Fat-layer intra-body communication

92 Mb/s intra-body communication with low-cost WLAN hardware

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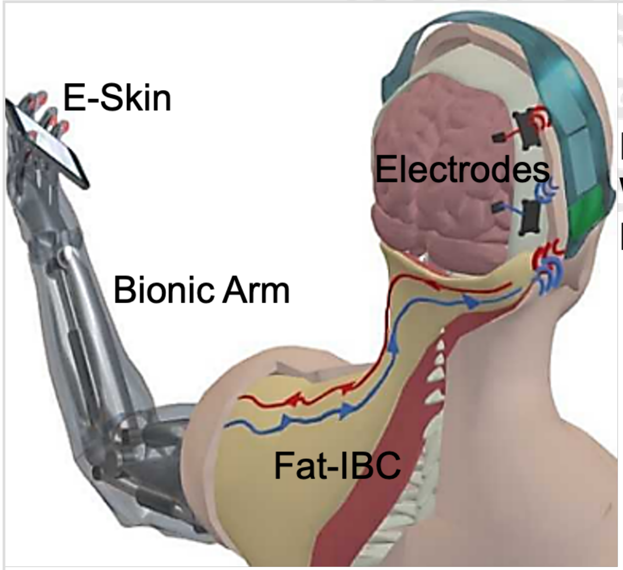
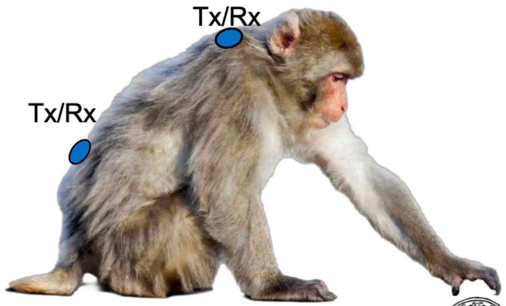
B-CRATOS:
"Wireless Brain-Connect inteRfAce TO machineS"

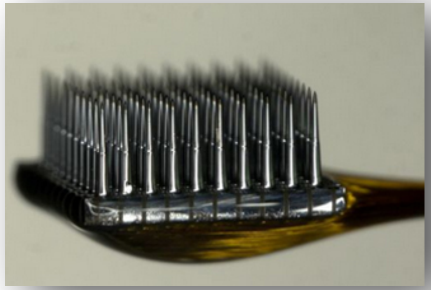


- Wireless, high data rate, full-duplex Brain-Prosthetic connectivity
- B-CRATOS overcoming challenges such as power consumption, batteries, sensing and data transmission through breakthroughs in high bandwidth, battery-free, bidirectional wireless communication technology and electronic skin

- Funded by EU H2020 FET-OPEN
- Project period: 2021-2024
- Partner groups: UU, NTNU, SSSA, SINANO, DPZ, BRME, LINKS



Two-way intra-body communication between brain and prosthetics: >32 Mb/s needed!



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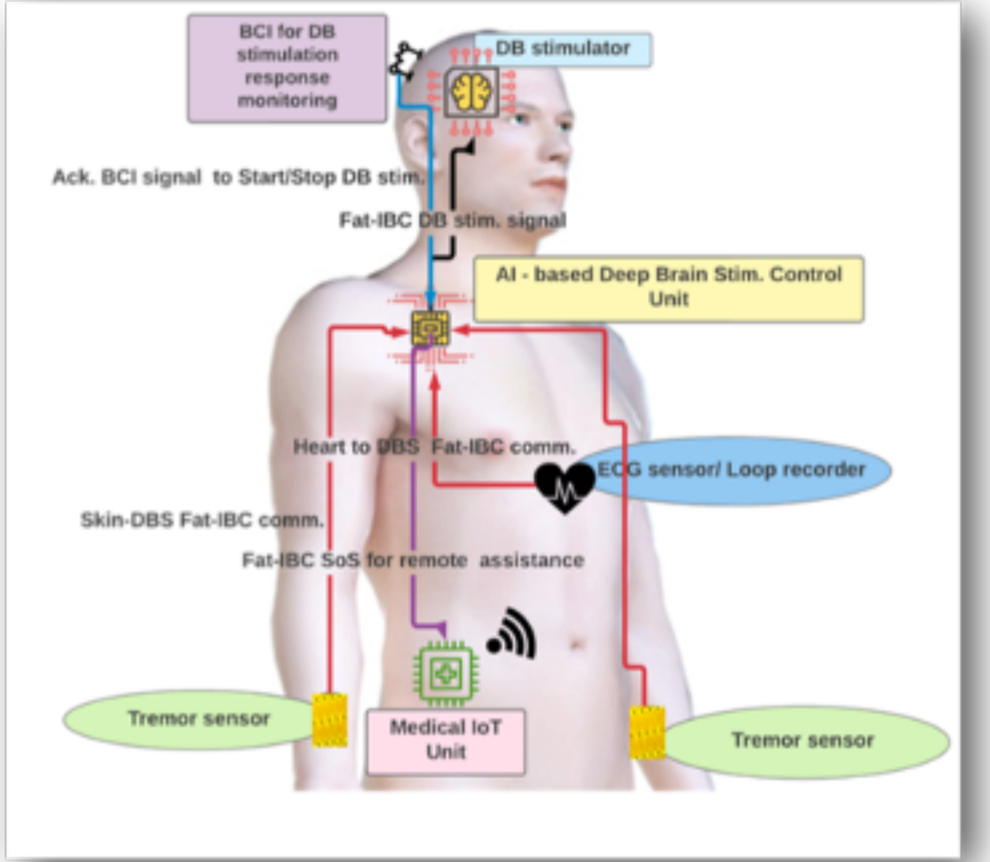
Contact person: Robin Augustine

BOS:
Software Principles & Techniques for a Body-Centric OS



- **Operating system** for **body computing** using information from sensors and actuators **in, on** and **outside human bodies**.

