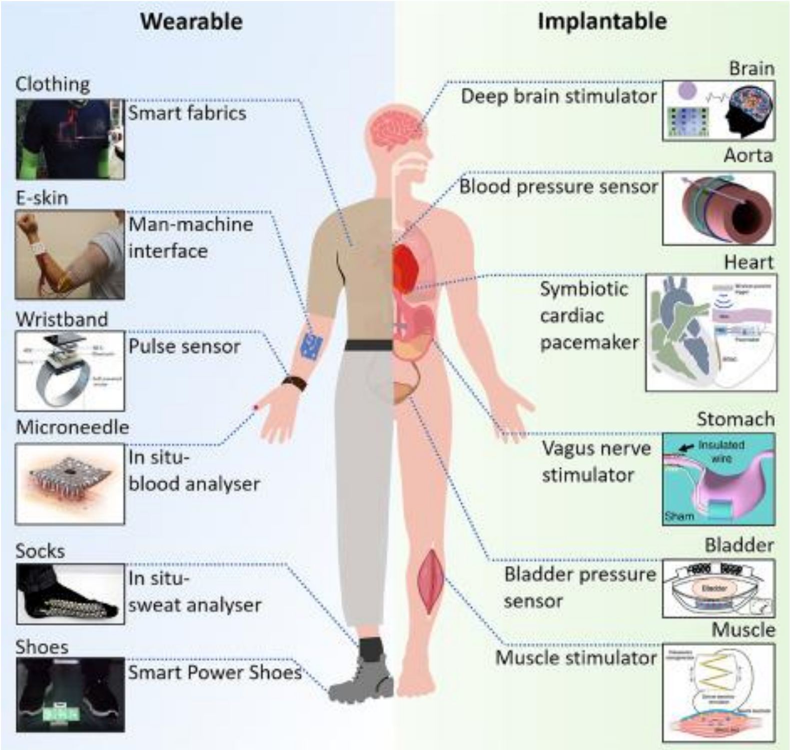
Overview

1. Human Bodycentric communication - HBC
2. Fat-Intrabody Communication
3. Where are we? A look back!
4. Fat-IBC in B-CRATOS
5. Future

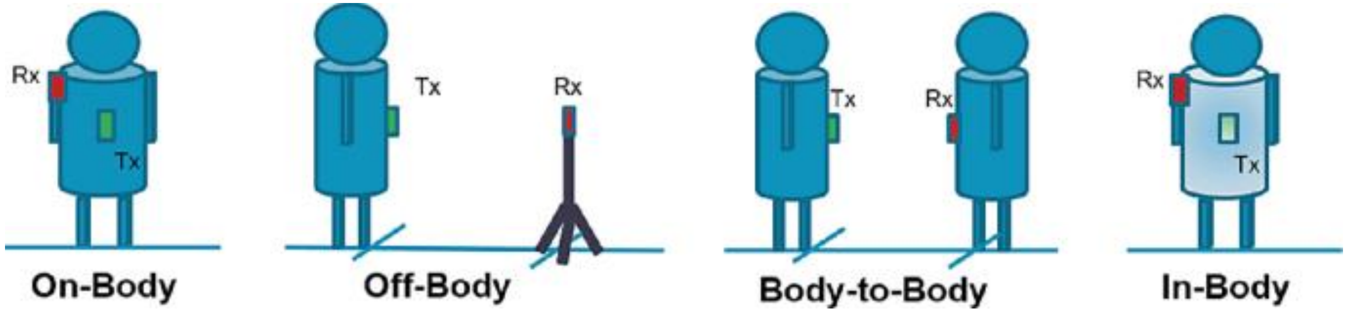
1. Human Bodycentric communication - HBC

Human body communication (HBC), which the **human body tissue** as the **transmission medium** to transmit health informatics, serves as a promising **physical layer solution** for the body area network (**BAN**). The human centric nature of HBC offers an innovative method to transfer the healthcare data, whose transmission requires **low interference** and **reliable data link**.

Jian Feng Zhao, Xi Mei Chen, Bo Dong Liang, Qiu Xia Chen, "A Review on Human Body Communication: Signal Propagation Model, Communication Performance, and Experimental Issues", Wireless Communications and Mobile Computing, vol. 2017, Article ID 5842310, 15 pages, 2017. https://doi.org/10.1155/2017/5842310



Courtesy: *Yang Zou, Lin Bo, Zhou Li, Recent progress in human body energy harvesting for smart bioelectronic system, Fundamental Research, Volume 1, Issue 3, 2021, Pages 364-382,*

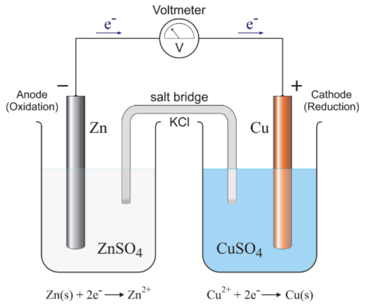


Courtesy*: Koul, S.K., Bharadwaj, R. (2021). Introduction to Body Centric Wireless Communication. In: Wearable Antennas and Body Centric Communication. Lecture Notes in Electrical Engineering, vol 787. Springer, Singapore. https://doi.org/10.1007/978-981-16-3973-9_1*

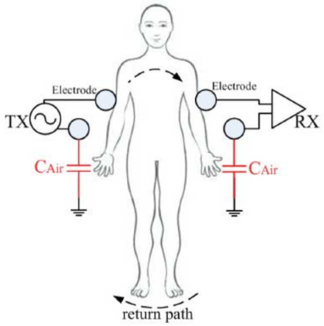
Vagal nerves: play key role to control involuntary functions like heart rate, breathing and digestion
Gastroparesis can be treated by VNS in brain!

Intra-Body Communication Modalities and SoA

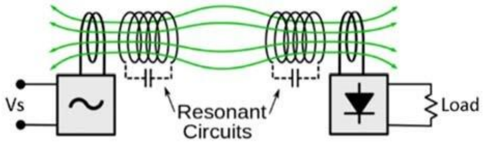
- Galvanic coupling (GC)
- Capacitive coupling (CC)
- Inductive coupling (IC)
- Ultra sound (US)
- RF coupling: BLE, Xbee



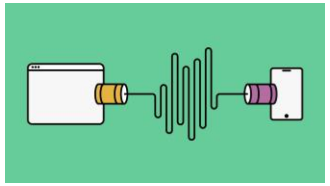
Galvanic cell



Capacitive coupling



Inductive coupling



Ultrasound communication

Bluetooth

Shortcomings of SoA

*

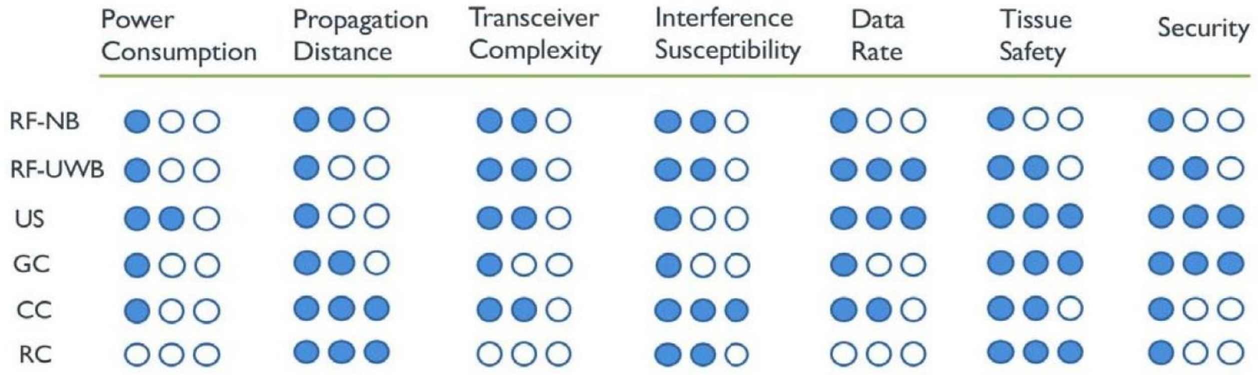
TABLE I
STATE OF THE ART INTRA-BODY / ON-BODY COMMUNICATION

Work	Technique	Frequency	Transmission coefficient, S_{21}	Path Loss
[17]	Galvanic coupling	40 kHz	–	∼−39 dB (d = 10 cm)
[18]	Galvanic coupling	100 kHz	–	∼−47 dB (d = 10 cm)
[30]	Galvanic coupling	100 MHz	∼−37 dB (d = 15 cm)	–
[17], [18]	Capacitive coupling	100 MHz	–	∼−27 dB (d = 15 cm)
[20]	Capacitive coupling	10 MHz	∼−18 dB d = 16 cm	–
[21]	Capacitive coupling	26 MHz	∼−32 dB (d = 30 cm)	–
[24]	RF	403.5 MHz	–	∼ 54 dB (d = 10 cm)
[25]	RF	915 MHz	−51.4 dB (d = 0.5 cm)	–
[26]	RF	1 GHz	∼−56 dB (d = 0.75 cm)	–

*d = transmission distance.

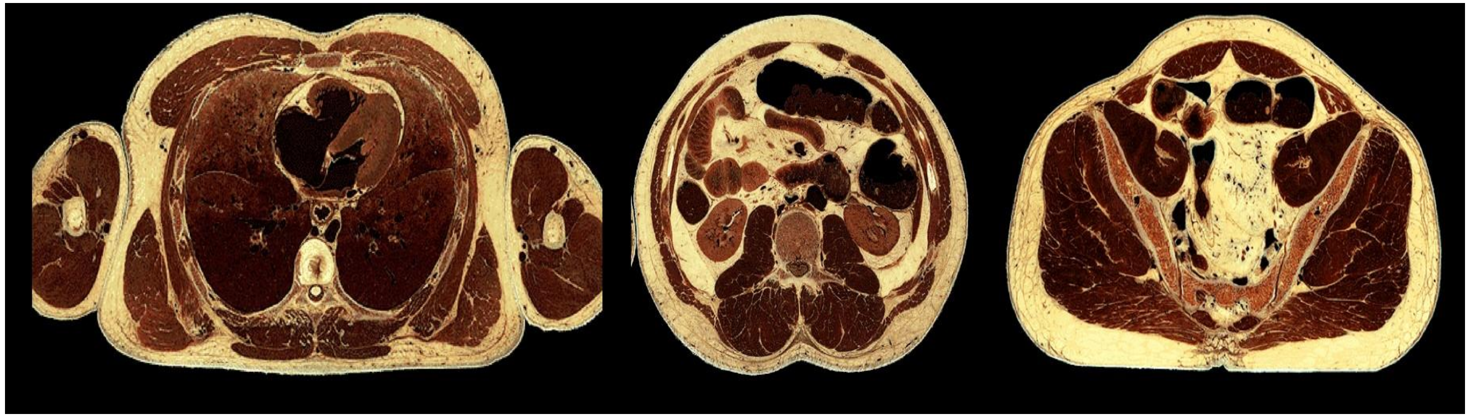
* N. B. Asan *et al.*, "Data Packet Transmission Through Fat Tissue for Wireless IntraBody Networks," in ***IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology***, vol. 1, no. 2, pp. 43-51, Dec. 2017, doi: 10.1109/JERM.2017.2766561.

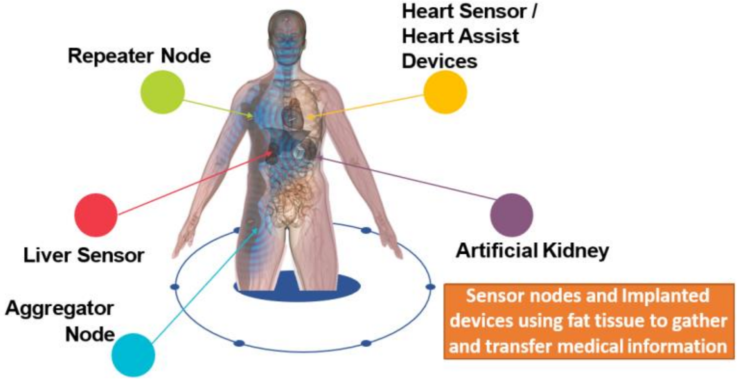
- Need of external ground (CC)
- Electrolytic variation (GC)
- Susceptible to external contact (GC)
- Attenuation, cavitation (US)
- Line of sight communication (RF)
- Susceptible to external factors (RF)
- Distance (IC, US)
- Low bandwidth (CC, GC, IC)
- Higher path loss (GC, CC, US, RF)
- Low security (CC, GC, RF)
- Low privacy (CC, GC, RF)
- Low data rate (CC, GC, IC, US)



2. Fat-Intrabody Communication (Fat-IBC)

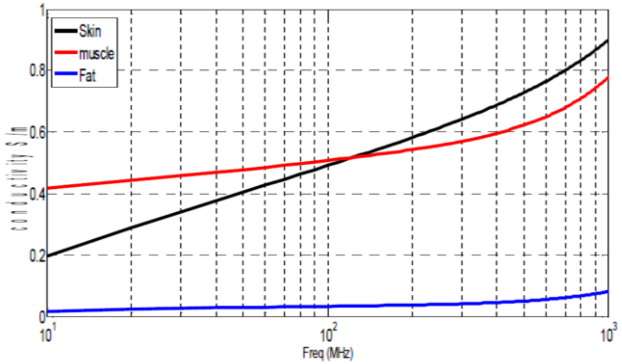
Naranjo, David & Reina-Tosina, Javier & Min, Mart. (2019). Fundamentals, Recent Advances, and Future Challenges in Bioimpedance Devices for Healthcare Applications. Journal of Sensors. 2019. 1-42. 10.1155/2019/9210258.

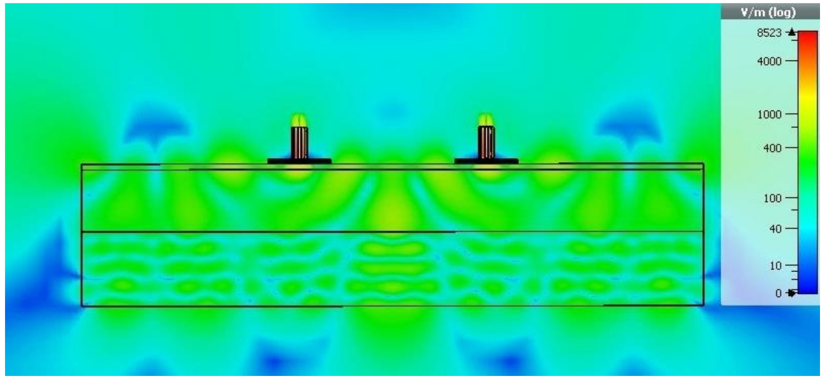




Human fat distribution

Source of Images from Department of Anatomy and Cellular Biology Cross Sectional Anatomy, http://cosmos.phy.tufts.edu/~rwillson/medgross/hip_a.jpg





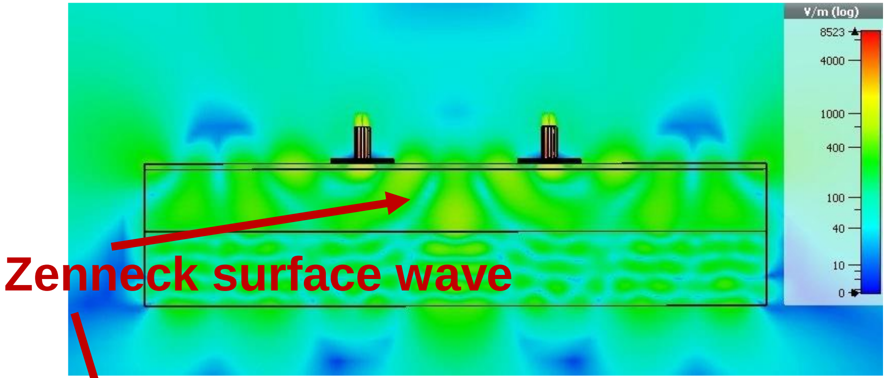
Wave propagation in the fat layer

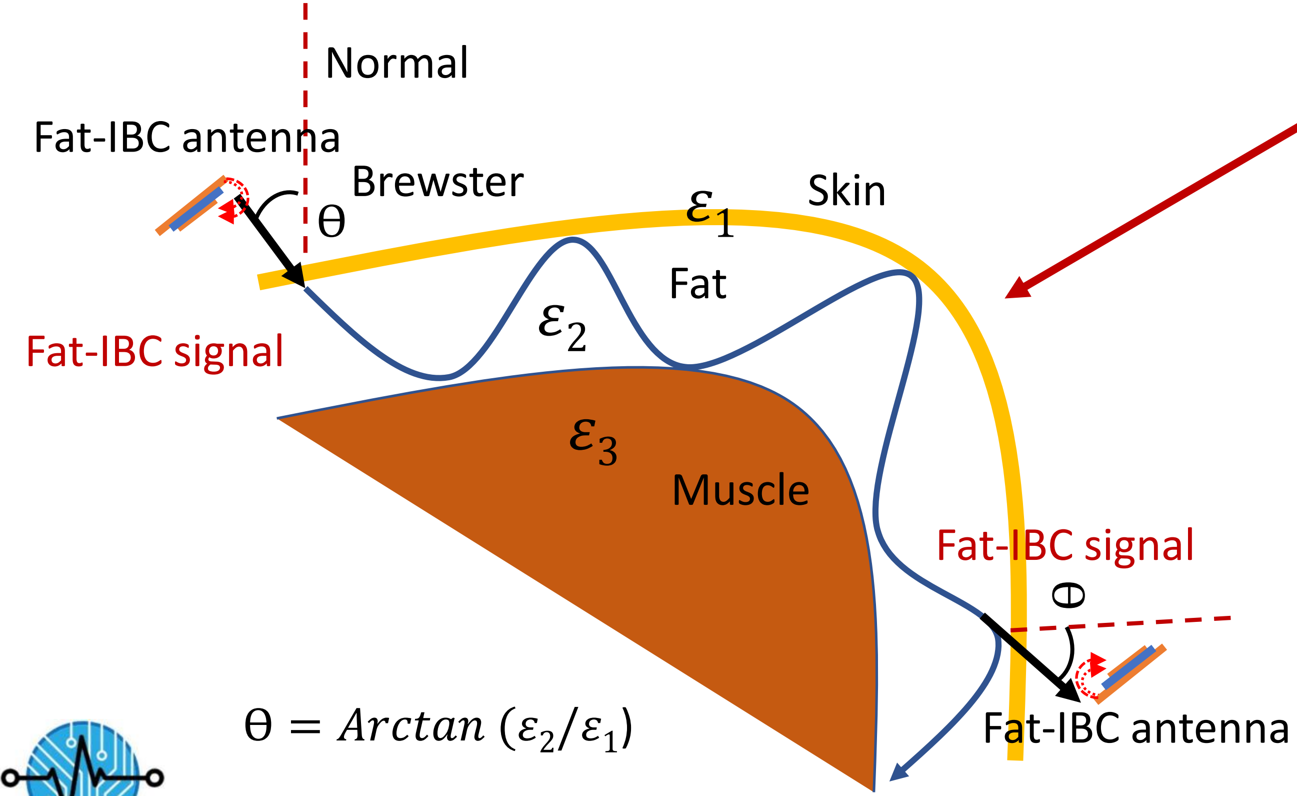
S. R. Mohd Shah et al., "Analysis of Thickness Variation in Biological Tissues Using Microwave Sensors for Health Monitoring Applications," in IEEE Access, vol. 7, pp. 156033-156043, 2019, doi: 10.1109/ACCESS.2019.2949179.