- **Deep brain stimulation** as the demonstrator for treating **movement disorders** associated with **Parkinson's disease**.

- UU (FTE + IT), KTH, RISE

- 5-year project 2022-2027
- Funded by SSF

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High-speed intra-body communication also needed

Contact person: Ted Johansson

1. Introduction: BAN and IBC communication speeds

- **Body-area networks (BAN)**, body-sensor networks (BSN): portable devices for health care, sports, and entertainment.
- WBAN: IEEE 802.15 standards for Internet of Things (IoT) protocols.
- Communication speeds in the order of **a few Mb/s.**

- **Intra-body communication (IBC)**
  - ultrasound, galvanic coupling, capacitive coupling, resonant coupling.
    - ultrasound: **tens of Mb/s**.
    - galvanic, capacitive: can reach up to **150 Mb/s** (short distance, custom circuits), requires grounded return path (outside the body).

- Fat-IBC
  - human skin/fat/muscle layers act as a waveguide for microwave transmissions,
  - **high-speed data communication not yet demonstrated**.

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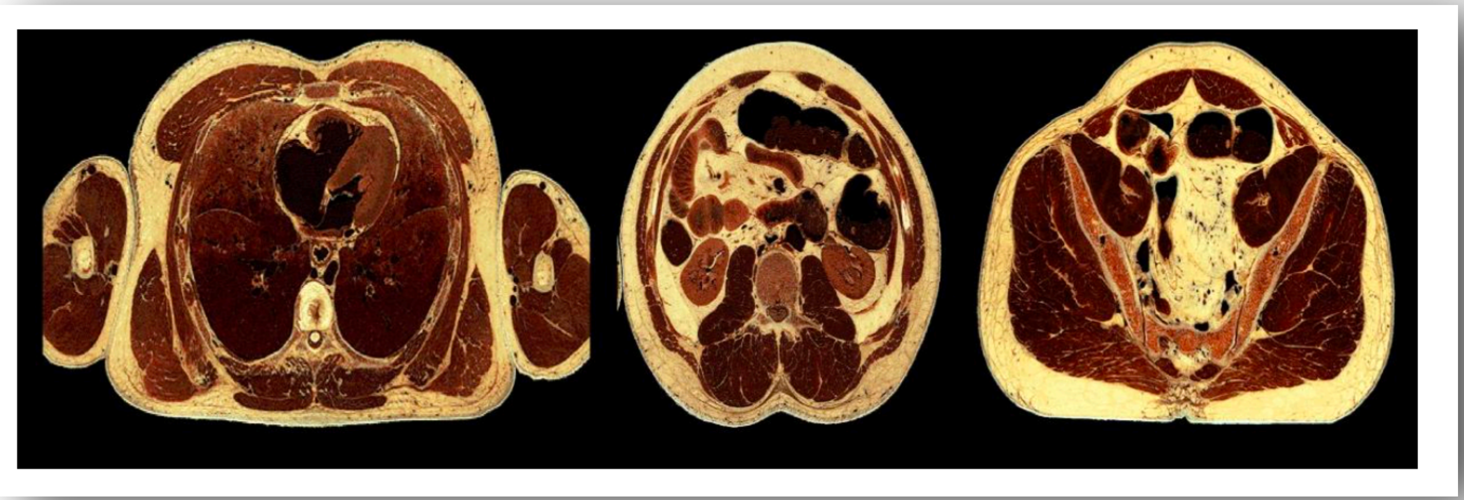
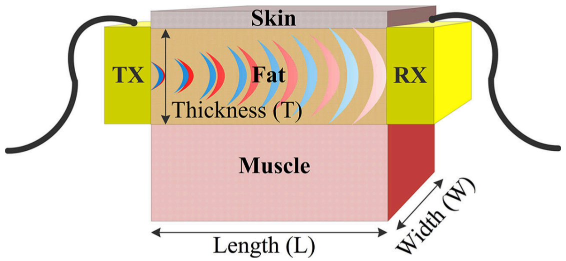
Fat-IBC (Asan, Healthcare Technology Letters, 2017)

- Human skin/fat/muscle layerd act as a waveguide for microwave transmissions
  - Lower losses for microwave propagation compared to other tissue (at least up to 8 GHz without significant increase in insertion loss)
  - Low loss as signal is confined with the skin and the muscle tissue
  - Data integrity
  - Higher bandwidth
- kb/s data communication demonstrated, Zigbee-like (Asan, IEEE JERM 2017)





The concept of channel propagation through the fat tissue.

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Fat-IBC for high-speed data communication

- Target: 64 + 2 Mb/s (B-CRATOS)

- Existing established communication standards
  - WPAN (802.15.x): https://en.wikipedia.org/wiki/IEEE_802.15
    - WPAN/Bluetooth (802.15.1): 1-2 Mb/s
    - High Rate WPAN (802.15.3a): UWB, 480 Mb/s @ 2 m (3.1 - 10.6 GHz): partly obsolete
    - 802.15.4 (e.g. Zigbee): only kb/s
    - ...
  - 4G or low/mid-band 5G (< 6 GHz)
  - WLAN (802.11): 2.4 and 5.8 GHz, many different versions

- Develop something own? Both PHY, MAC, protocol, etc. have to be included.

WLAN 802.11 for Fat-IBC?

- Target: 64 + 2 Mb/s (B-CRATOS)
- To reach > 32 Mb/s, preferably 64 Mb/s, we need to go to **802.11n:**
  - Up to 150 Mb/s
  - Single antenna:
    - 65 - 72.2 Mb/s using BW = 20 MHz
    - 2x capacity if using BW = 40 MHz
  - 2.4 GHz, 5 GHz
  - 4x MIMO: 600 Mb/s
  - 16-QAM or 64-QAM

Wi-Fi Generations

Generation	IEEE Standard	Maximum Linkrate (Mbit/s)	Adopted	Radio Frequency (GHz)[1]
Wi-Fi 7	802.11be	40000	TBA	2.4/5/6
Wi-Fi 6E	802.11ax	600 to 9608	2020	2.4/5/6
Wi-Fi 6			2019	2.4/5
Wi-Fi 5	802.11ac	433 to 6933	2014	5
Wi-Fi 4	802.11n	72 to 600	2008	2.4/5
(Wi-Fi 3)*	802.11g	6 to 54	2003	2.4
(Wi-Fi 2)*	802.11a	6 to 54	1999	5
(Wi-Fi 1)*	802.11b	1 to 11	1999	2.4
(Wi-Fi 0)*	802.11	1 to 2	1997	2.4

*: (Wi-Fi 0, 1, 2, 3, are unbranded common usage.[2][3])

[wikipedia]

HT MCS DATA RATES IN IEEE 802.11N FOR A SINGLE SPATIAL STREAM WITH A GUARD INTERVAL OF 800 NS

MCS index	Modulation	Coding	Data rate (Mb/s) HT20	Data rate (Mb/s) HT40
0	BPSK	1/2	6.5	13.5
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6	64-QAM	3/4	58.5	121.5
7	64-QAM	5/6	65.0	135.0

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2. Experimental: Materials and Methods

- Research question: explore **Fat-IBC as a communication link** with both **in-body and on-body antennas** and **skin/fat/muscle phantoms** using IEEE **802.11n** wireless communication with **low-cost off-the-shelf hardware** in the 2.4 GHz band.
  Can 64 Mb/s be reached?

- two antenna types: in-body (implanted), on-body (on the skin)
- phantoms to emulate human body skin/fat/muscle
- build, simulate, and verify a shielded box for the measurements
- measure important radio parameters (small-signal, modulated)
- use commercial low-cost WLAN hardware for the radio link
- use the 2.4 GHz band (antennas already available)

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- Research question: explore **Fat-IBC as a communication link** with both **in-body and on-body antennas** and **skin/fat/muscle phantoms** using IEEE **802.11n** wireless communication with **low-cost off-the-shelf hardware** in the 2.4 GHz band.
  Can 64 Mb/s be reached?
  May we name it ”Fat-Fi”?

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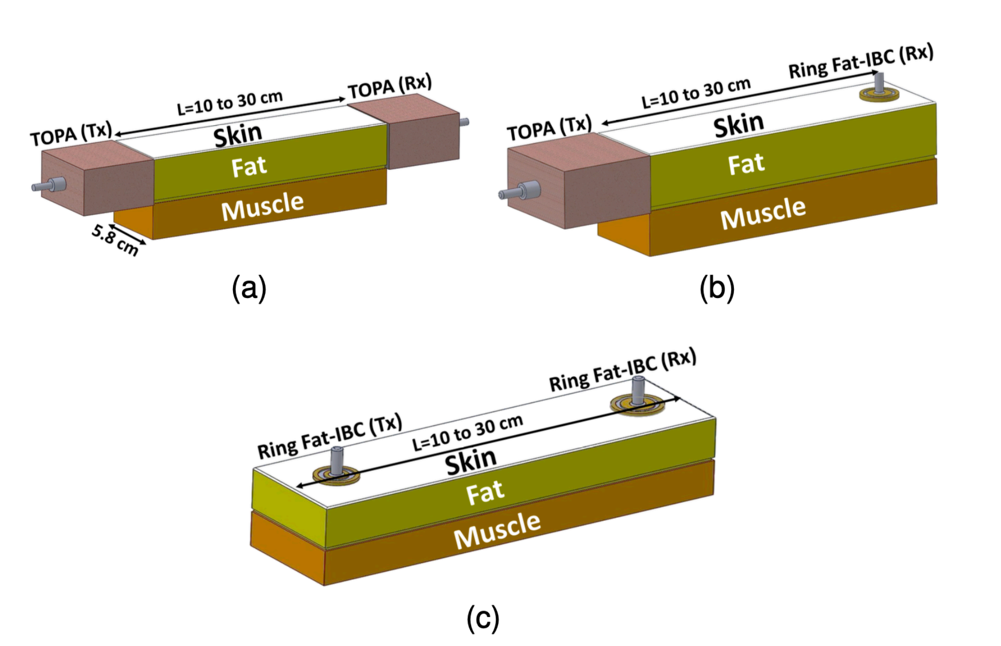
Antenna and phantoms combinations

- Two antennas:
  - "In-body" (implanted): topology-optimized planar antennas (TOPAs).
  - "On-body" (on the skin): ring-shaped novel design (to be published).
- Three layer phantoms, emulating skin, fat, and muscle.
  - Previously developed: 500 MHz - 20 GHz, emulates properties of human tissue.
  - Electrical properties verified by Keysight 85070E slim probe measurements and reference data from the IFAC database.
- Three combinations of antenna connection to the phantoms were studied, for phantom lengths of 10, 20, and 30 cm:
  - Case 1: In-body to In-body antennas
  - Case 2: In-body to On-body antennas
  - Case 3: On-body to On-body antennas



Antenna connections to the phantoms:
(a) Case 1: In-body to In-body antennas,
(b) Case 2: In-body to On-body antennas,
(c) Case 3: On-body to On-body antennas.