Fat Intrabody communication (Fat-IBC) ***is the methodology by which microwave signals are excited in the subdermal fat layer situated above muscle tissue either from the surface of the skin / through an implanted node / a semi implanted node and propagate through the fat layer, distributed across the body!***

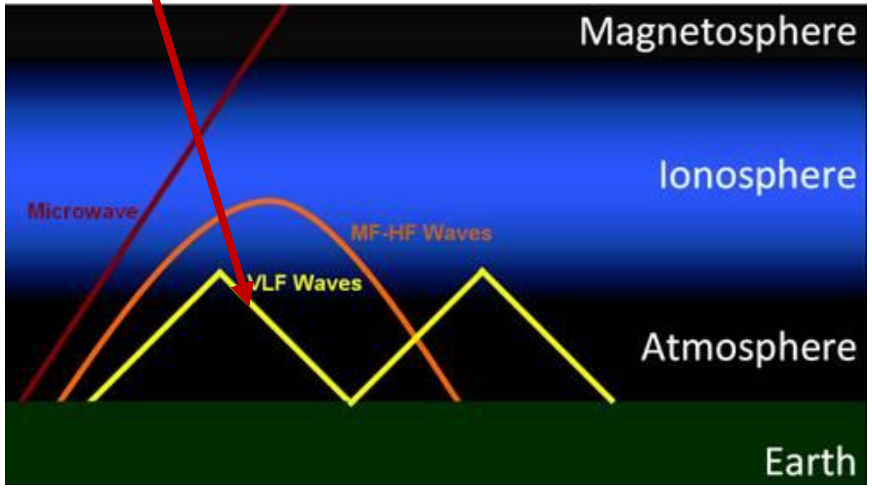
Fat-IBC Principle

*The **Zenneck wave**, Zenneck surface wave or Sommerfeld-Zenneck surface wave is a longitudinal, inhomogeneous or non-uniform electromagnetic plane wave incident at the complex Brewster's angle onto a planar or spherical boundary interface between two homogeneous media having different dielectric constants.





$$\theta = Arctan\ (\varepsilon_2/\varepsilon_1)$$



Fat-IBC is re-inforced by the presence of additional Conducting skin/muscle boundary, ensuring the confinement.

*P.O. Risman,, Journal of Microwave power and electromagnetic energy, 1994, p161-170.

4. Where are we? A look back!

1. *Intra-body microwave communication through adipose tissue
2. *Data packet transmission through fat tissue for wireless intra-body network
3. Reliability of the fat tissue channel for intra-body microwave communication
4. Effect of thickness inhomogeneity in fat tissue on in-body microwave propagation

*IET Healthcare Technology Letters; Asan, N. B. *et. al*

*IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology; Asan, N. B. *et. al*

IEEE Conference on Antenna Measurement CAMA 2017; Asan. N. B. *et. al*

IEEE International Microwave Biomedical Conference (IMBioC 2018); Asan. N. B. *et. al*

UPPSALA
UNIVERSITET

Characterization of the Fat Channel for Intra-Body Communication at R-Band Frequencies 5

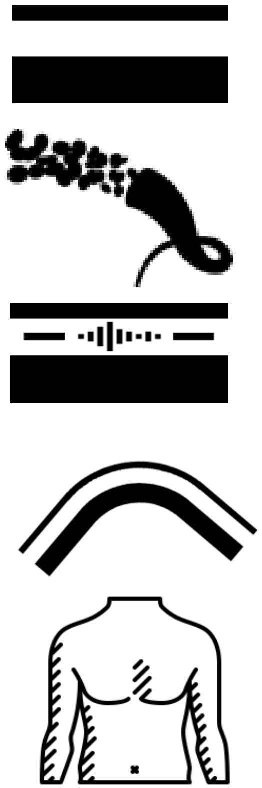
Assessment of Blood Vessel Effect on Fat-Intrabody Communication using Numerical and Ex-vivo Models at 2.45 GHz. 6

2.4 GHz Implant Antenna 7

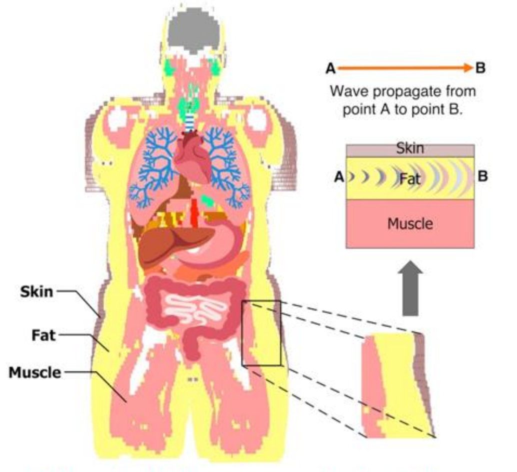
Fat Channel Bending / Polarization 8

N. B. Asan et al., "Fat-IntraBody Communication at 5.8 GHz: Verification of Dynamic Body Movement Effects Using Computer Simulation and Experiments," in IEEE Access, vol. 9, pp. 48429-48445, 2021, doi: 10.1109/ACCESS.2021.3068400.

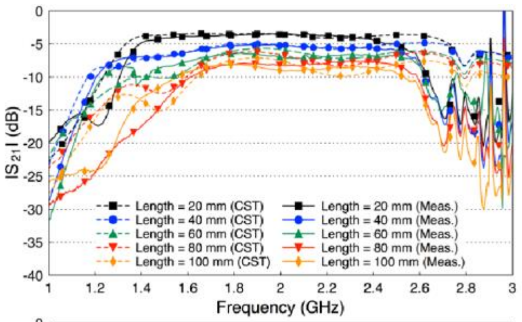
Front to Back Transmission (Torso Model) 9



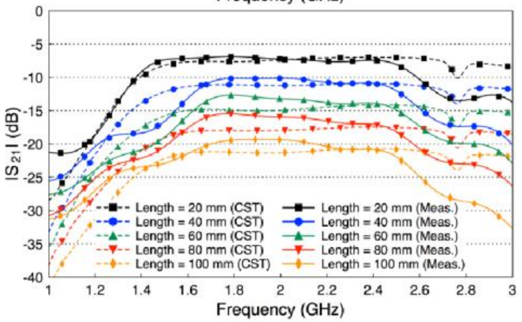
Intra-body microwave communication through adipose tissue



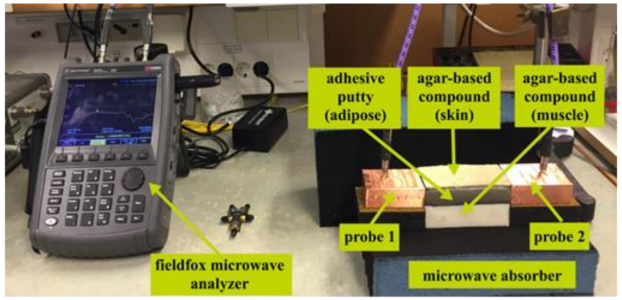
The model shows the fat tissue surrounding the vital organs in the abdomen.
The example of the three tissues is taken to characterize the intra-body microwave transmission through the fat tissue

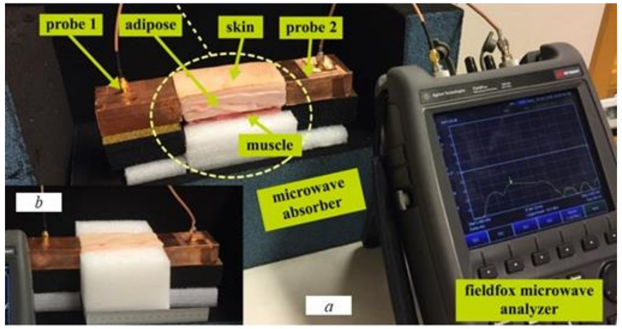


Phantom

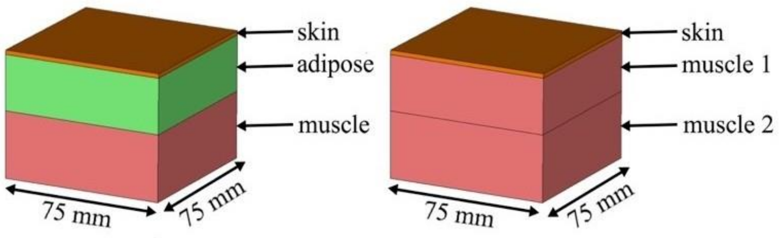


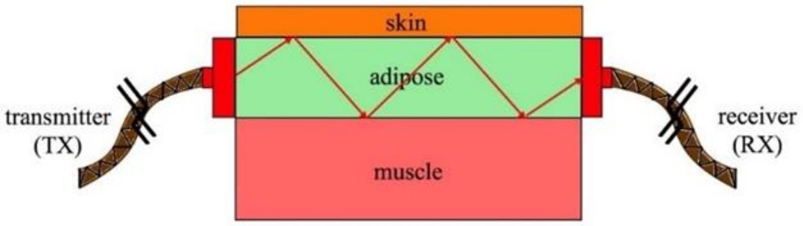
Ex-vivo





Laboratory setup for fat channel characterization



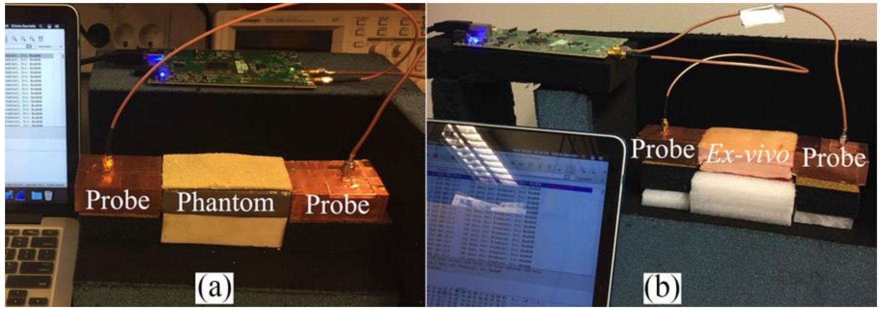


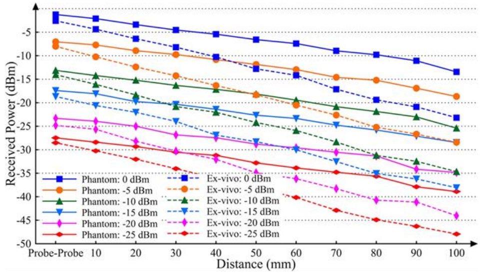
Simulation setup of models of the human tissues (a) Model A: Skin-fat-muscle layer (b) Model B: Skin-muscle-muscle layer

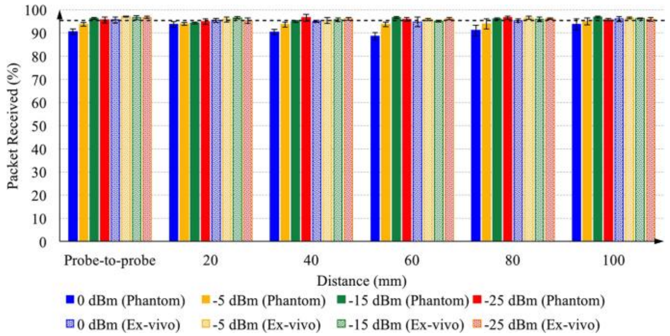
Name	Permittivity	Conductivity (S/m)
Skin	38.1	1.43
Fat	5.29	0.1
Muscle	52.7	1.74

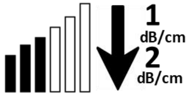
Asan, N.B., Hassan, E., Velander, J., Mohd Shah, S.R., Noreland, D., Blokhuis, T.J., Wadbro, E., Berggren, M., Voigt, T. and Augustine, R., 2018. Characterization of the fat channel for intra-body communication at R-band frequencies. Sensors, 18(9), p.2752.

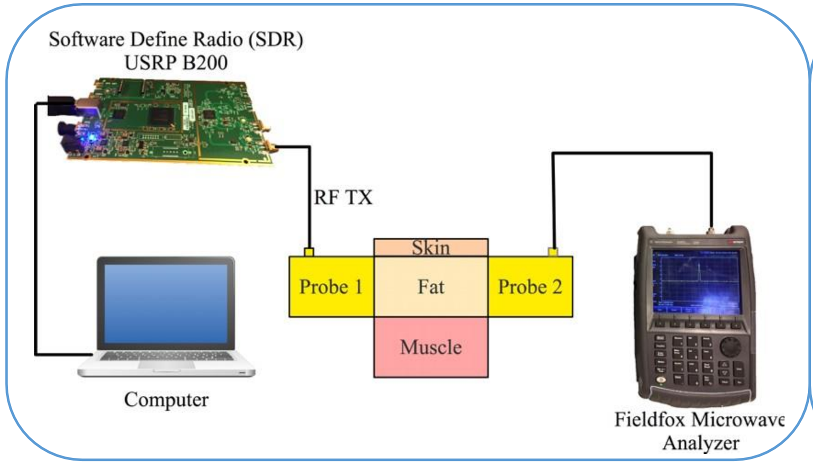
Data packet transmission through fat tissue for wireless intra-body network

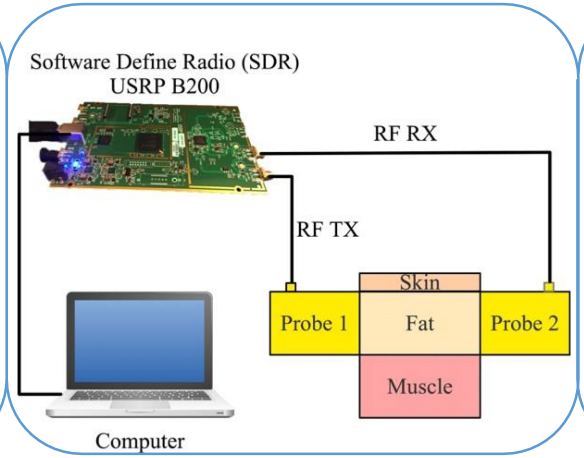


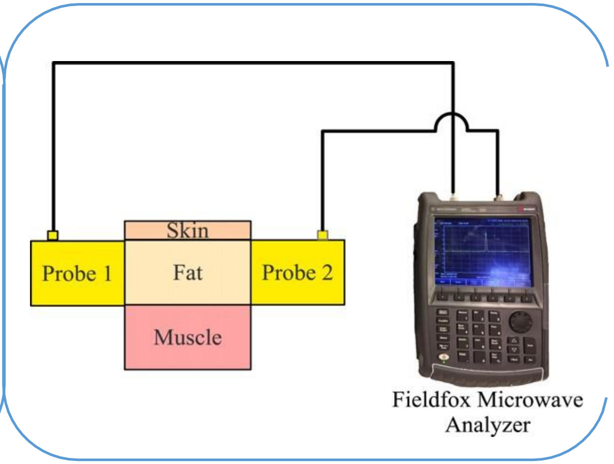




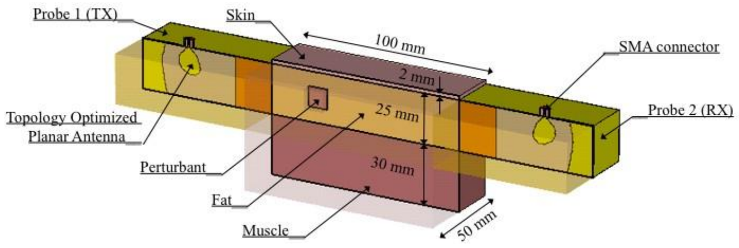


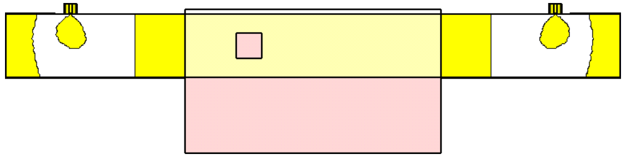


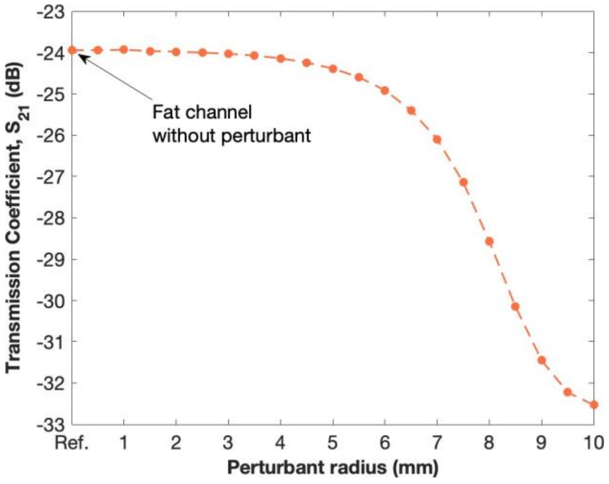


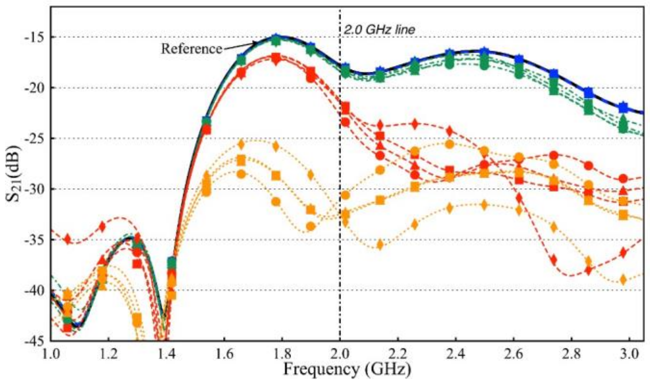


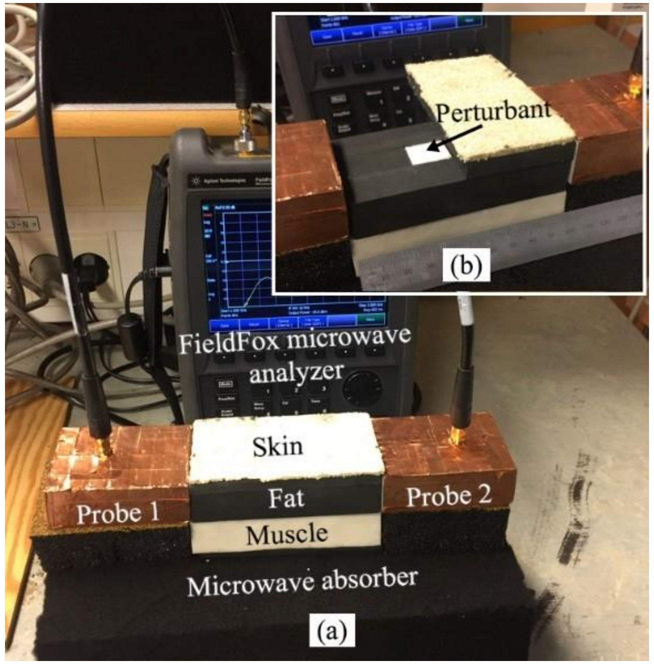
Reliability of the fat tissue channel for intra-body microwave communication

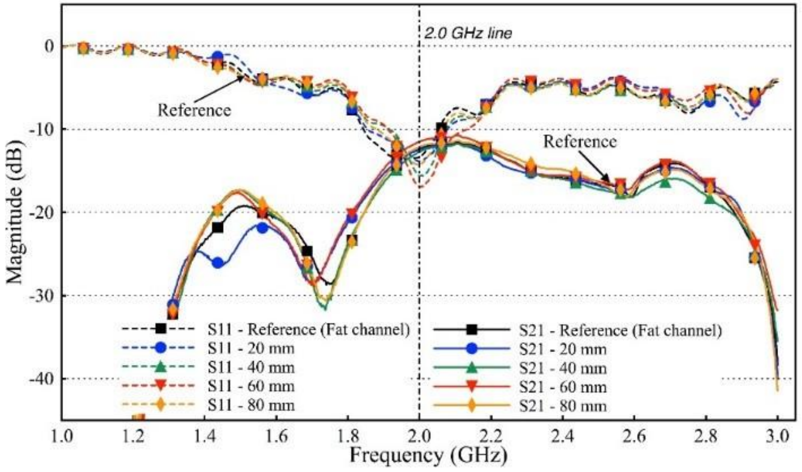




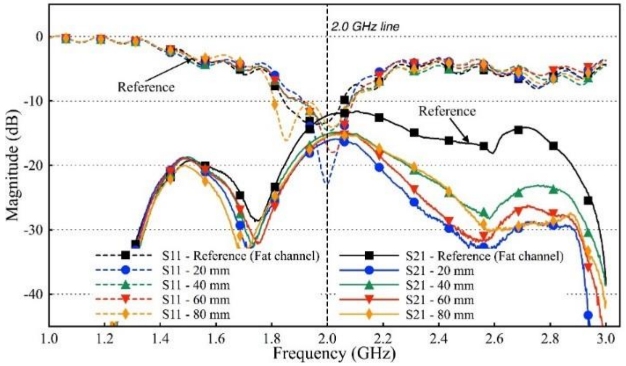




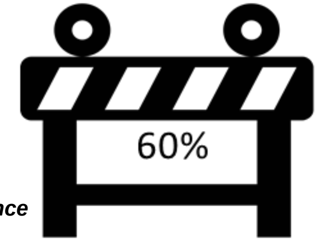




Perturbant size = 10 mm

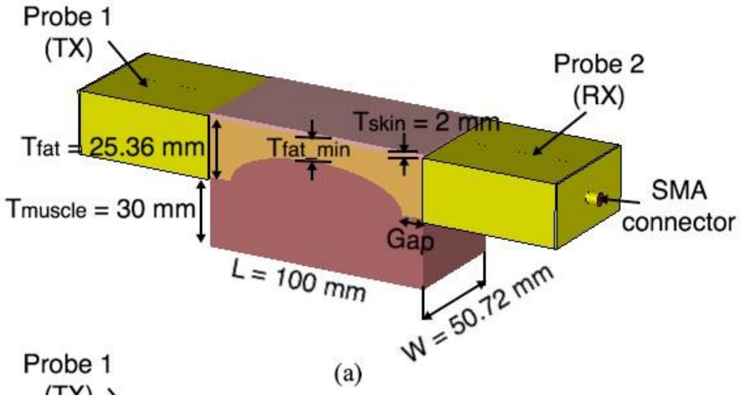


Perturbant size = 15 mm

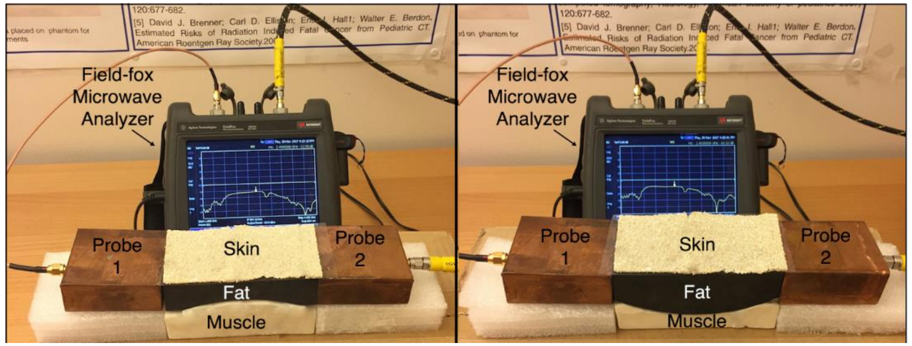


N. B. Asan et al., "Reliability of the fat tissue channel for intra-body microwave communication," 2017 IEEE Conference on Antenna Measurements & Applications (CAMA), 2017, pp. 310-313, doi: 10.1109/CAMA.2017.8273435.