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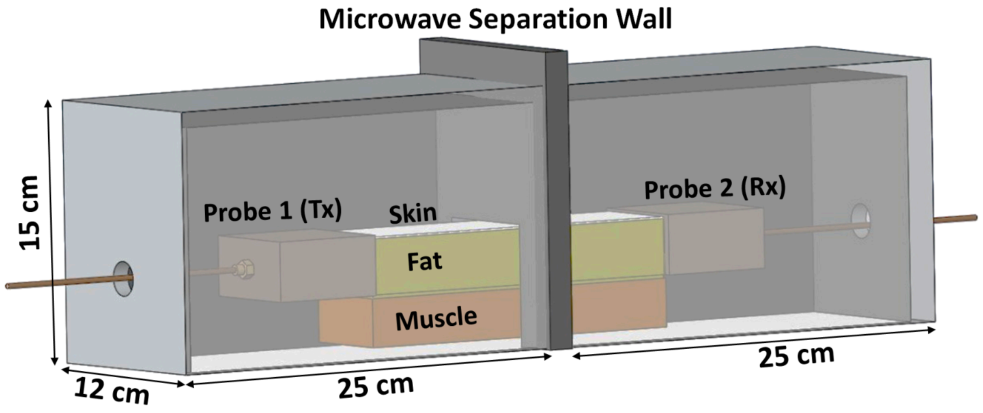
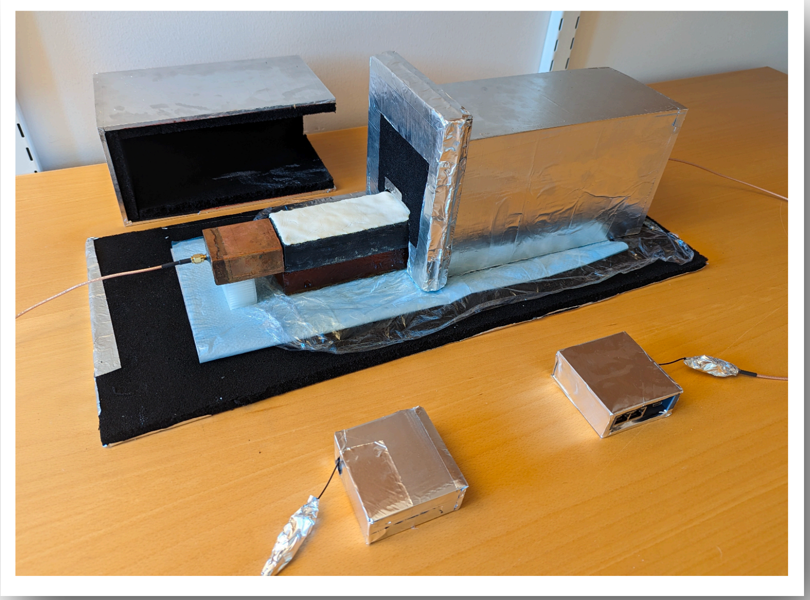
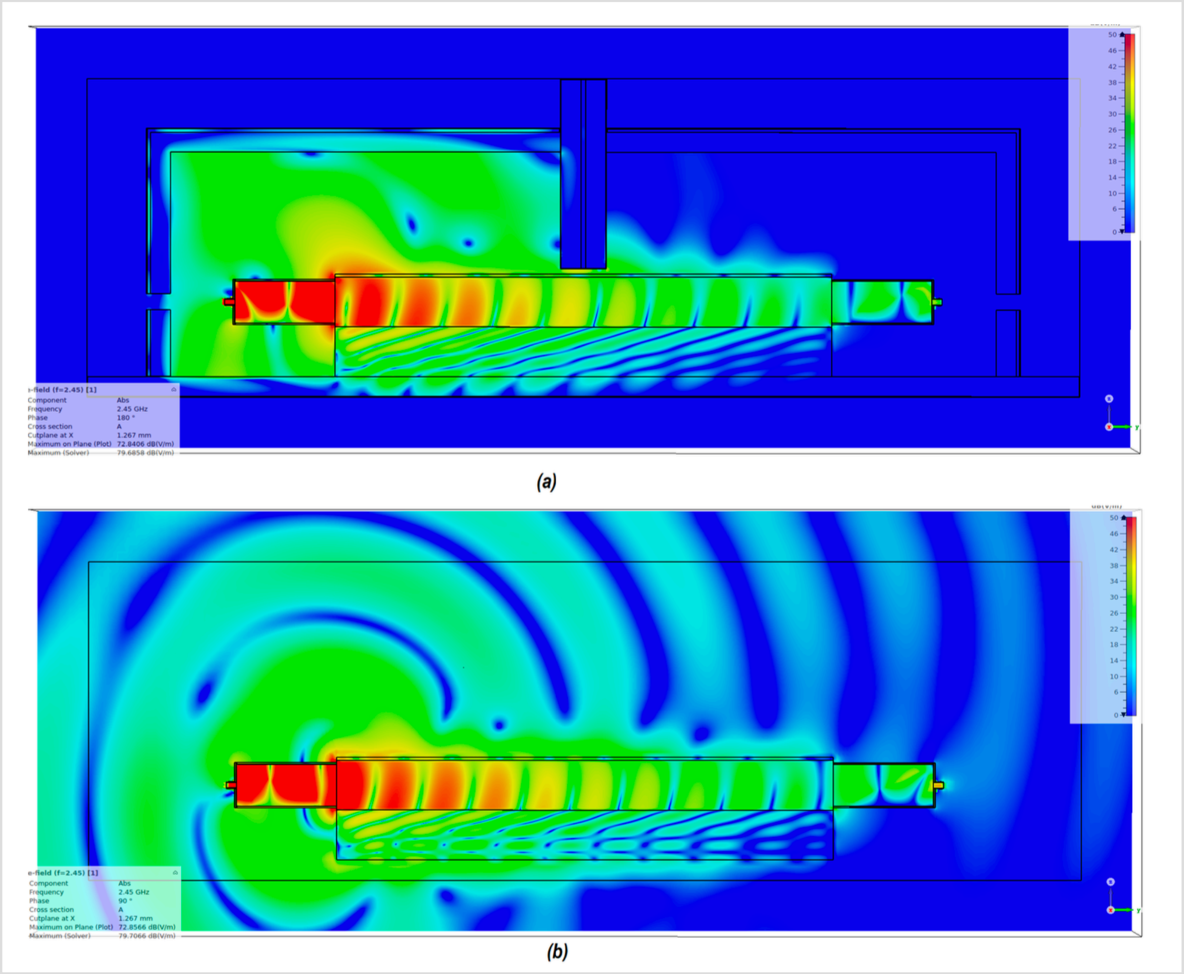
Shielded box