Effect of thickness inhomogeneity in fat tissue on in-body microwave propagation

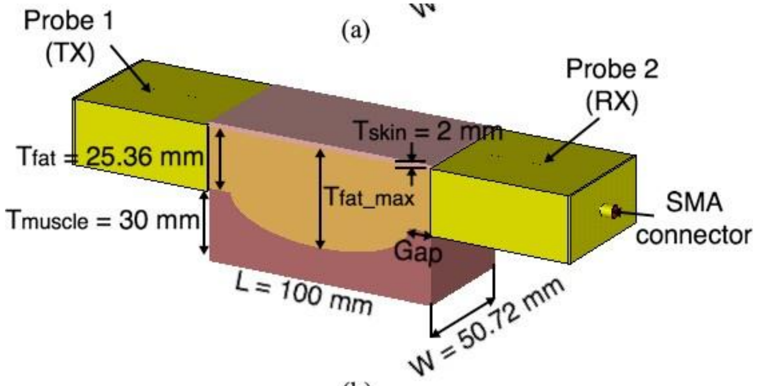


(a)



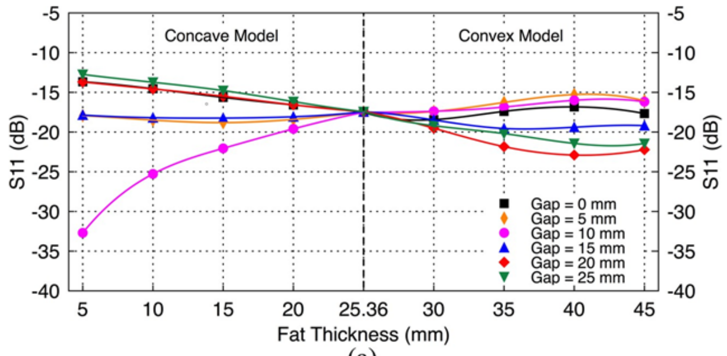
$T_{fat\_concave}$ = 20 mm
Gap = 10 mm

T_{fat_convex} = 35 mm
Gap = 10 mm



(b)

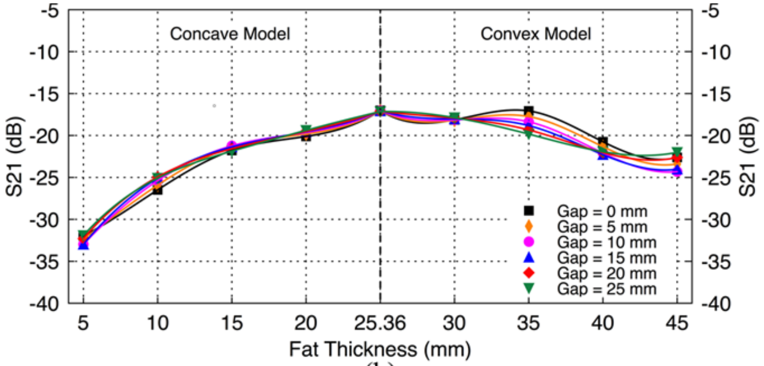
Reflection Coefficient, $|S_{11}|$ dB



(a)

A good channel matching below -10 dB with respect to the fat thickness variation and the *Gap* distance.

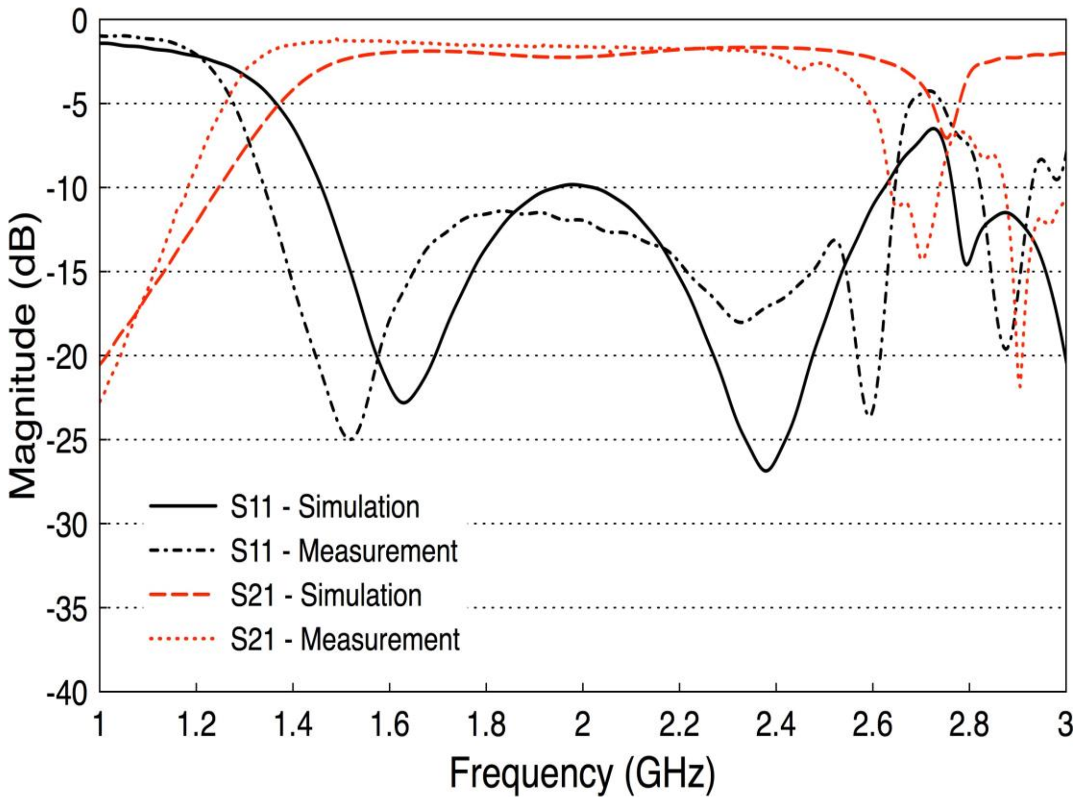
Transmission Coefficient, $|S_{21}|$ dB



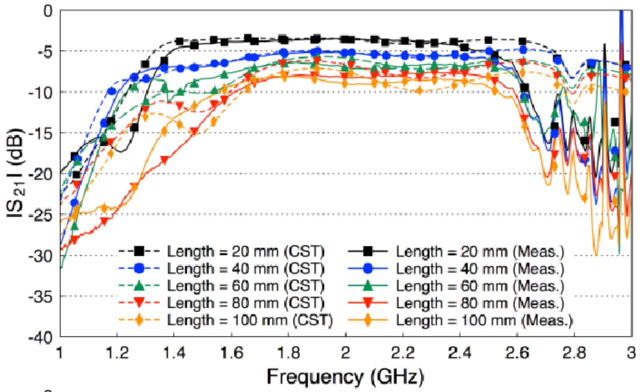
(b)

Gap : Has a very little impact on the signal coupling.
The concave model appears to gradually increase with increasing the thickness of fat from 5 mm until it reached a maximum value of 25.36 mm.

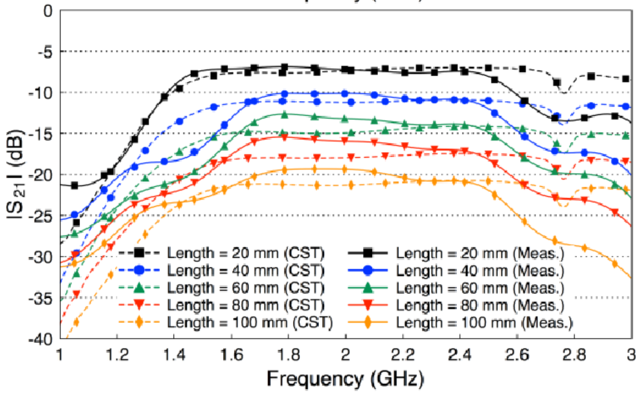
Characterization of the Fat Channel for Intra-Body Communication at R-Band Frequencies



Simulation



Phantom

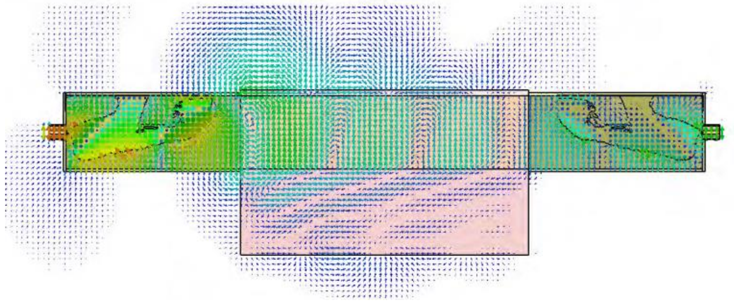


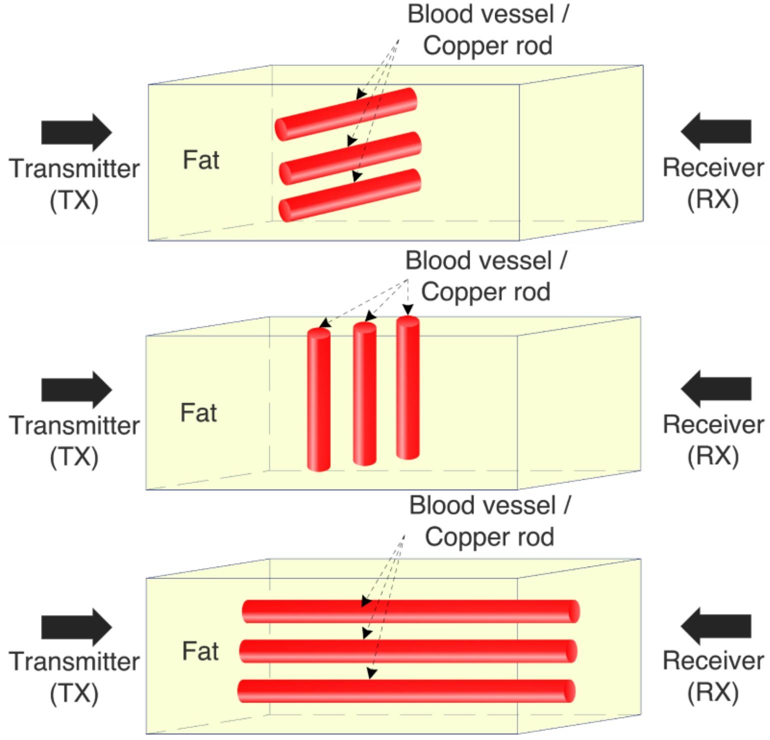
Ex-vivo

[redacted]

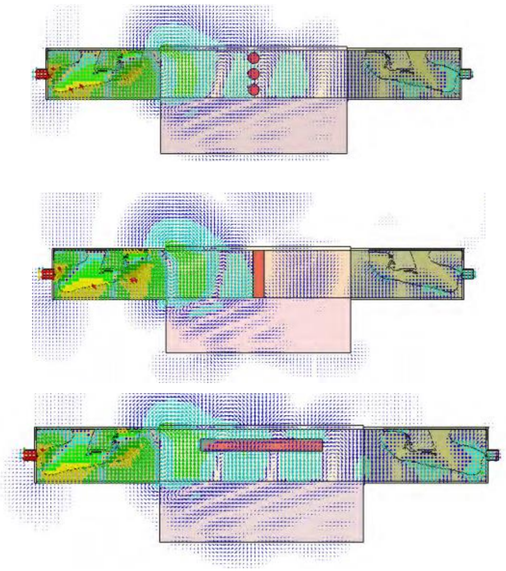
Asan NB, Hassan E, Shah JVSRM, Noreland D, Blokhuis TJ, Wadbro E, Berggren M, Voigt T, Augustine R. Characterization of the Fat Channel for Intra-Body Communication at R-Band Frequencies. Sensors (Basel). 2018 Aug 21;18(9):2752. doi: 10.3390/s18092752. PMID: 30134629; PMCID: PMC6165426.

Assessment of Blood Vessel Effect on Fat-Intrabody Communication using Numerical and Ex-vivo Models at 2.45 GHz.



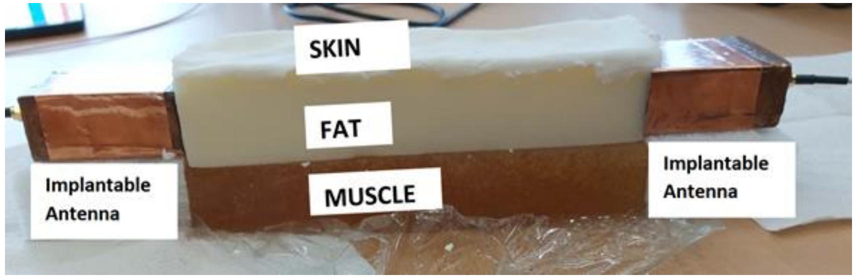


- Dissimilarities of each configuration in their signal transmission performances are attributable to the position of the blood vessel.
- Blood vessels in the **transverse-horizontal plane** function as a splitter and recombiner.
- In the **transverse-vertical plane**, higher reflection is seen due to their reflector-based behaviour.
- The **longitudinal plane** is characterised by blood vessel that functions as a splitter, whereby there is no electric field recombination due to mismatched signal propagation.

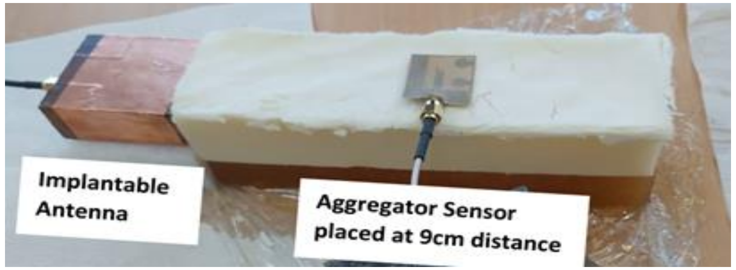


N. B. Asan et al., "Assessment of Blood Vessel Effect on Fat-Intrabody Communication Using Numerical and Ex-Vivo Models at 2.45 GHz," in IEEE Access, vol. 7, pp. 89886-89900, 2019, doi: 10.1109/ACCESS.2019.2926646.

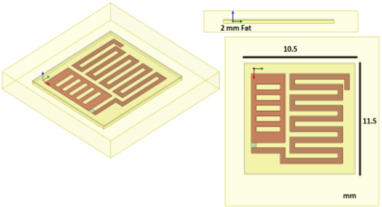
2.4 GHz Implant Antenna

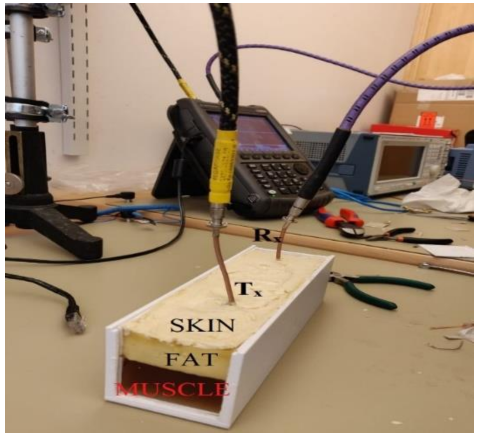


A radio link from two Fat-IBC matched antennas through a skin-fat-muscle planar phantom model

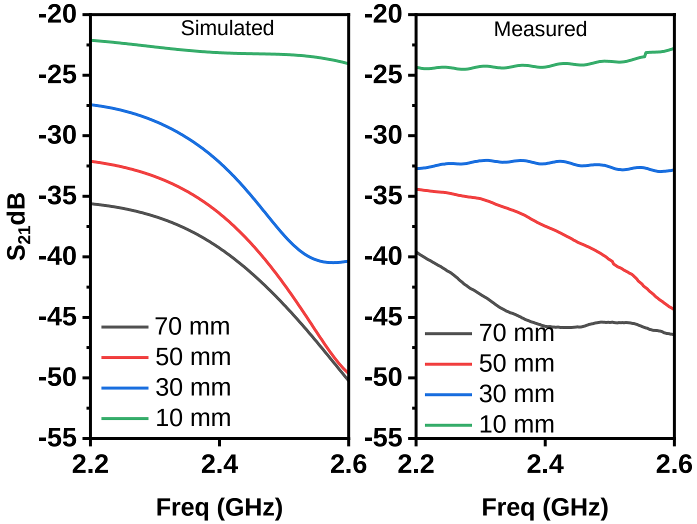


A Fat-IBC antenna on a skin-fat-muscle phantom model to test communication performance



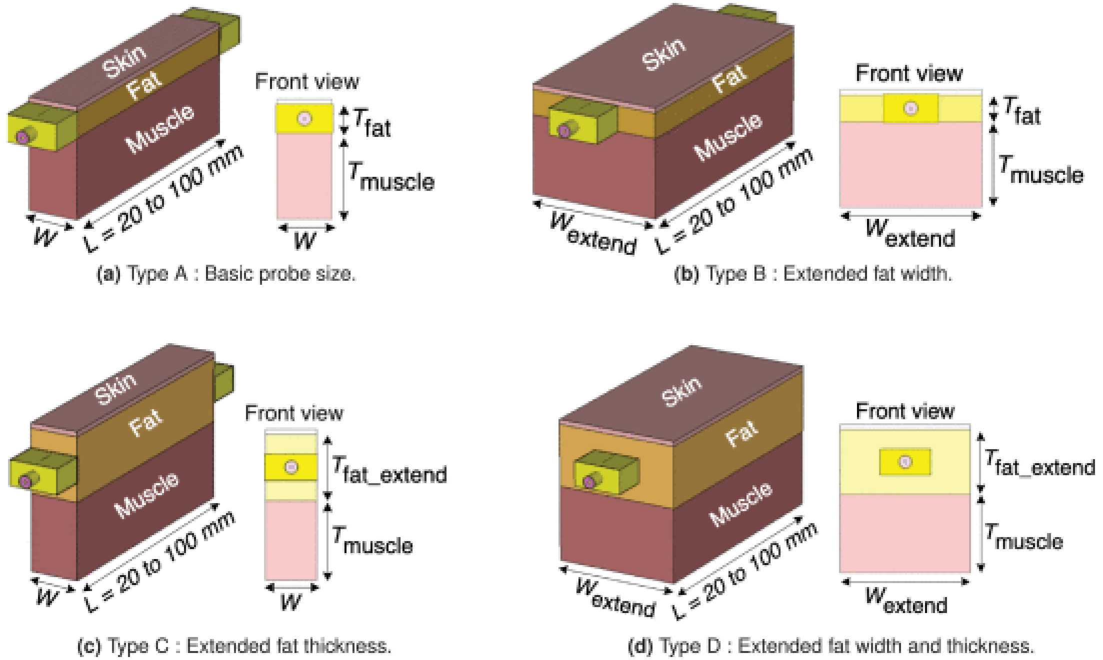


Test setup in a skin-fat-muscle planar phantom model

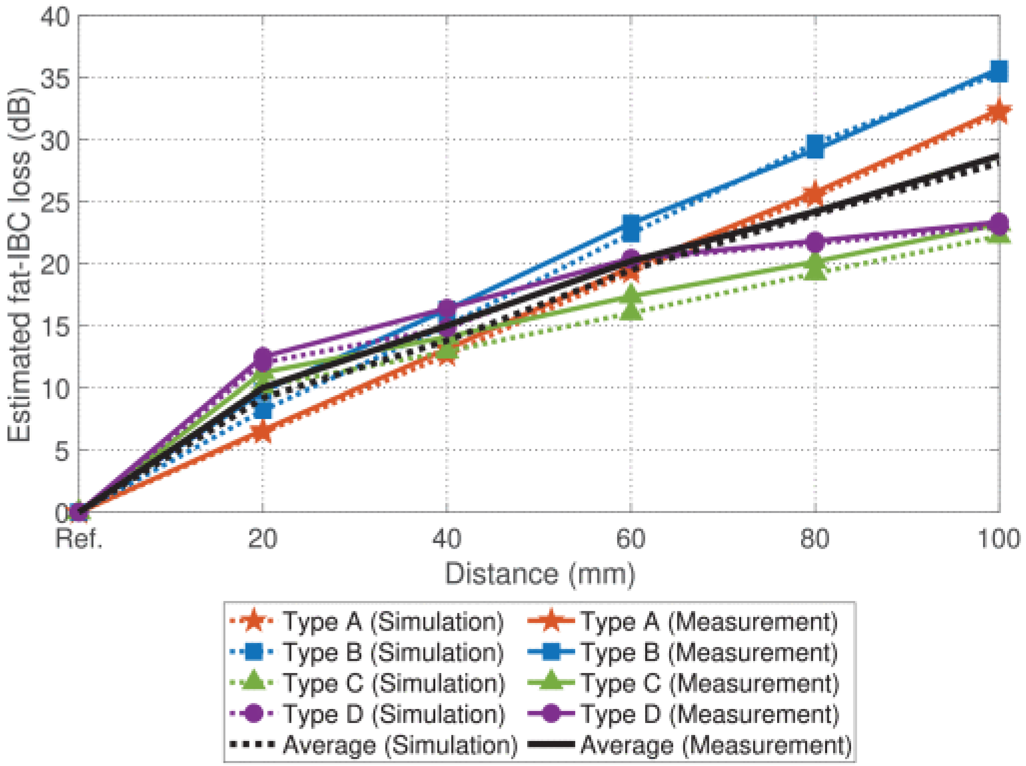


Coupling signal variation of proposed implanted antenna in 2.4GHz inside the fat channel in various distance

Fat Channel Polarization



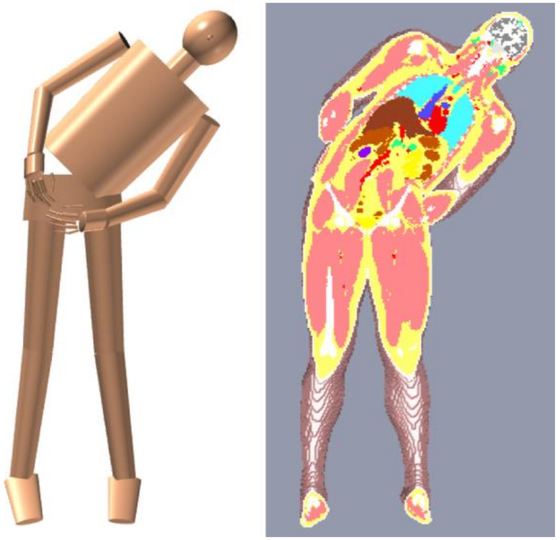
(a) Type A : Basic probe size.
(b) Type B : Extended fat width.
(c) Type C : Extended fat thickness.
(d) Type D : Extended fat width and thickness.

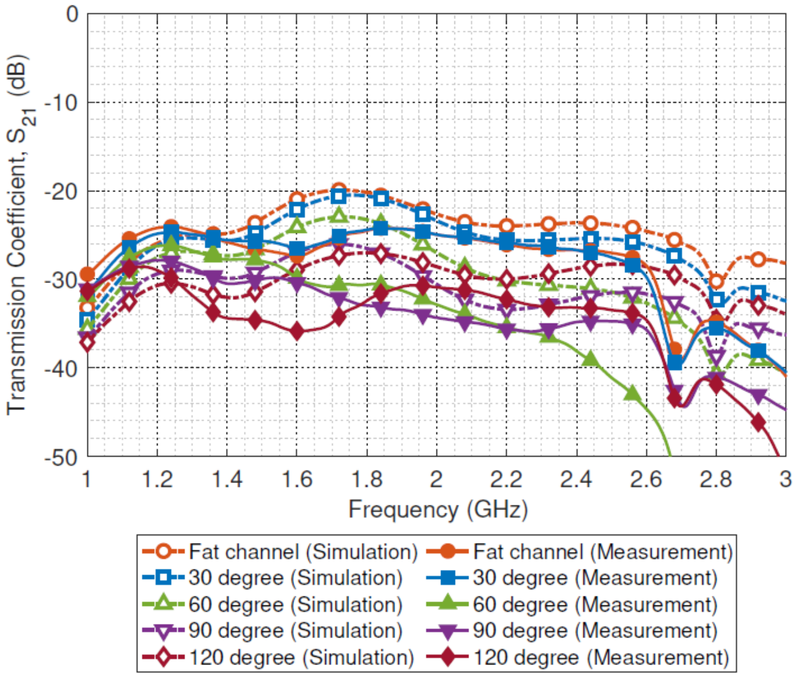


Four configurations of three-layered tissue model structure to characterize fat-IBC performance both numerically and experimentally

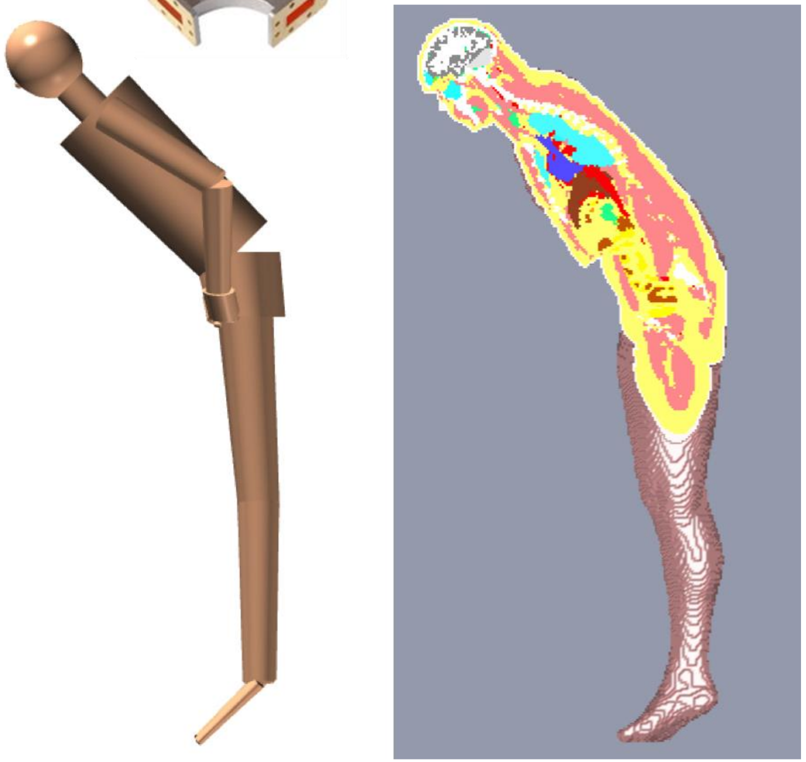
N. B. Asan et al., "Fat-IntraBody Communication at 5.8 GHz: Verification of Dynamic Body Movement Effects Using Computer Simulation and Experiments," in IEEE Access, vol. 9, pp. 48429-48445, 2021, doi: 10.1109/ACCESS.2021.3068400.

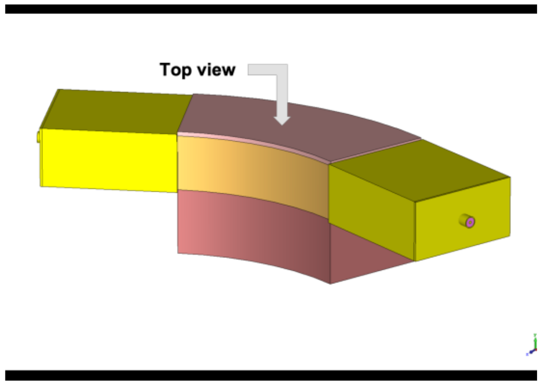
Fat Channel Bending



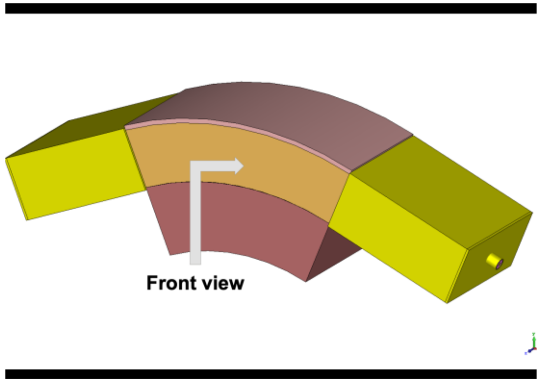


(b) Transmission coefficient, S_{21} (dB)



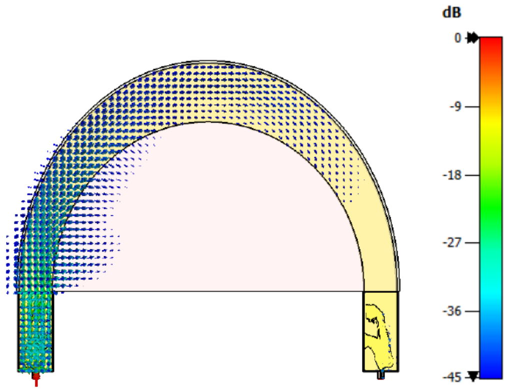


Horizontal-bent vertical plane: To demonstrate front or back
fat communication

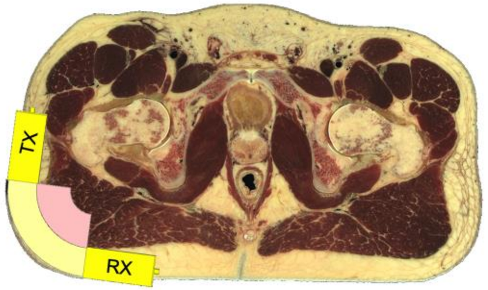


Vertical-bent vertical plane: To demonstrate the front-to-back
fat communication.

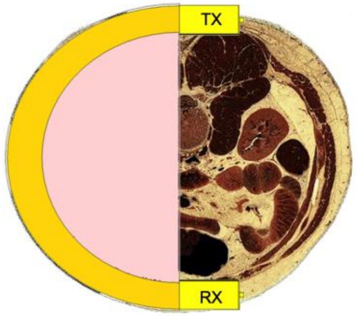
Front to Back Transmission (Torso Model)



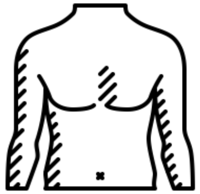
(c) Power flow

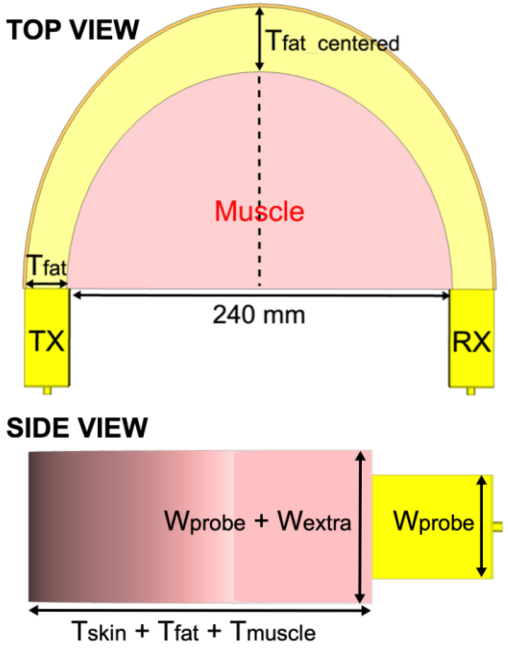


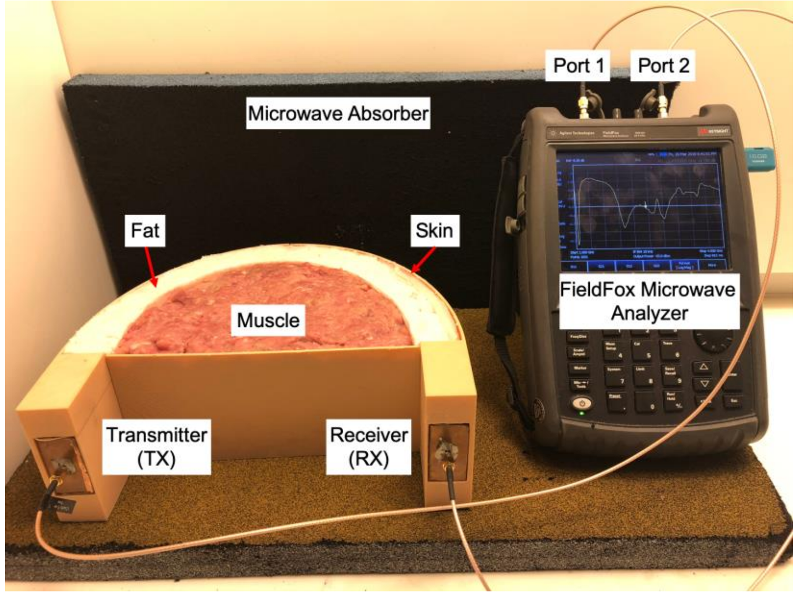
Pelvic



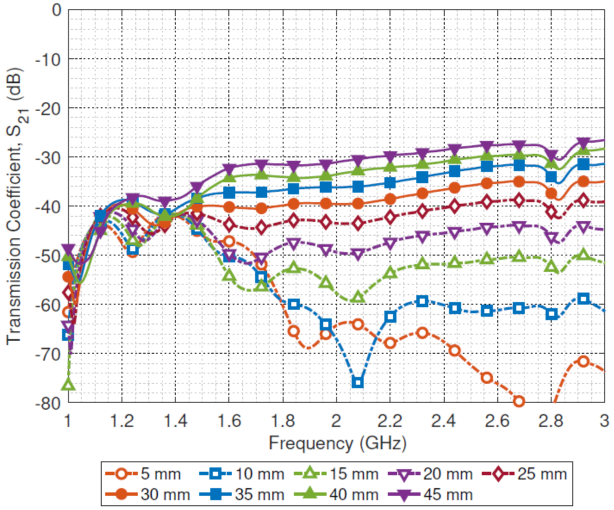
Abdomen







Measurement setup



(b) Transmission coefficient, S_{21} (dB)

N. B. Asan et al.: Impact of In-body Propagation Dynamics and Measurement of Front-to-back Fat-IBC at R-band Frequencies in IEEE Access, June 2022

Signal Leakage in Fat Tissue-Based In-Body Communication: Preserving Implant Data Privacy

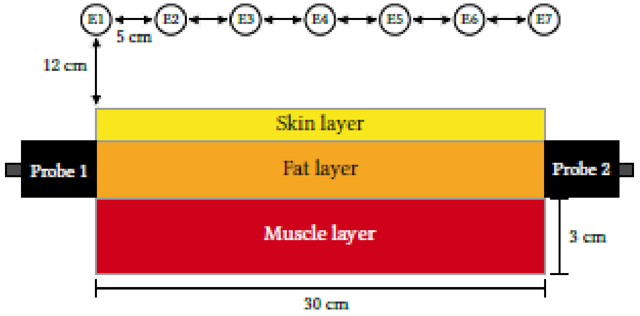


Figure 1: Illustration of the three-layer planar phantom setup used to measure the signal attenuation by human skin.

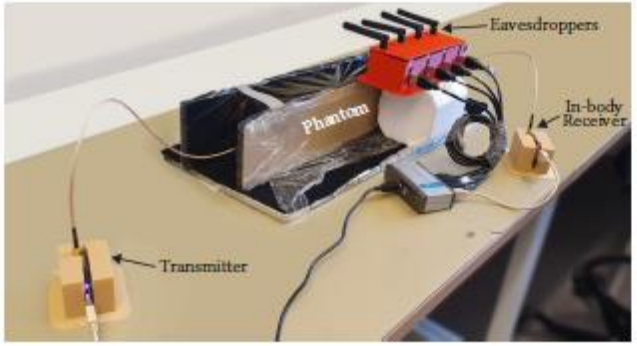


Figure 2: Photo of the measurement setup. The phantom lies between microwave-absorbing sheets, which prevents signal leakage from the sides of the phantom not covered by skin.

Madhushanka Padmal, Johan Engstrand, Robin Augustine, & Thiemo Voigt

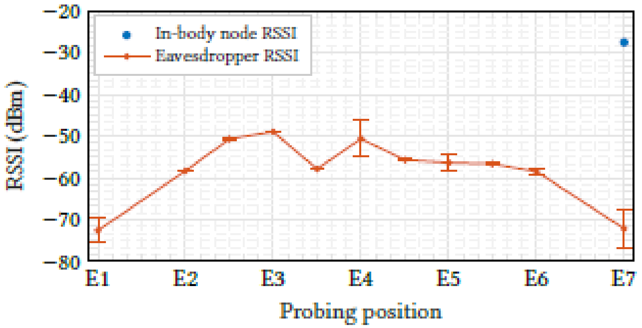


Figure 4: Average RSSI at 12 cm above along the longitudinal center-line of the phantom and at the in-body receiver.