Th shielded box, with two TOPAs (topology-optimized planar antennas), and a phantom.



The shielded chamber with one chamber segment removed, exposing the three-layer phantom and TOPAs inside. In front are the two Raspberry Pis inside aluminum-clad cases.



Longitudinal-cutplane views of the simulated 3D electric field distribution at 2.45 GHz for Case 1 with a 30 cm phantom: (a) with the shielded chamber, and (b) without.

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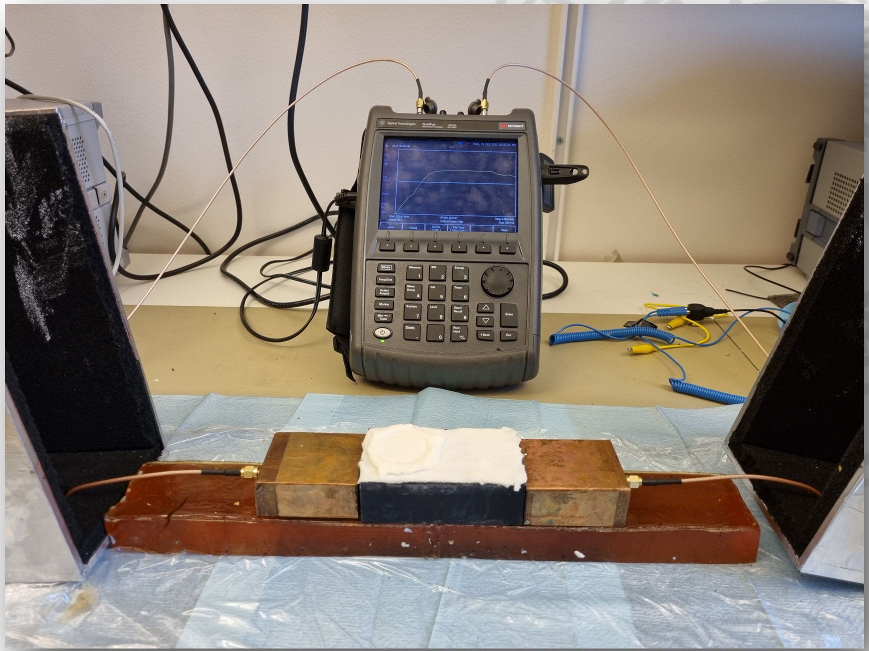
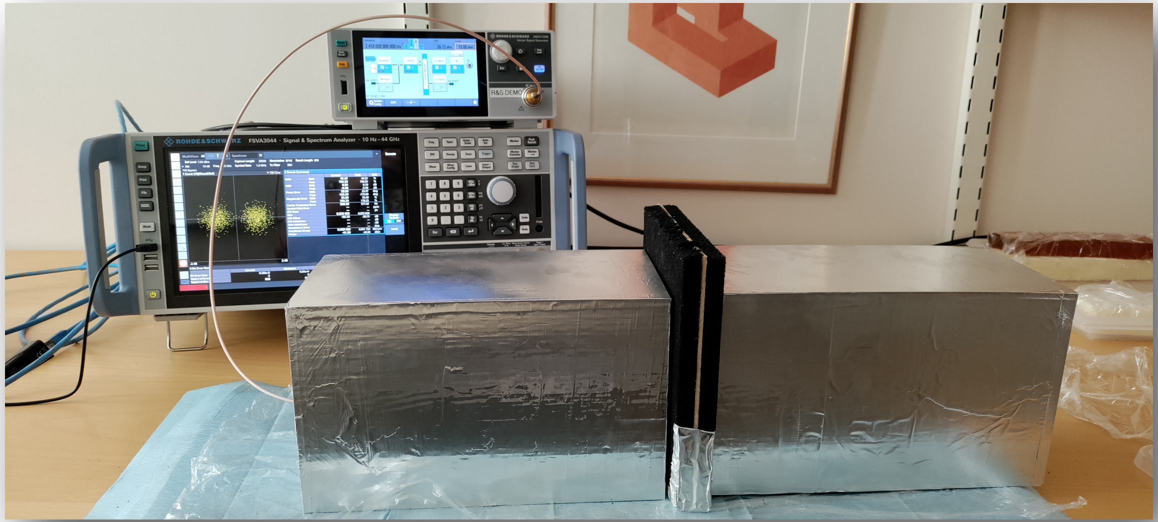
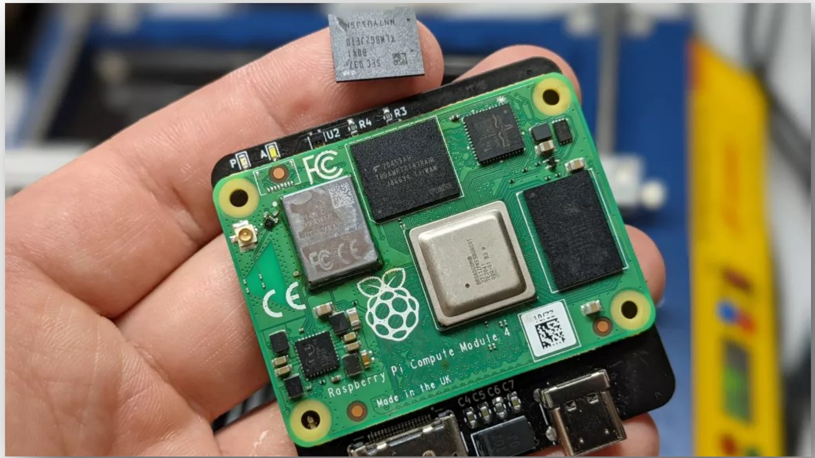
Radio measurements