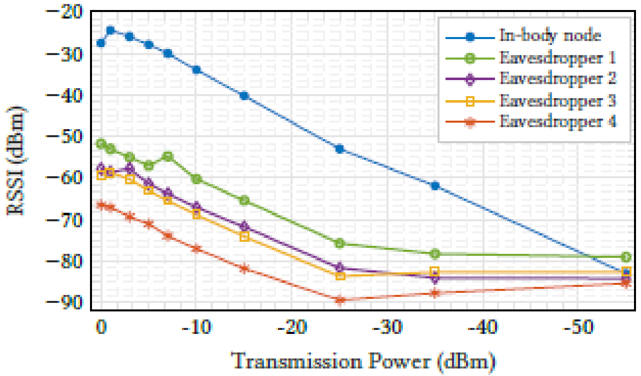
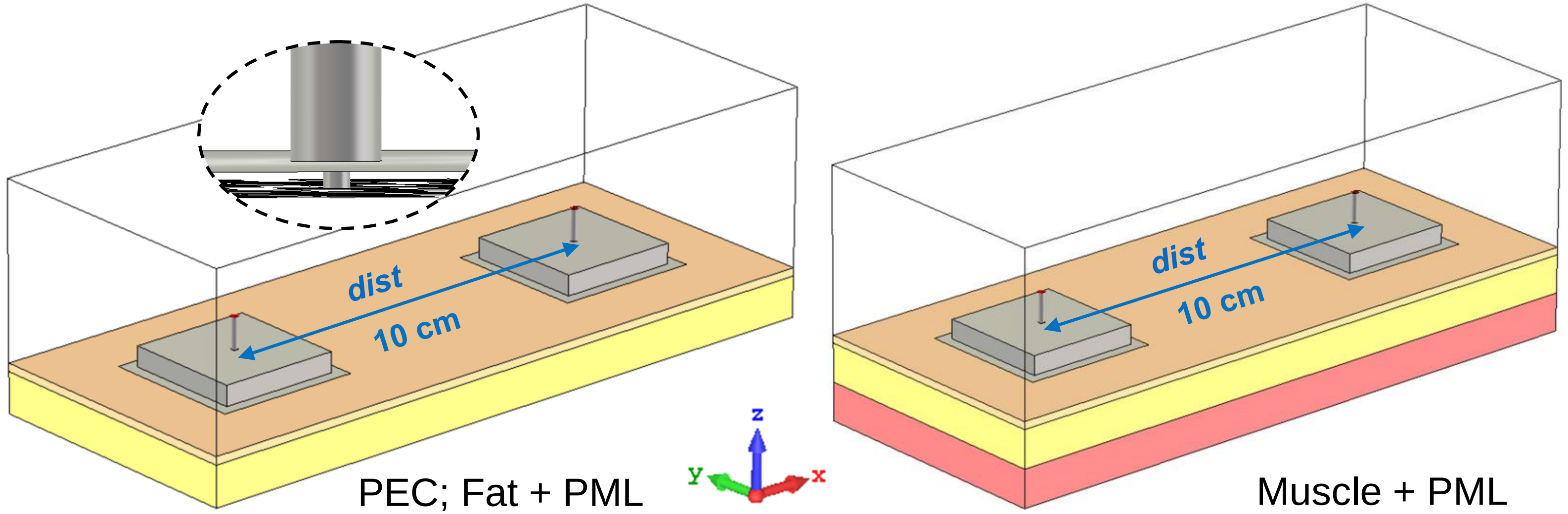


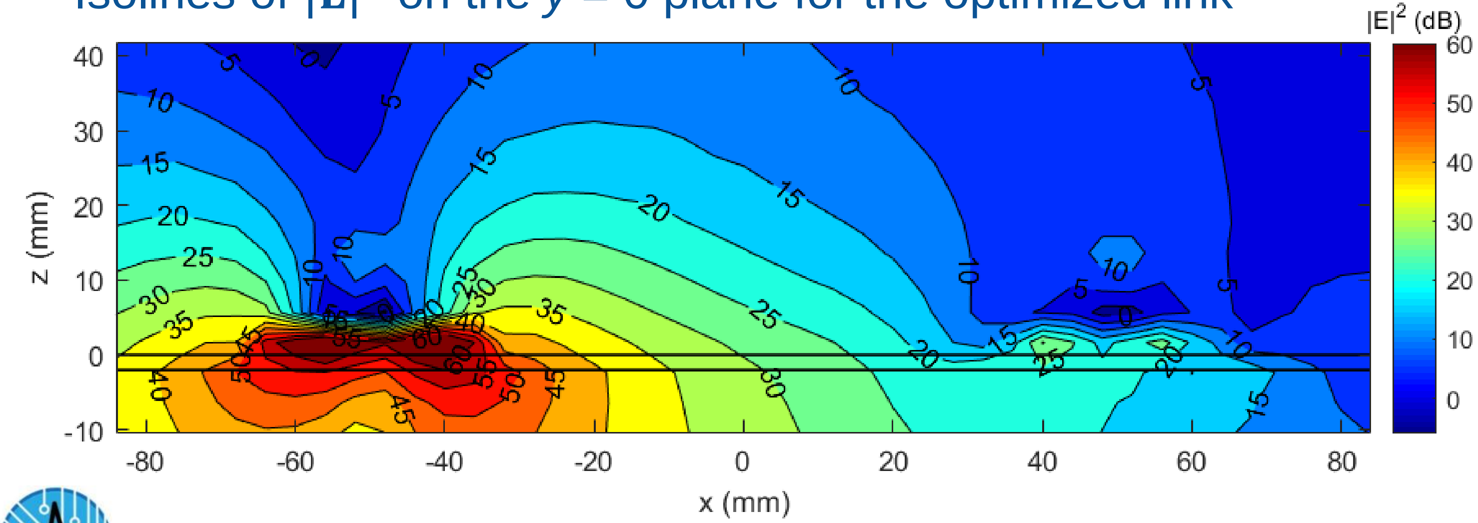
Figure 6: Variation of average RSSI measurements at different receiving nodes for different transmission power levels.

GA for Antenna Design

- Cross validation: the optimized link is simulated in CST MWS.
- Different conditions are used below the 10mm-Fat layer.
- A good radiation coupling into the body is observed; transmission losses lower than 5 dB/cm are achieved.

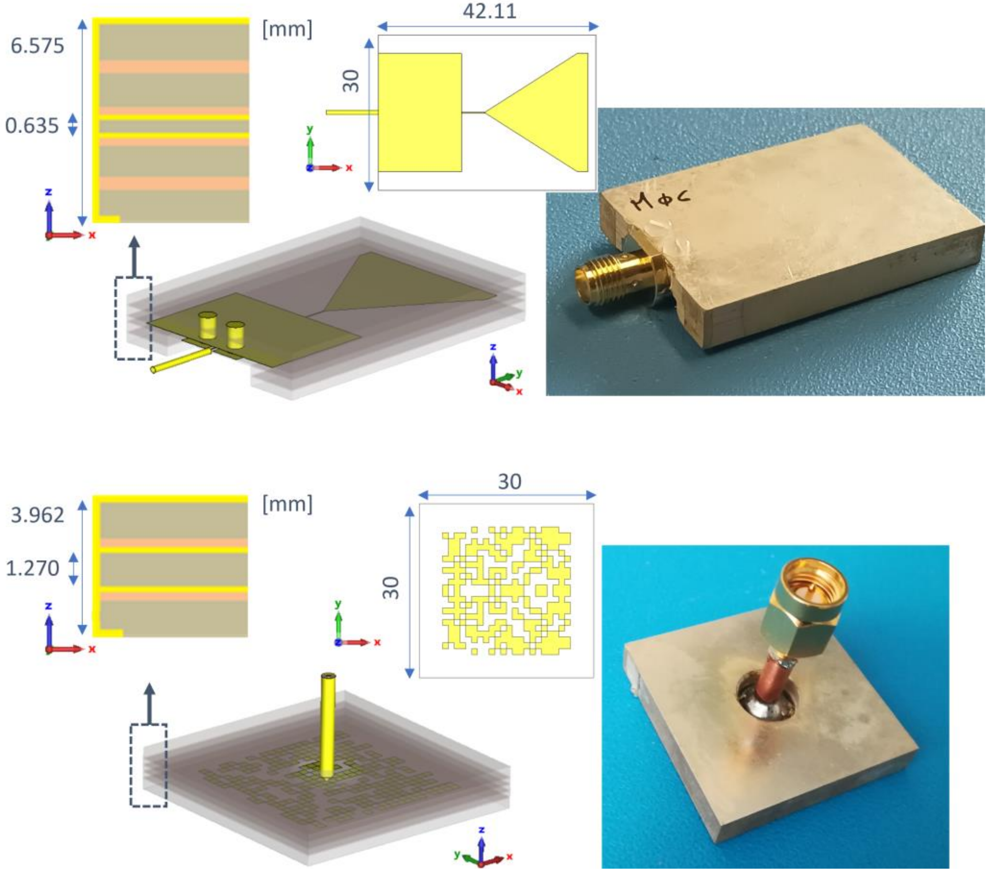


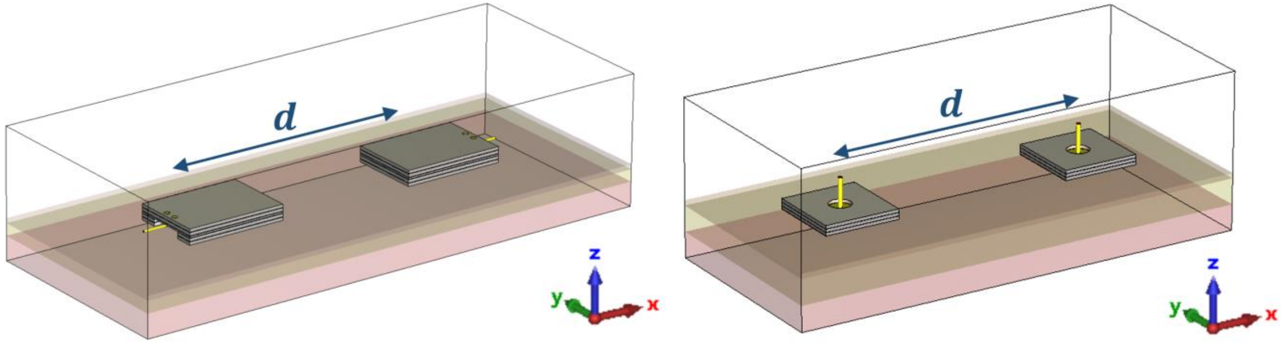
Isolines of $|\mathbf{E}|^2$ on the y = 0 plane for the optimized link



Next steps:

- Optimization of the antenna with a thinner (3-5 mm) Fat layer (more realistic).
- Implementation of an experimental prototype for testing on real phantoms.
- Simulation of the antenna performance on the NHP numerical phantom.





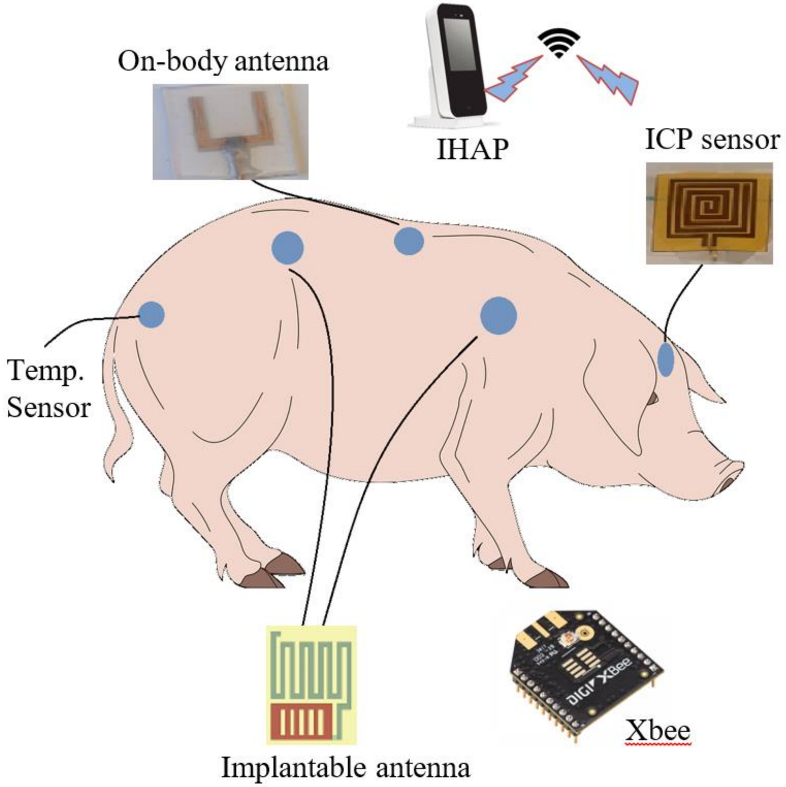
Upper row: Printed monopole antenna with triangular-shaped radiating element; lower row: pixelated patch antenna.

Simulation setup reporting a couple of monopole antennas (left) and a couple of pixelated patch antennas (right) on a three-layers phantom.

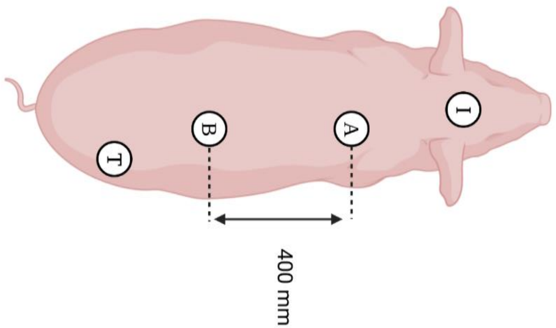
R. Gaffoglio *et al*., "Compact Antenna Solutions for Data Transmission Using Fat-Intrabody Communication (Fat-IBC)," *2024 18th European Conference on Antennas and Propagation (EuCAP)*, Glasgow, United Kingdom, 2024, pp. 1-4, doi: 10.23919/EuCAP60739.2024.10501435.

Pig trial

UPPSALA
UNIVERSITET



End-to-End Transmission of Physiological Data from Implanted Devices to a Cloud-Enabled Aggregator Using Fat Intra-Body Communication in a Live Porcine model, Accepted for Publication in EuCAP 2022, Madrid Spain



- The pig was placed in the prone position.
- Two antennas (denoted node A and node B) were implanted 400 mm apart along the back area, together with the ICP sensor implanted at the cranium.
- The DHT11 temperature sensor (T) was placed on the skin on the back of the pig, towards the hind leg. The aggregator was placed against the skin in between
- Node A and node B, with 200mm separation between either nodes.
- A web server was written in Python with the help of the ‘HTTPServer’ module. The server was set up on port 80 and replied to any HTTP POST request sent to it with a code ‘200’ response.

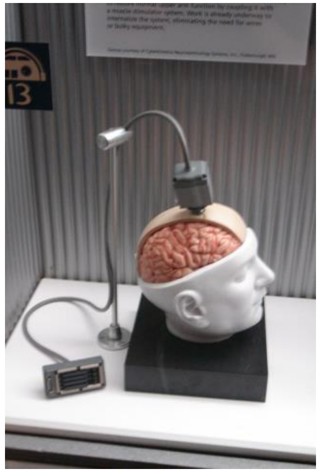
End-To-End Transmission of Physiological Data from Implanted Devices to a Cloud-Enabled Aggregator Using Fat Intra-Body Communication in a Live Porcine Model, Engstrand et. al, Eucap 2022, Madrid Spain

MMG
Microwaves in Medicine

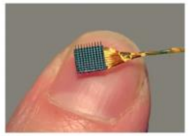
4. Brain – Machine Interface: B-CRATOS

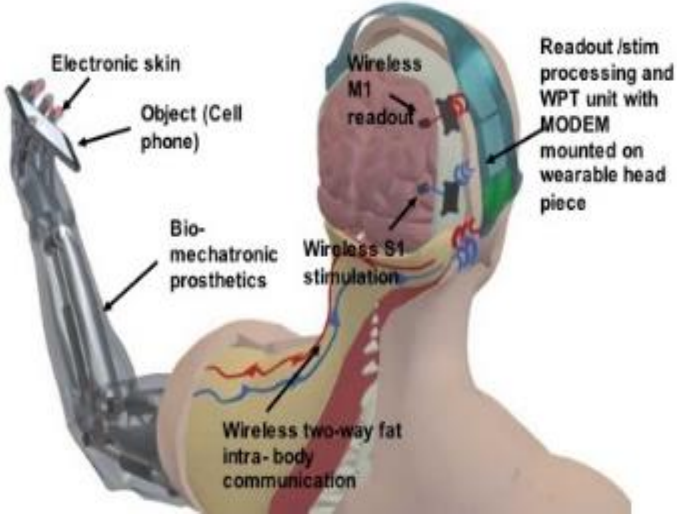
Device	In-body location	Data rate	Data flow direction
Temperature	Forehead	48 bps	Uplink
Heart Beat Rate	Finger tip	48 bps	Uplink
Pulse Oximetry	Finger tip, at injured site	48 bps	Uplink
pH Sensor*	Implanted in oral cavity	48 bps	Uplink
CardioMEMS	Pulmonary artery	1.44 kbps	Uplink
Fall detection	Waist 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

https://synapsebristol.blogspot.com/2013/02/the-ai-lab-brain-computer-interfaces.html



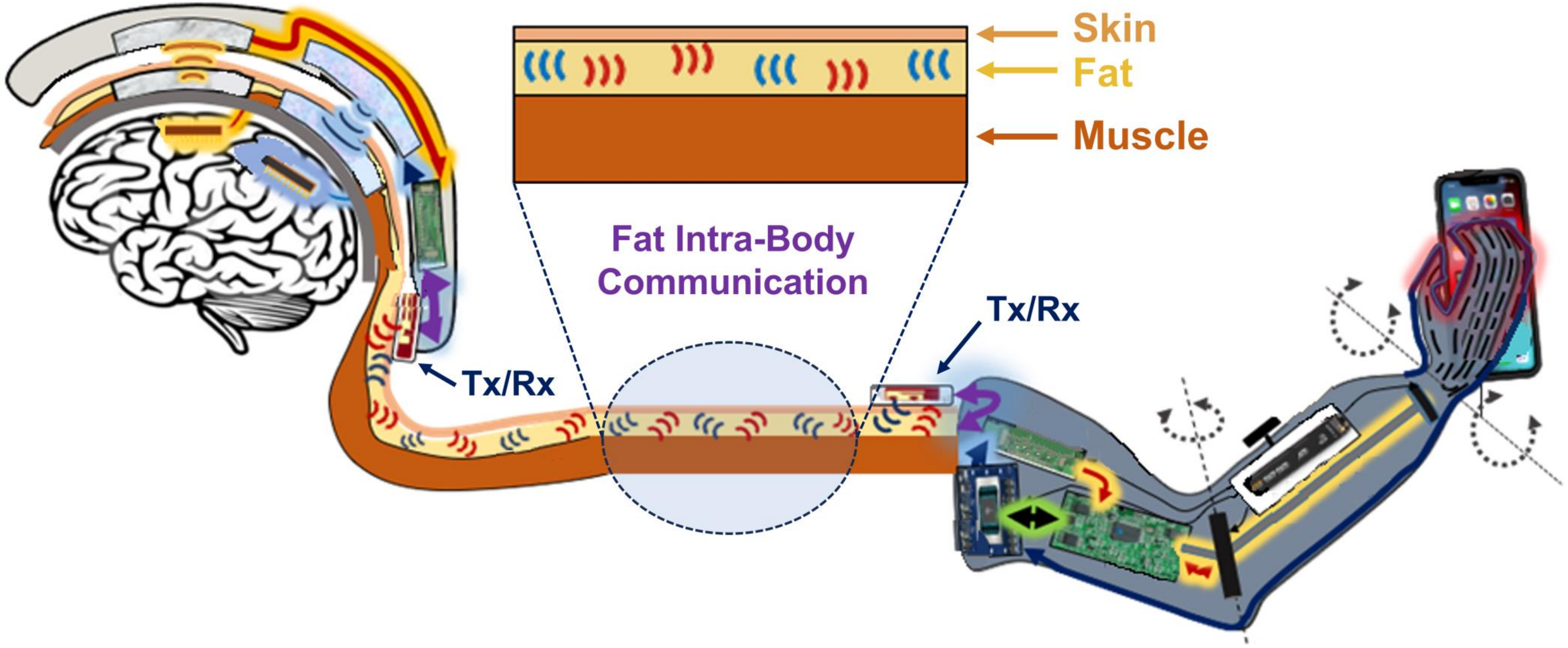
https://psynso.com/brain-computer-interface/





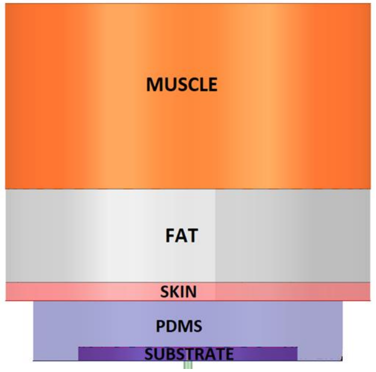
BMI in B-CRATOS : Uplink 64 Mbps and Downlink 2 Mbps, Full-duplex, low latency (10s of ms) requirements!

www.b-cratos.eu

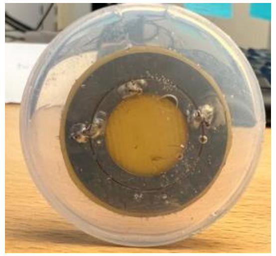


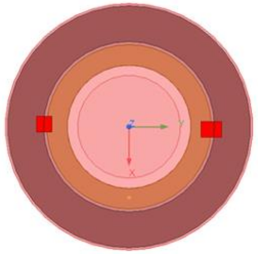
Bidirectional wireless connection between brain implants and a prosthetic arm exploiting Fat-IBC. (Courtesy of B-CRATOS project).

NHP antenna design



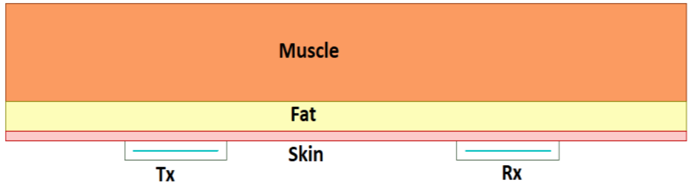
Dual Ring-Shaped Fat-IBC antenna with a three-layer tissue model (Details dimension is not provided due to confidentiality)



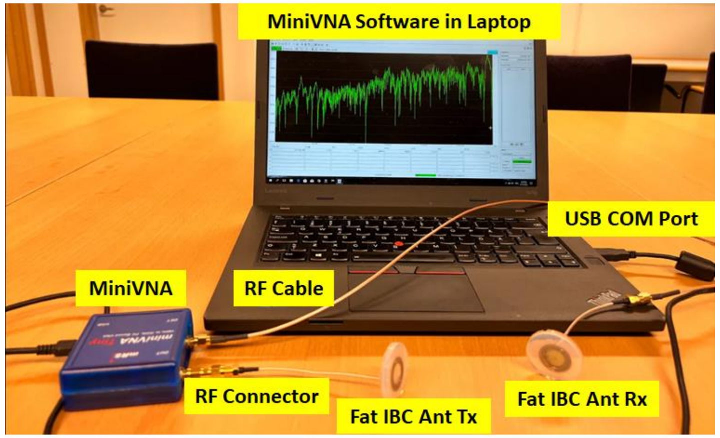


Fabricated and Schematic diagram of Dual Ring-Shaped Fat-IBC antenna with a three-layer model (Details dimension is not provided due to confidentiality)

Dual Ring Circular Loop Patch Antenna

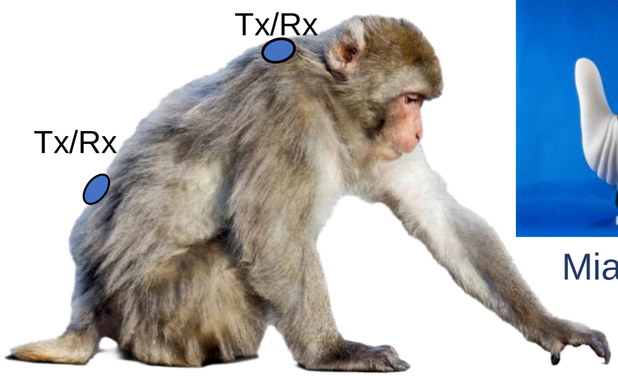


CST Simulation model in three layer condonation including Tx and RX mode



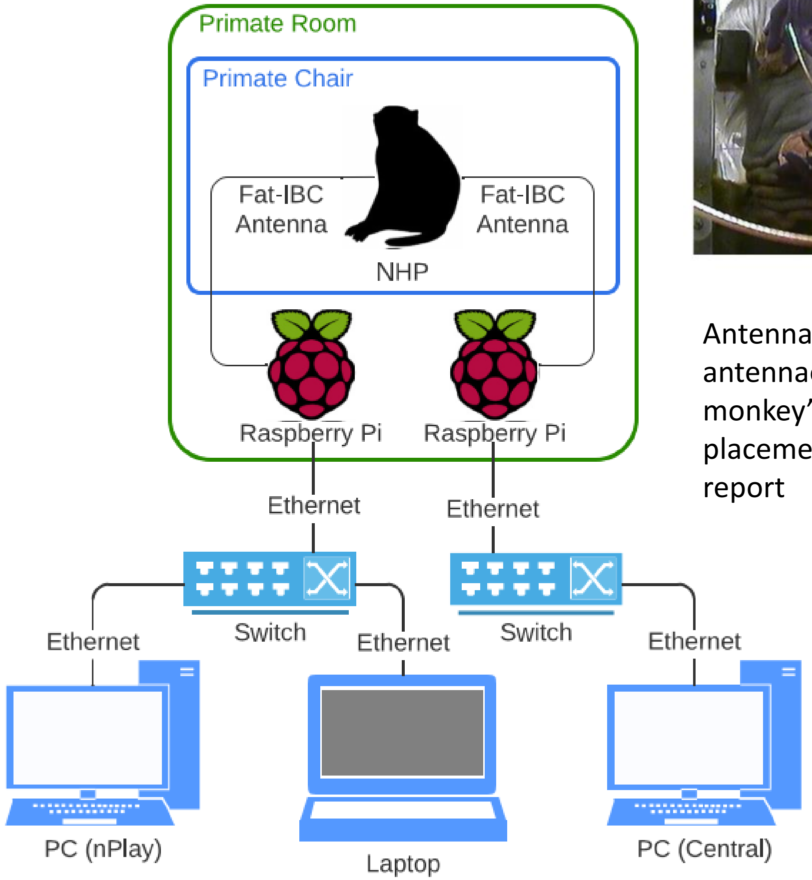
TxR system for NHP Fat-IBC channel measurement

Next step: In-vivo transmission measurement on monkey models for NHP channel characterization and interface optimisation

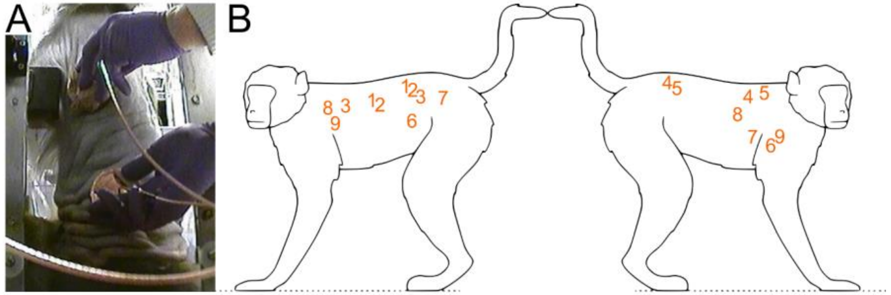


Mia Hand

In-vivo testing of fat channel communication



Network diagram of the in-vivo Fat-IBC test

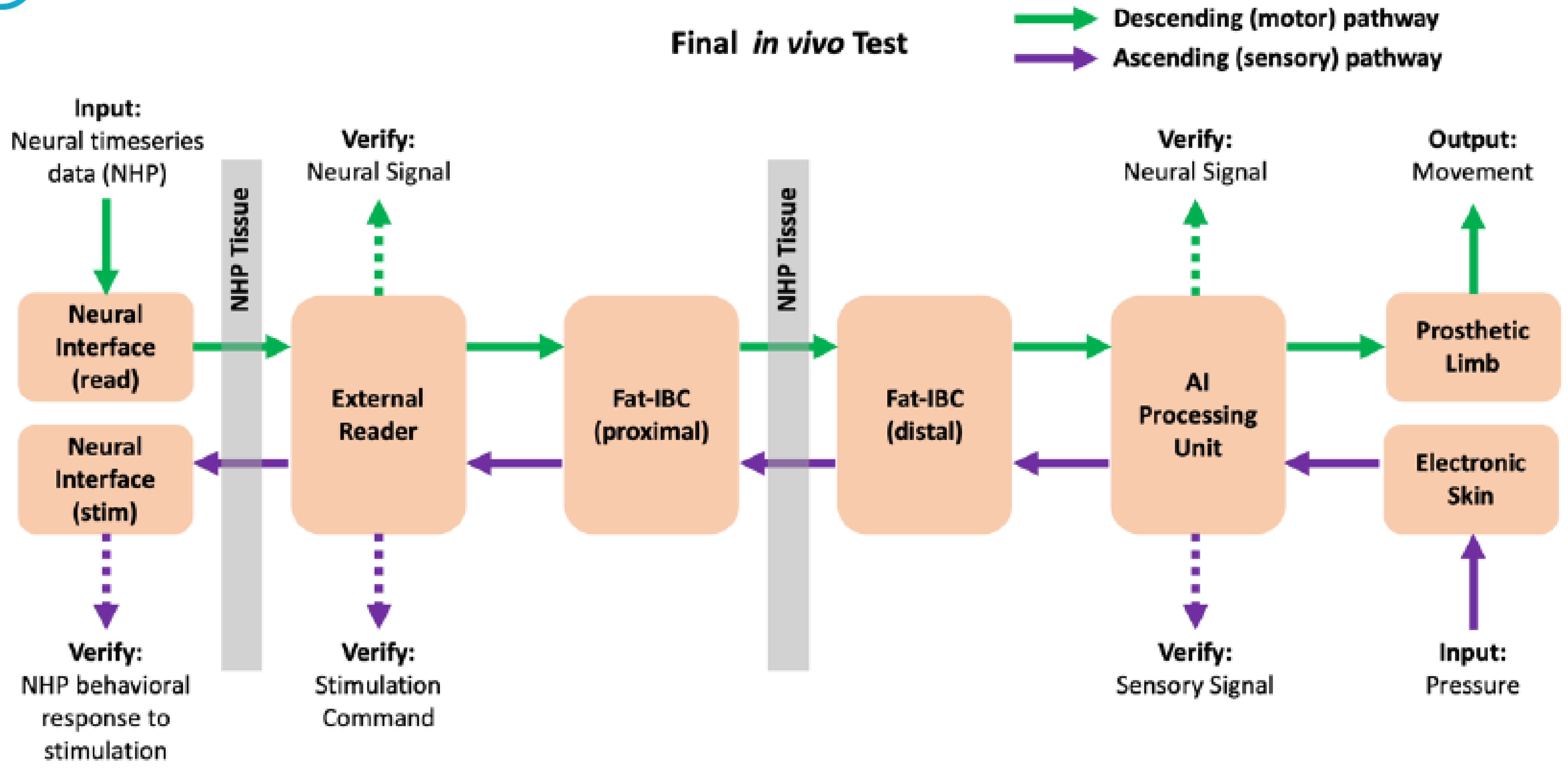


Antenna placements. A| Photograph depicting the antennae's third (17cm) configuration on the monkey's back. B| Diagram of antenna placements for each of the 9 conditions in the test report

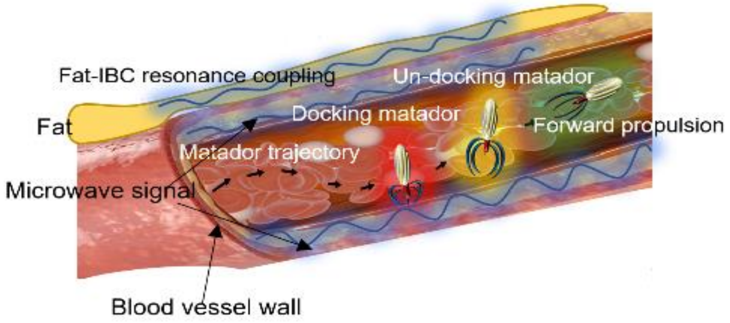
Perspective view of the shielded antenna. The antenna itself measures ~24 mm in diameter.

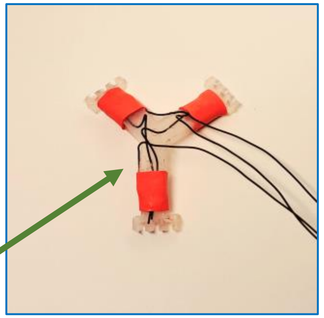
Index	Distance (cm)	Site 1	Site 2	Power (mW)	Data rate (Mbits/s)	Packets lost	Signal strength (dBm)
1	8	L Lower Back	L Mid Back	1	76.9	89/49415	-70.8
2	8	L Lower Back	L Mid Back	10	82.1	0/70879	-64.4
3	17	L Lower Back	L Upper Back	10	48.5	0/41846	-78.9
4	20	R Lower Back	R Upper Back	10	76.7	0/66190	-75.5
5	20	R Lower Back	R Upper Back	10	76.7	0/66190	-75.5
6	20	L Lower Back	R Upper Arm	10	60.9	0/52598	-79.5
7	25	L Lower Back	R Upper Back	10	29.0	1/25019	-84.0
8	15	L Shoulder	R Upper Back	10	90.5	0/78089	-61.9
9	10	L Shoulder	R Upper Arm	10	78.5	48/67747	-70.1

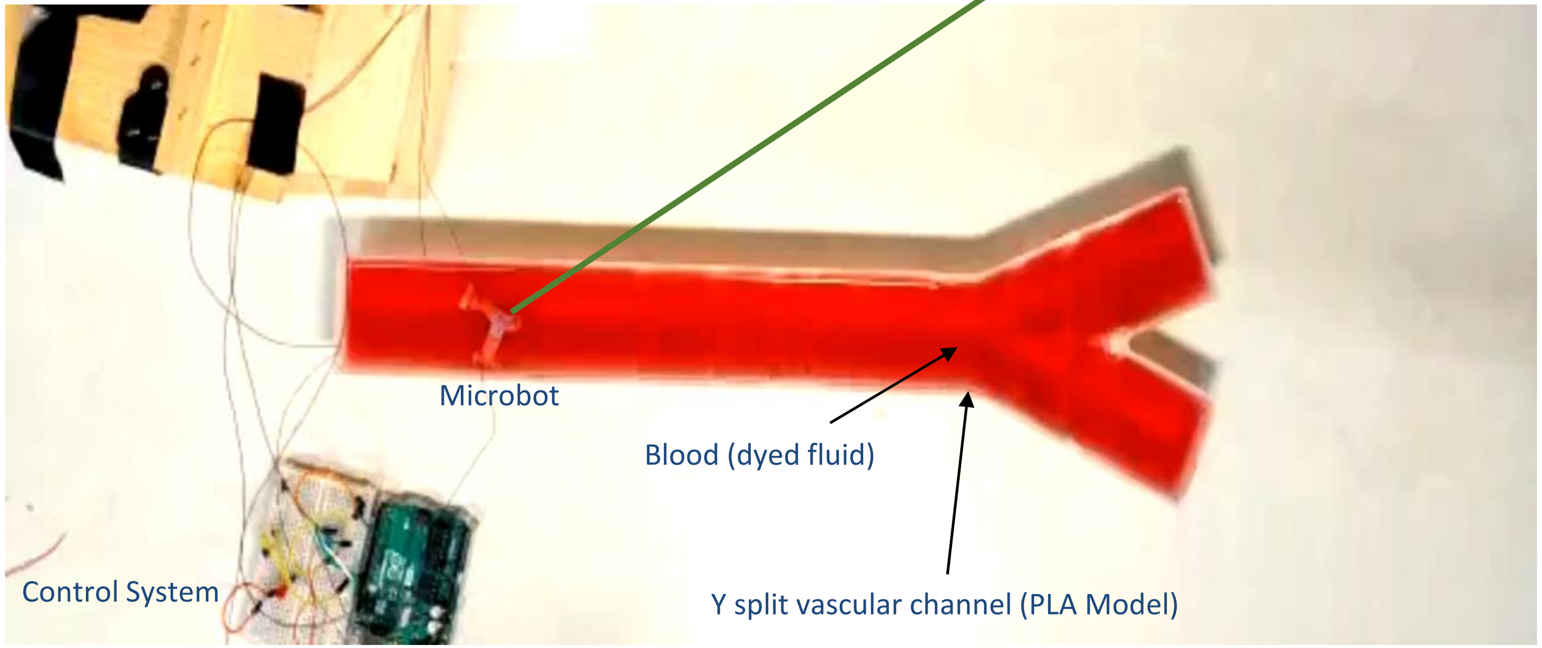
Final *in vivo* Test

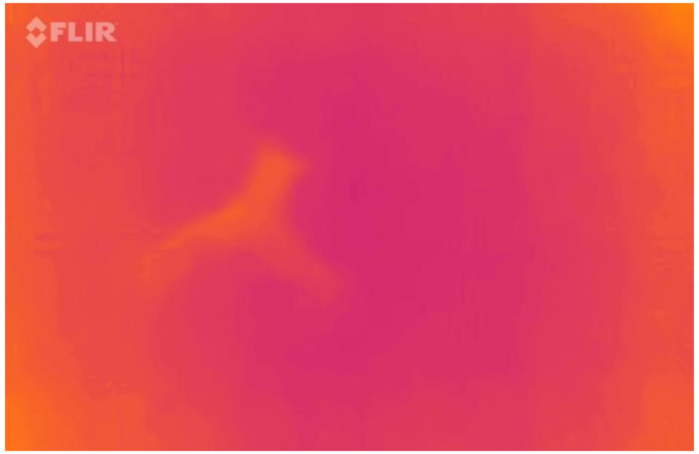


FAT-IBC controlled miniature medical robot/ drug delivery-monitoring applications









Rating: 3.2 V, 700mA ,2.24W

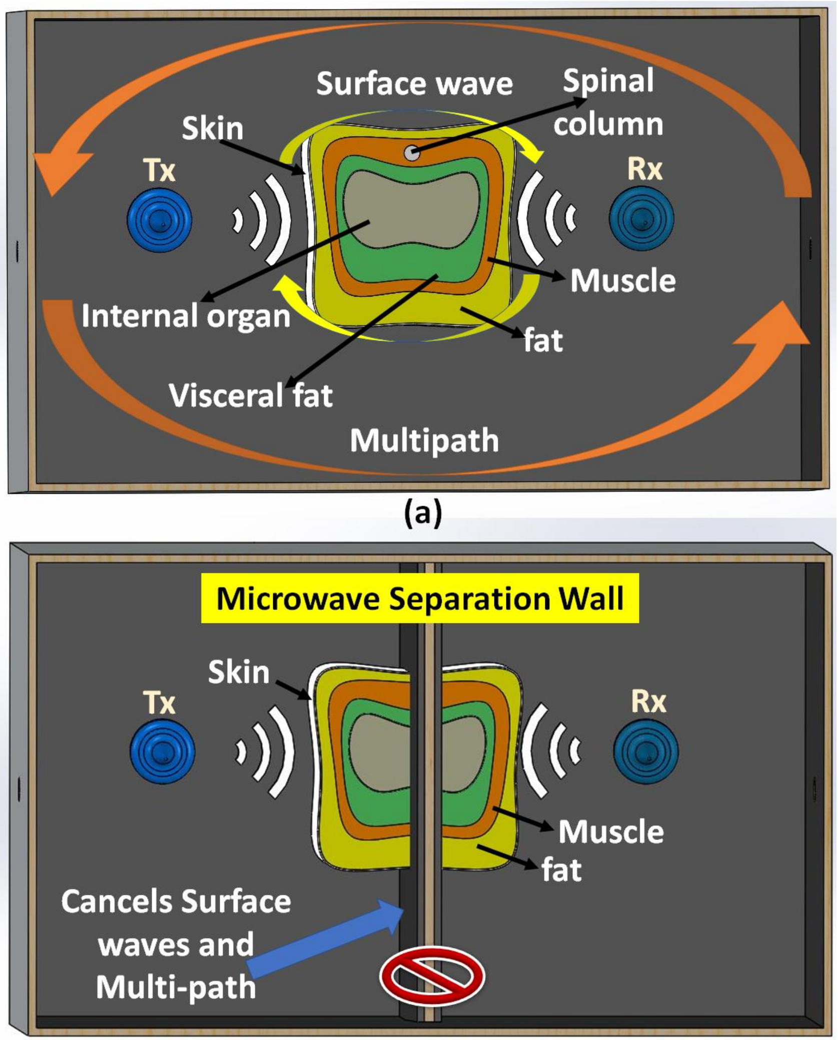
Vascular robot

Bobins Augustine, Arvind Selvan Chezhian, Johan Engstrand, Ted Johansson and Robin Augustine *, “FAT-IBC controlled vascular robot for drug delivery & thrombectomy Application”, Under submission in Nature communication 2023

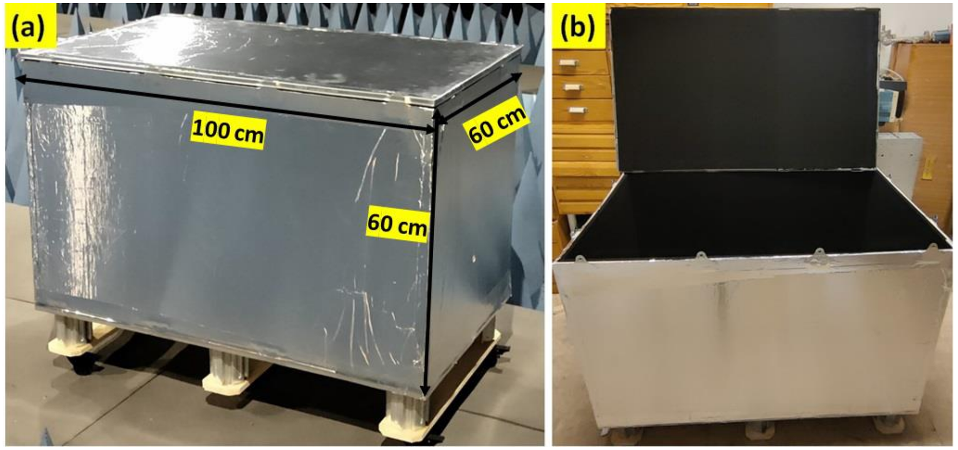
Surface waves vs Fat-IBC

(a) problem of external microwave path for the Fat-IBC, and

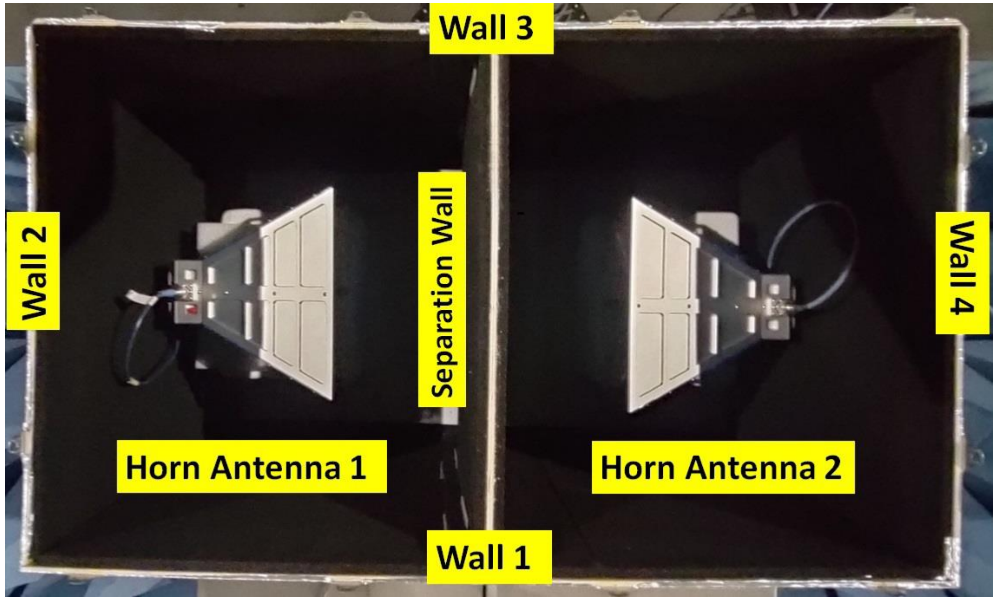
(b) solution by introducing the microwave separation wall across the torso phantoms.