- s-parameters: Keysight N9918A Fieldfox microwave analyzer
- SNR (E_b/N_0): R&S SMCV100B VSG + FSVA3000 VSA.
  Pout = 10 dBm, modulation: BPSK .. 512-QAM.
- WLAN:
  - 2x Raspberry Pi Compute Module 4 (2 GB RAM, 8 GB flash, WLAN 802.11n + BT), Pout = 10 dBm to external antennas.
  - 2x DFRobot IoT Carrier Board Mini
  - RP OS Lite v.10
- Target the 2.4 GHz band

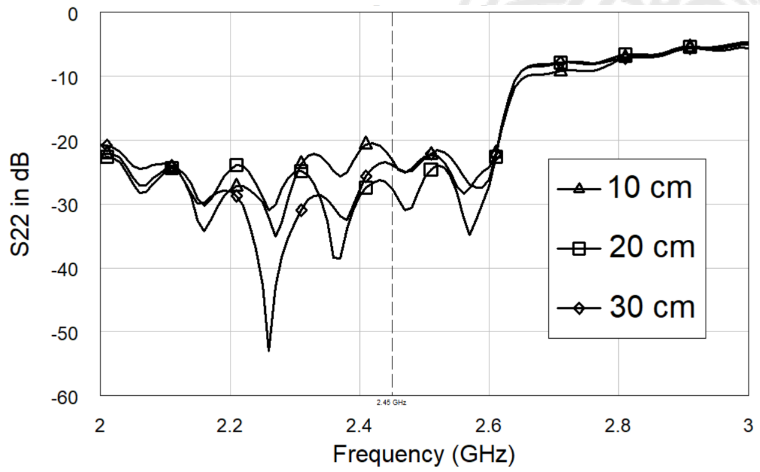






3. Results

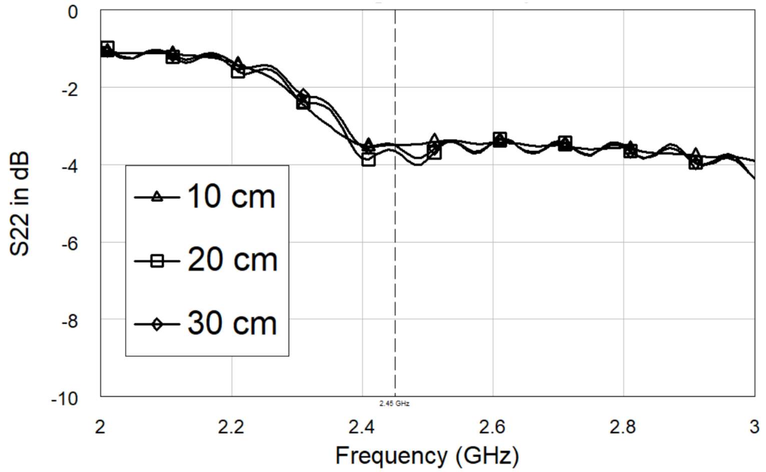
in-body antenna

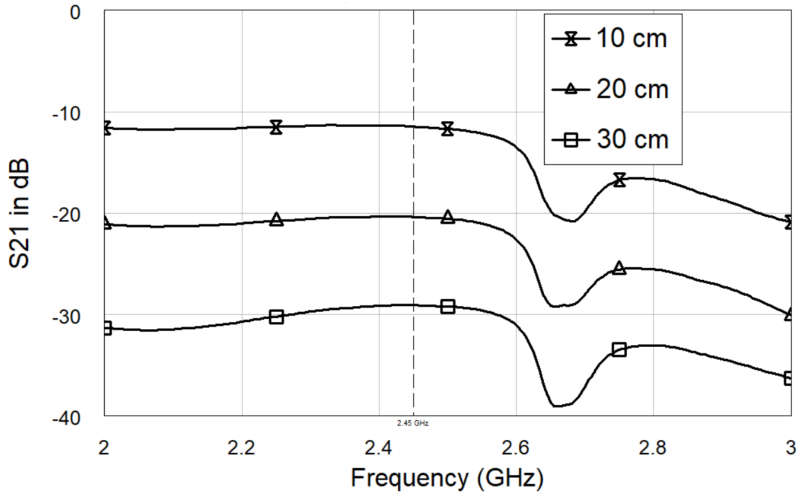


s-parameters

- good coupling with in-body antennas to fat channel