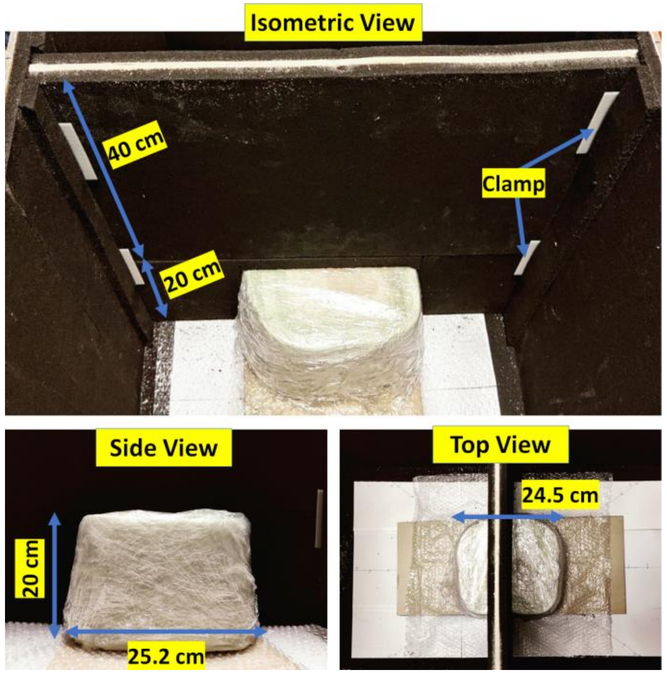
Semi-shielded anechoic chamber for Fat-IBC testing



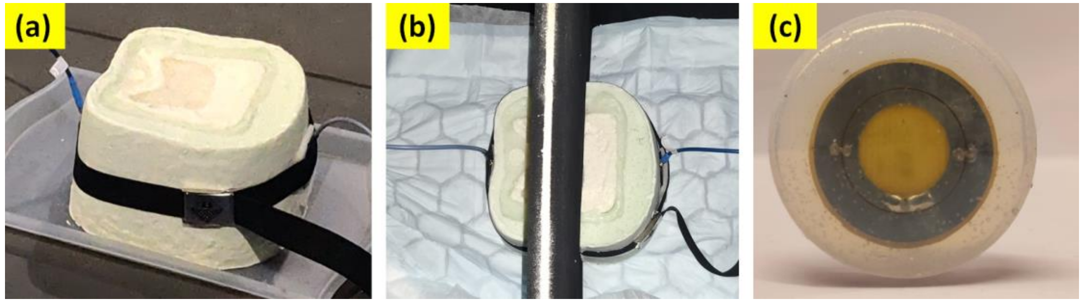
Fat-IBC chamber



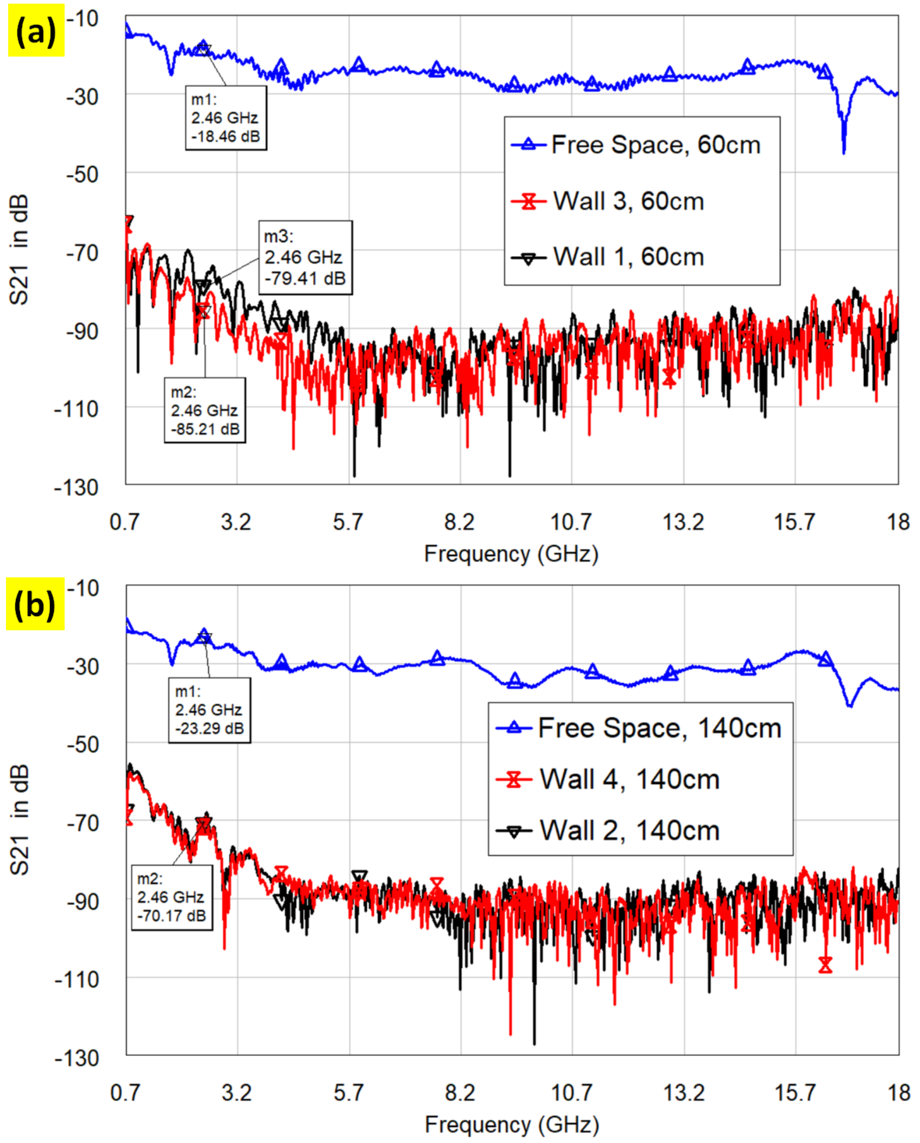
Chamber isolation testing



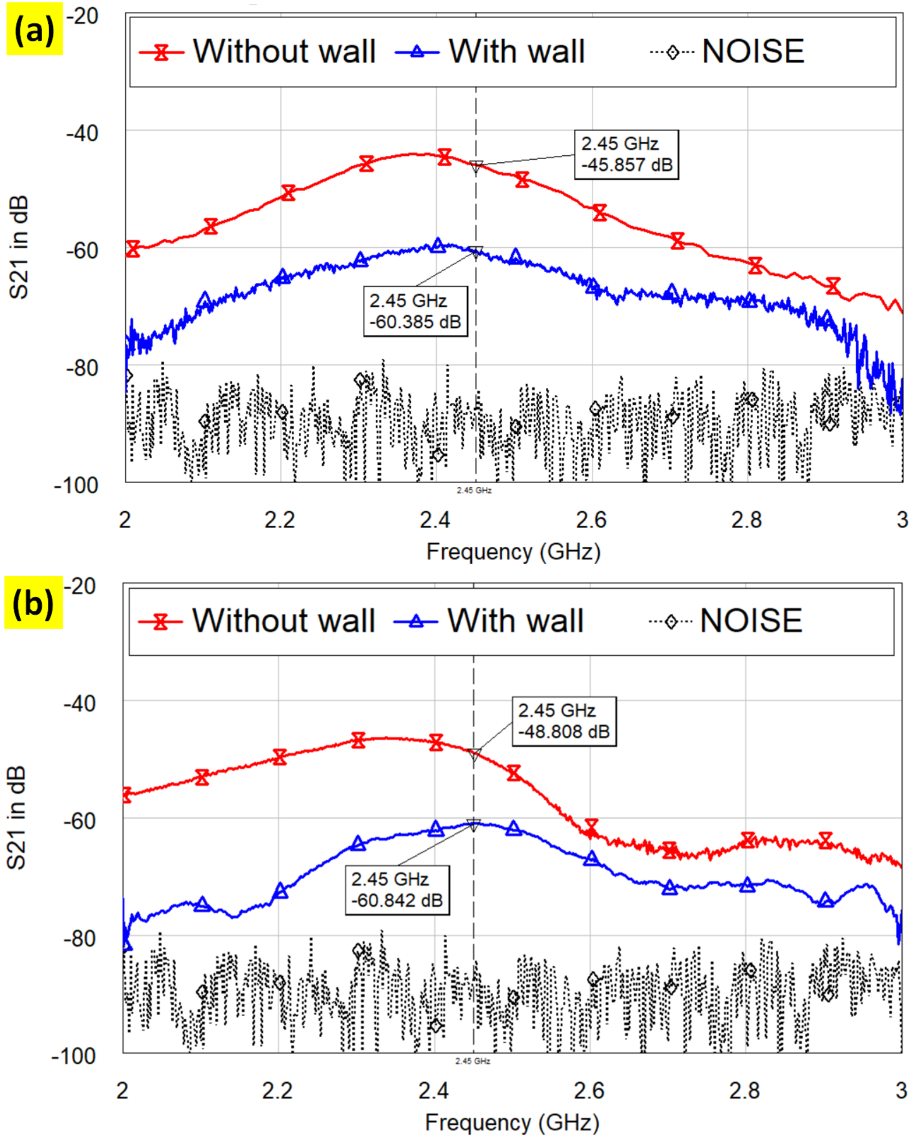
Chamber with torso phantom for testing



Torso phantom with Fat-IBC antenna

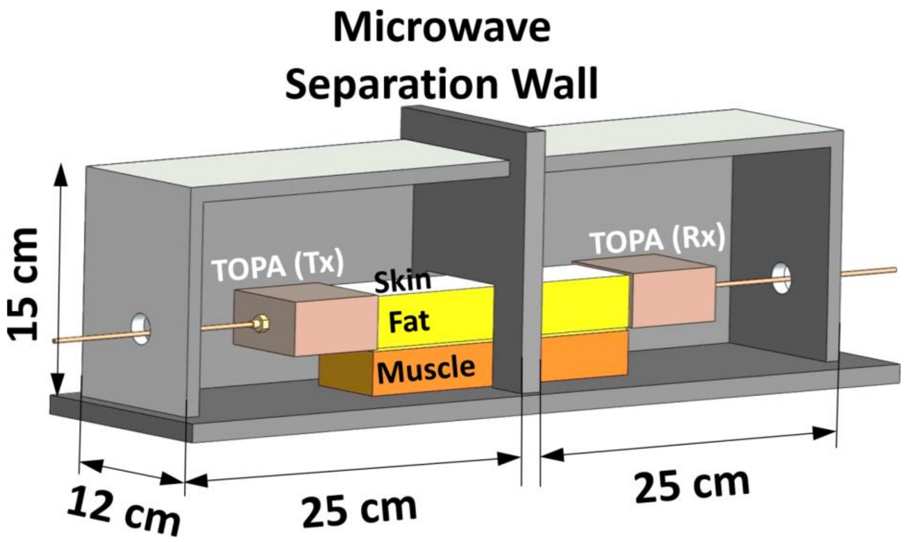


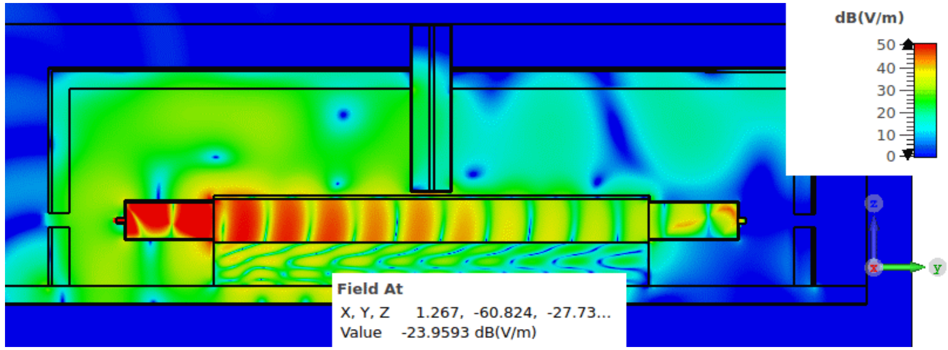
Chamber isolation

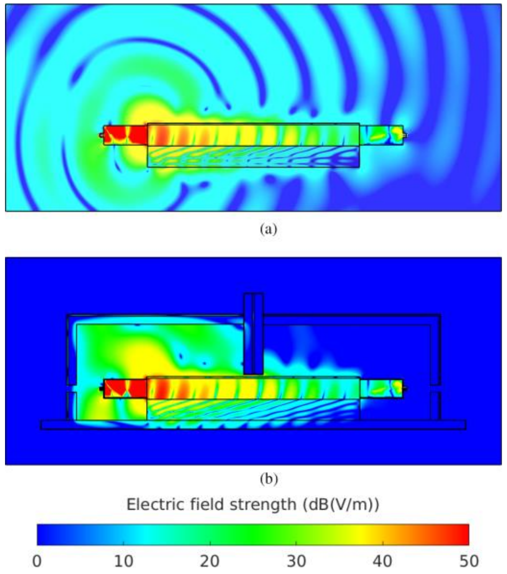


Fat-IBC vs Surface waves

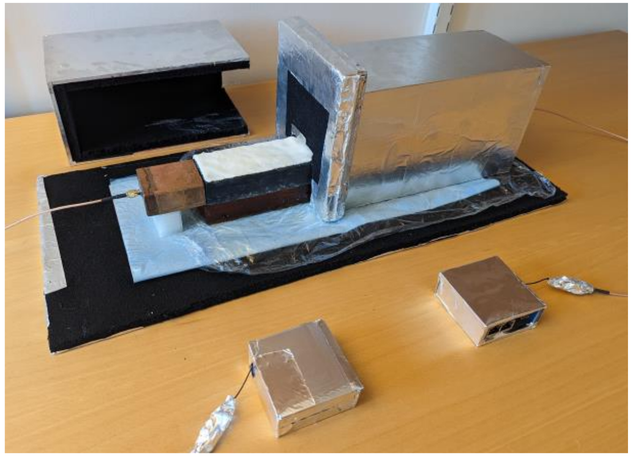
Evaluation of Fat Intra-Body Communication







(a)
(b)



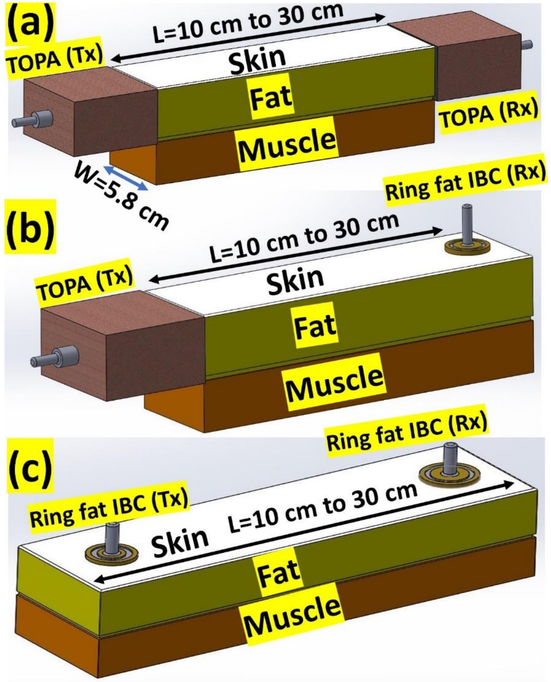
- The suppression of:

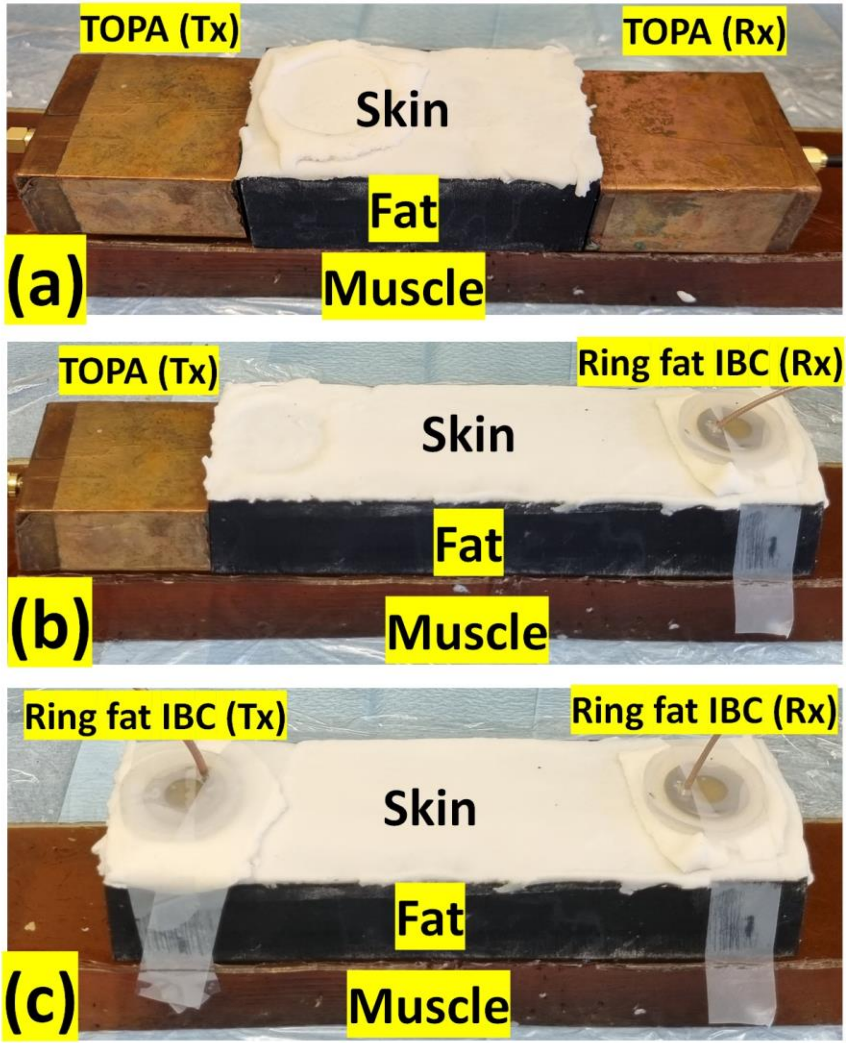
  External microwaves

  Surface waves

  Multi-path propagation

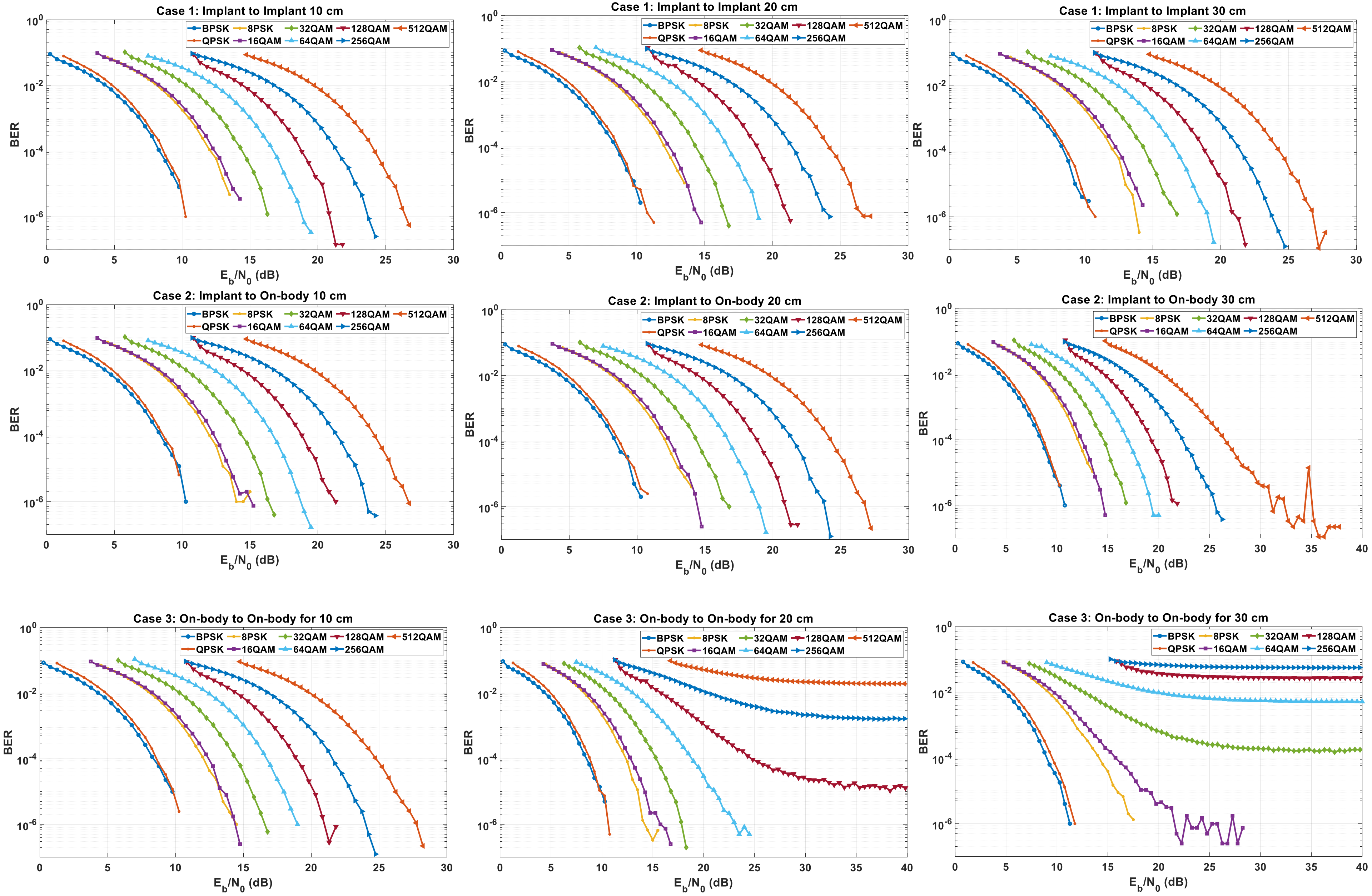
Model Types





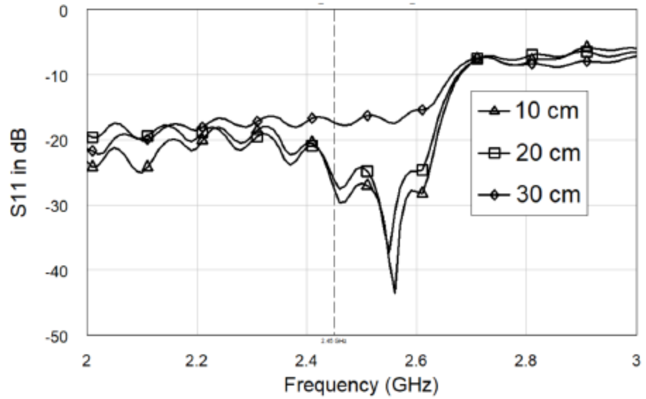
- Case 1: Implant to Implant
- Case 2: Implant to On-body
- Case 3: On-body to On-body

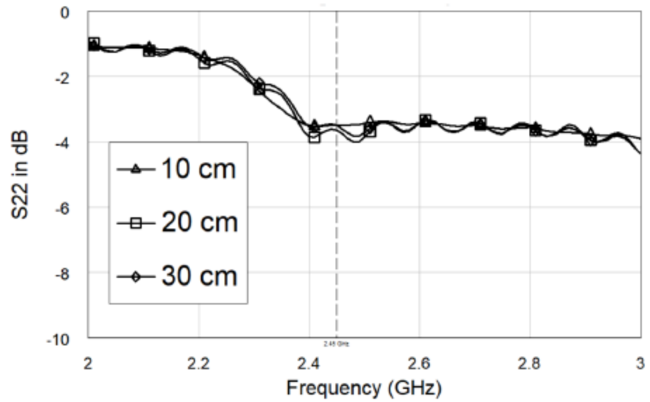
SNR vs BER Measurements

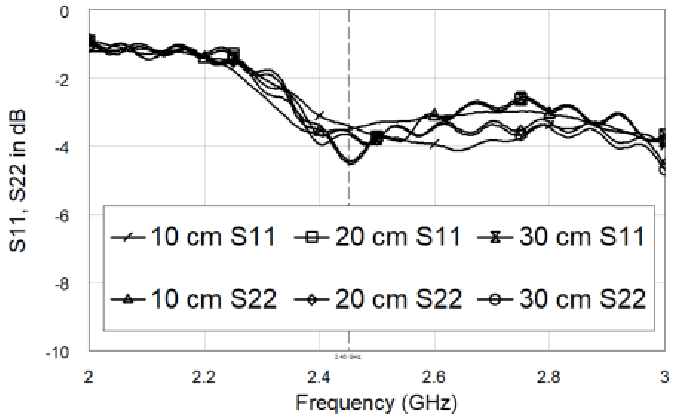


S-parameters Measurements

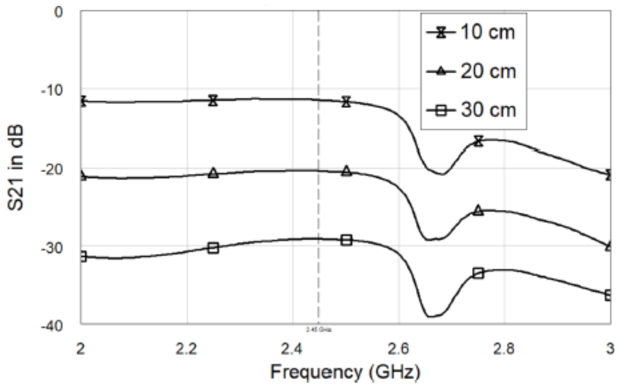
Reflection

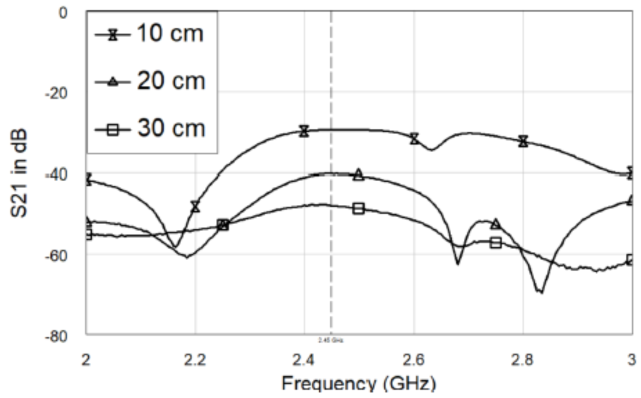


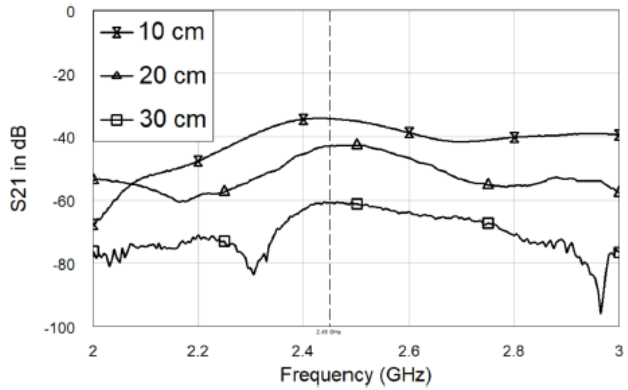


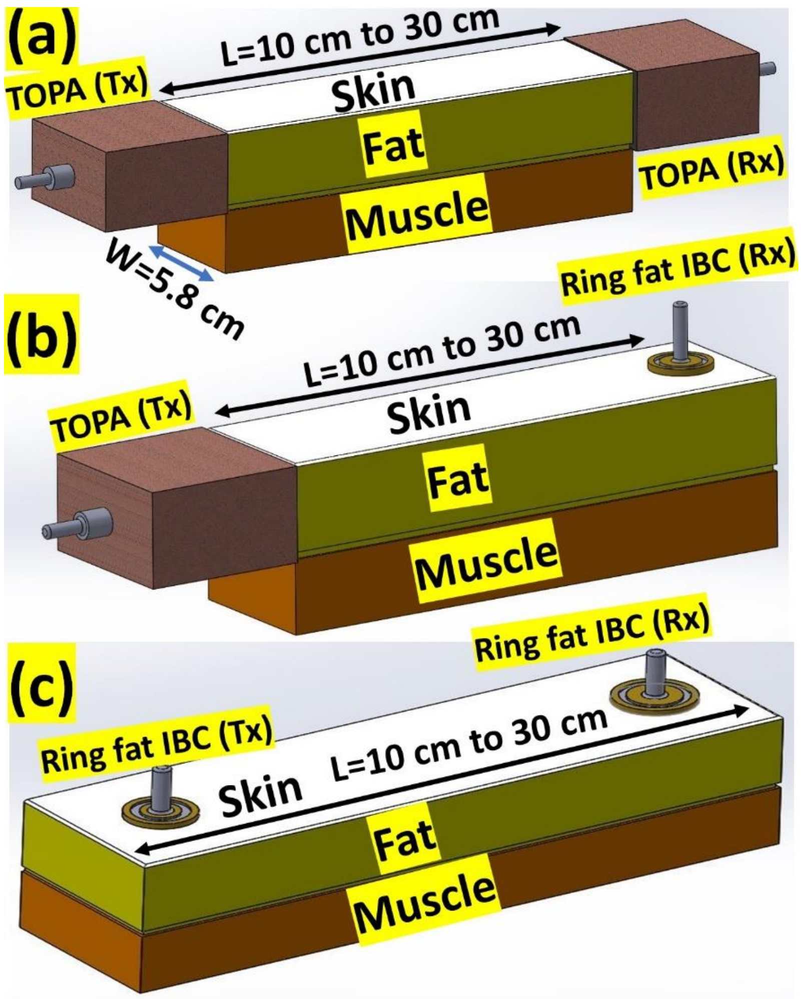


Transmission









Data rates achieved with WLAN

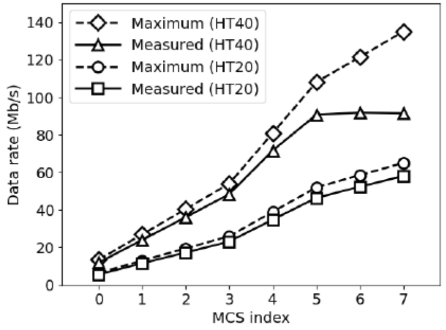


Fig. 7. Case 1: Date rate vs. MCS index for bandwidths of 20 MHz and 40 MHz, 30 cm phantom length.

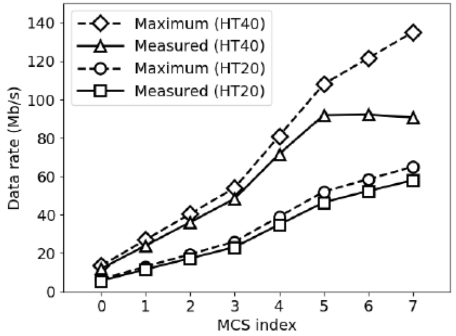


Fig. 10. Case 2: Date rate vs. MCS index for bandwidths of 20 MHz and 40 MHz, 30 cm phantom length.

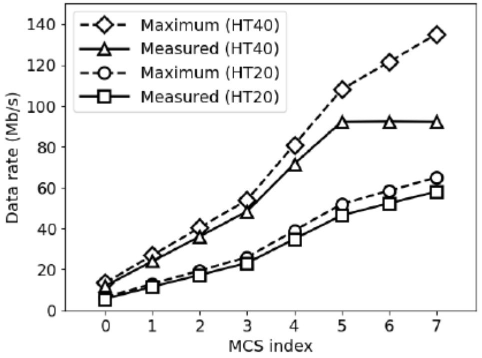


Fig. 13. Case 3: Date rate vs. MCS index for bandwidths of 20 MHz and 40 MHz, 30 cm phantom length.

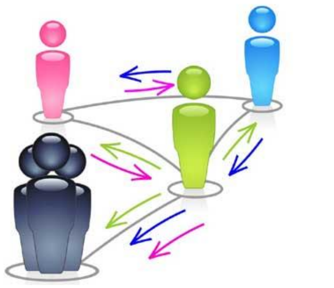
COMPARISON WITH OTHER SIMILAR IN-BODY COMMUNICATION

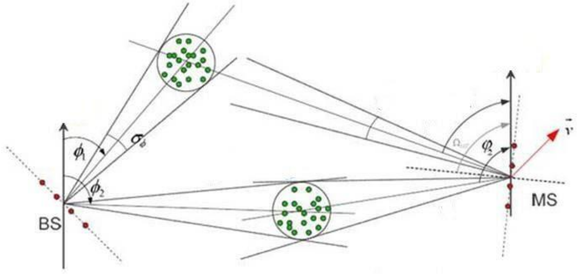
Ref	Ho [30]	Jeon [31]	Lee [10]	This work
Year	2014	2019	2020	2023
Method	CC-BCC	GC-BCC	CC-BCC	Fat-IBC
Speed	60 Mb/s @100 cm	100 Mb/s @10 cm (est)	150 Mb/s @ 20 cm 10 Mb/s @100 cm	90 Mb/s@ 30 cm
Hardware	65 nm CMOS	180 nm CMOS	65 nm CMOS	"off-the-shelf"
Comm	3-level Walsh	Bipolar RZ	DFE	802.11n
Freq band [MHz]	10–80	1–100	$>$ 500	2400–2450
Bandwidth [MHz]	up to 80	100	150	40

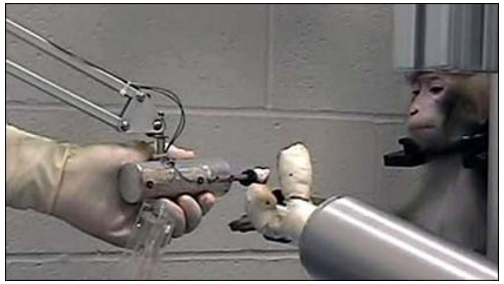
5. Near future

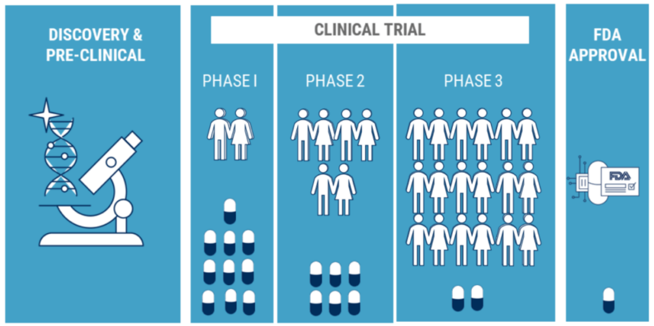
- Incorporation of dynamics
- Advanced channel modelling and theory
- Fullduplex communication
- Functional NHP system
- Clinical trials

Duplex

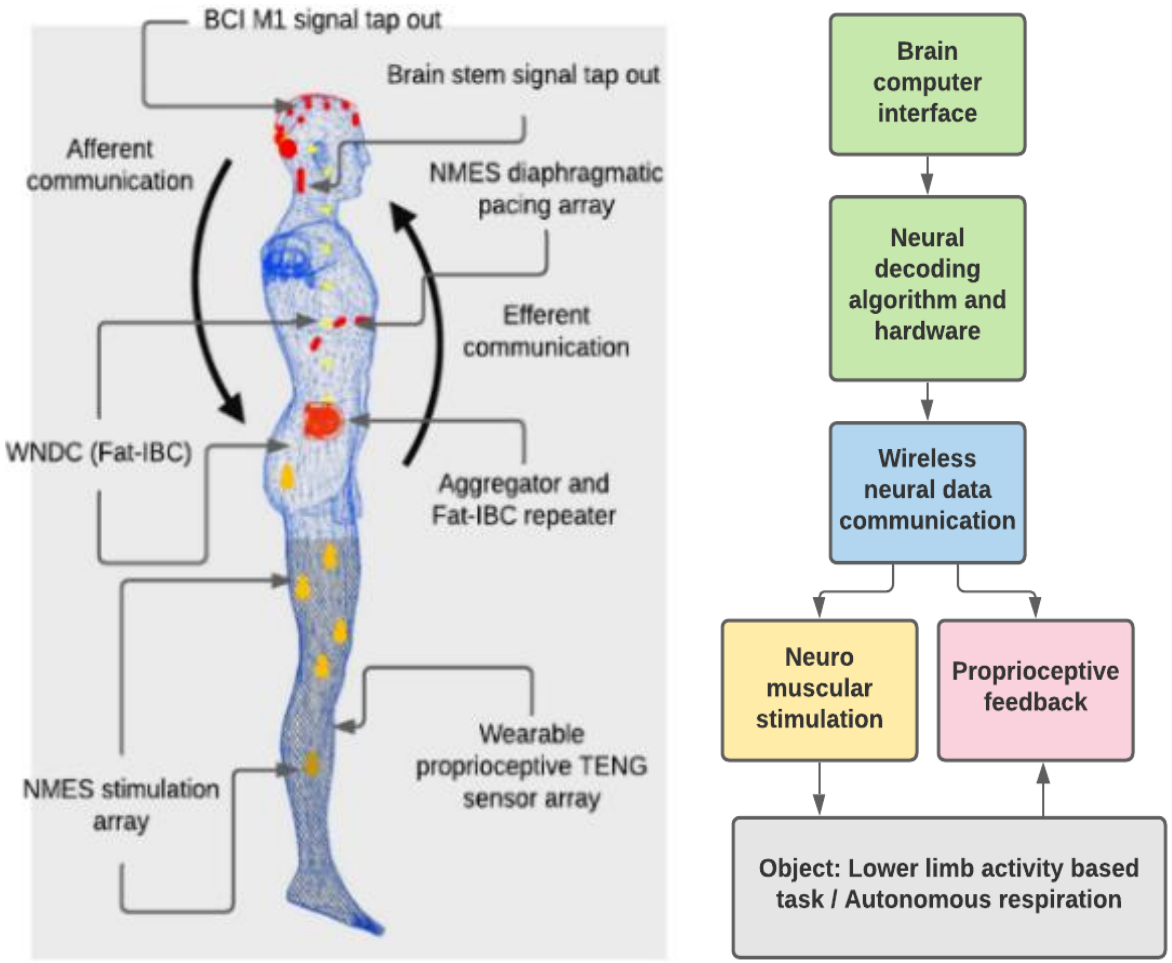








Grand vision!



Wireless Neural Data Communication (WNDC) platform technology

Thank You!!!

VINNOVA | eurostars | Vetenskapsrådet | EU | Stiftelsen för Strategisk Forskning | OLLE ENGKVISTS STIFTELSE | HORIZON 2020 | CARL TRYGGERS STIFTELSE FÖR VETENSKAPLIG FORSKNING

Thank You for Your Attention