- less good coupling with on-body antennas to fat channel
- 1 dB/cm loss in the fat channel @ 2.45 GHz

on-body antenna





loss in the fat channel

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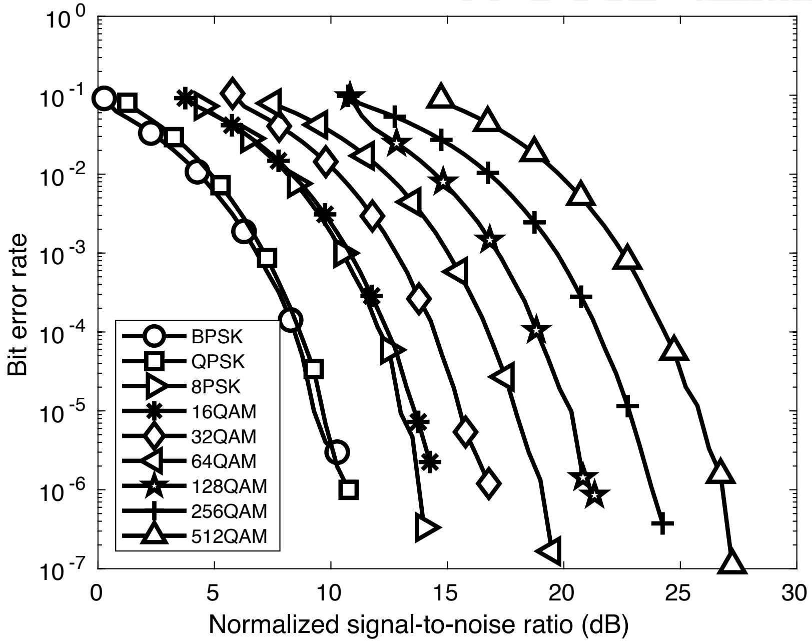
Modulated signals (2.45 GHz)

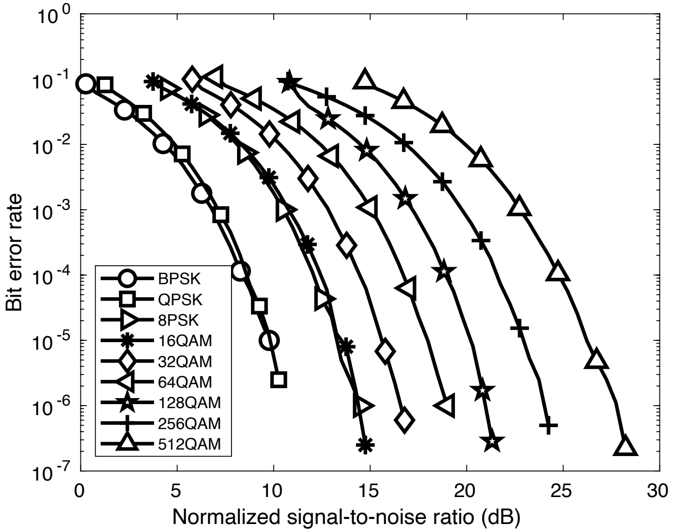
- All modulations work with in-body antennas
- For on-body antennas, BER degradation is observed for the longer phantoms

  (WLAN will still connect using 64-QAM, next slide)
- Test signal: 1 Msamples/s, no error correction, etc.

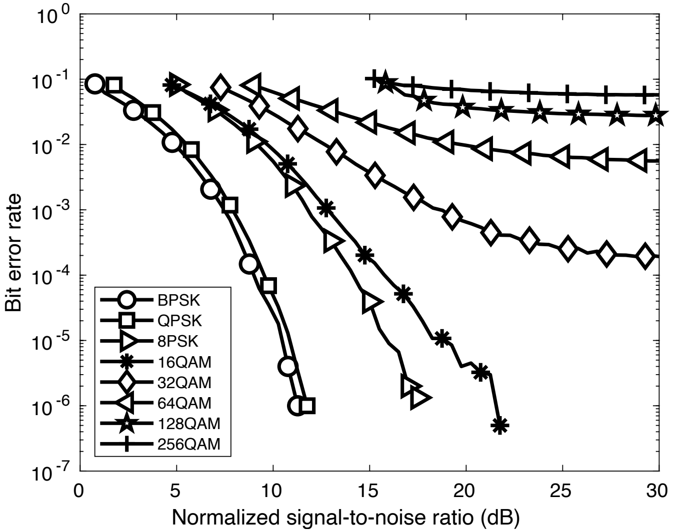
in-body antenna



on-body antenna, 10 cm phantom



on-body antenna, 30 cm phantom



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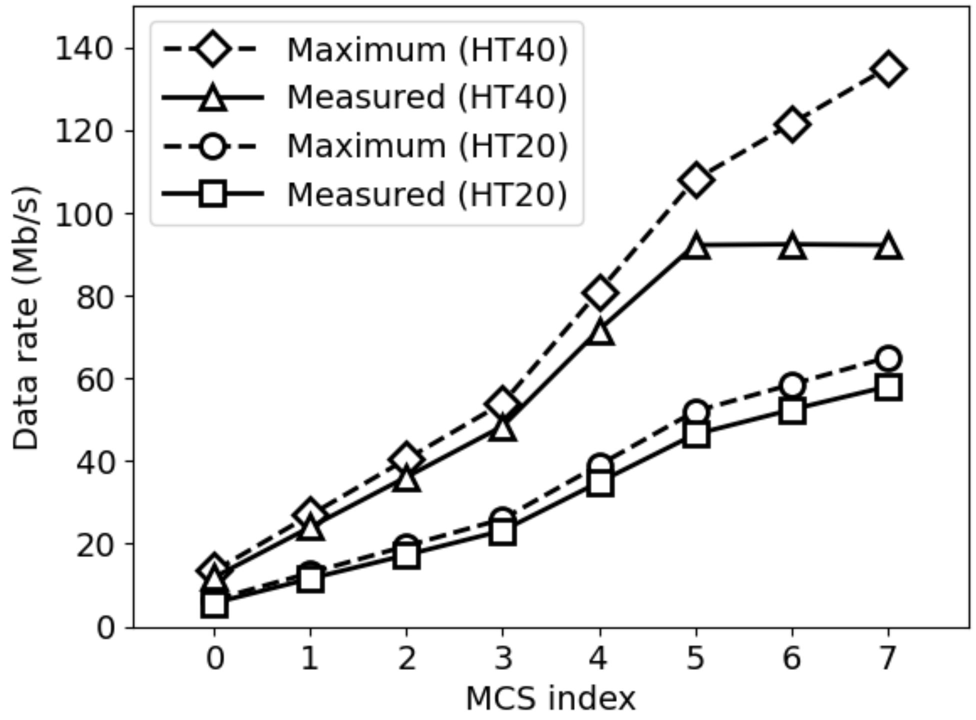
WLAN (802.11n, 2.4 GHz band)

- same results for all antenna combinations and phantoms.

- sweeping the MCS:
  - BW = 20 MHz: 58-60 Mb/s
  - BW = 40 MHz: 92 Mb/s using MCS 5–7 (64-QAM)
- "just connect":
  - 92 Mb/s using MCS 7 (64-QAM), 40 MHz bandwidth

- The speed limited by communication between the compute module circuits, not the link in the fat layer

- latency = 1-2 ms (comparable to LAN).



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4. Summary, conclusions

- s-parameters
  - in-body antennas: excellent coupling to the fat channel,
  - on-body antennas: improvements needed to couple the signal to the fat channel,
  - 1 dB/cm loss in the fat channel,
  - with in-body antennas, transmission at >= 60 cm should be possible, and longer at reduced modulations (speed).
- SNR for different modulations
  - link is very linear and can handle modulations as complex as 512-QAM without any degradation of the BER.
  - degradation observed for long phantoms (signal loss), but better results with full WLAN

- WLAN
  - 92 MB/s with 802.11n, 40 MHz BW, in the 2.4 GHz band obtained,
  - limited by the hardware (135 Mb/s should be possible with one-antenna 802.11n).

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Comparison with other similar in-body communication

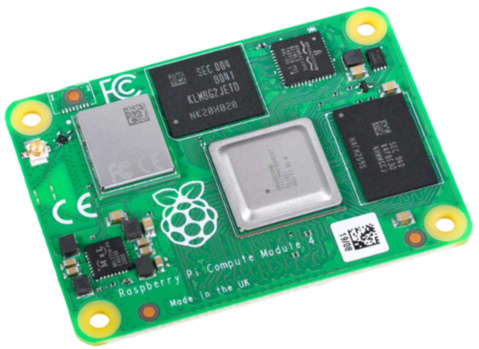
Ref	Ho [31]	Jeon [32]	Lee [10]	This work
Year	2014	2019	2020	2023
Method	CC-BCC	GC-BCC	CC-BCC	Fat-IBC
Speed	60 Mb/s @100 cm	100 Mb/s @10 cm (est)	150 Mb/s @ 20 cm 10 Mb/s @100 cm	92 Mb/s@ 30 cm
Hardware	65 nm CMOS	180 nm CMOS	65 nm CMOS	"off-the-shelf"
Comm	3-level Walsh	Bipolar RZ	DFE	802.11n
Freq band [MHz]	Baseband	Baseband	Baseband	2400–2450
Bandwidth [MHz]	up to 80	100	150	40

Obtained data rate is among the highest reported for intra-body communication.

Future work (short-term)

- Similar experiments at 5.8 GHz and larger bandwidths (IEEE 802.11ac),
- increased transmitted/coupled power (SAR-limited),
- optimized on-body antennas,
- other phantoms with different geometries

to explore the limits of Fat-IBC communication.



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