TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Faculty of Electrical and Computer Engineering
Institute of Acoustics and Speech Communication
Chair of Speech Technology and Cognitive Systems

Diplom Thesis

Wireless data transmission for an intraoral assistive device

Zungenmaus- Drahtlose übertragung der sensor daten

Hamza Ben Hassen

Supervisor: **Dipl.-Ing. Kathleen Große**

19.11.2020

Contents

Introduction and Motivation

Introduction and Motivation

We rely heavily on hands for mobility and interaction with digital world.

Several factors can result in loss of hand functions:

- Accidents
- Illness
- Aging

–> Motivation for alternative input methods

Source

Source

Source

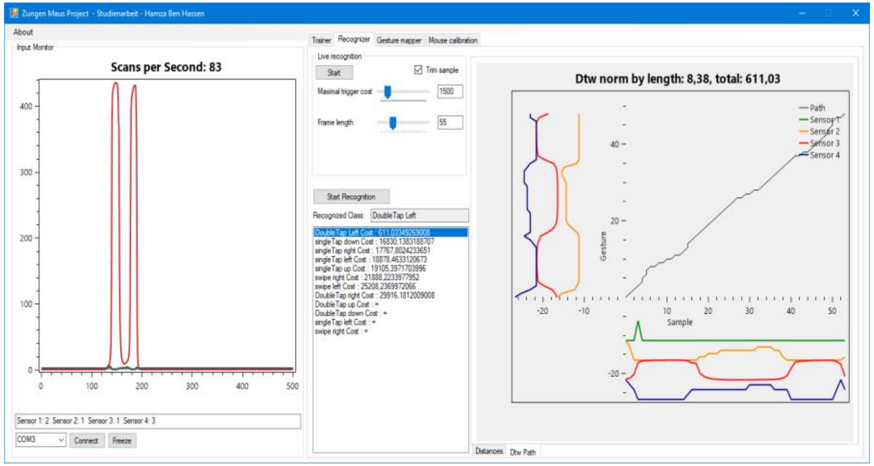
Source

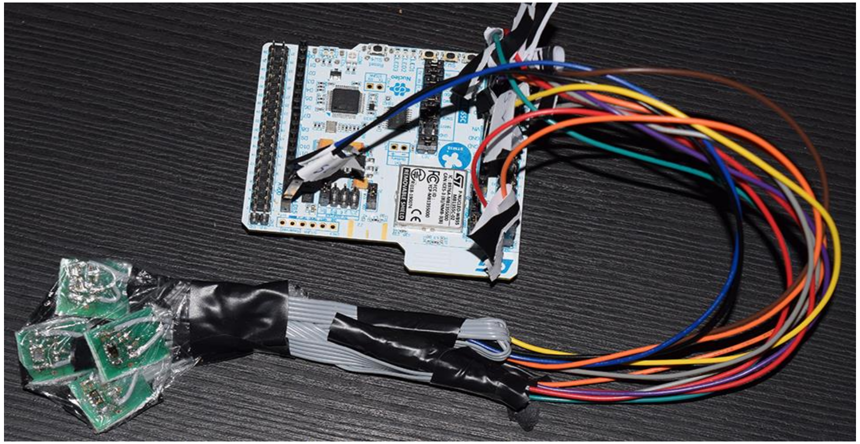
Introduction and Motivation

Zungenmaus – Studienarbeit 2019

- Optical sensors to detect tongue position
- DTW gesture recognition
- Wired connection to PC

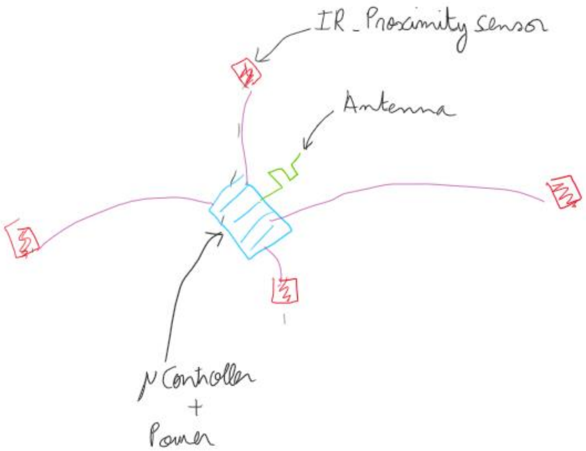
→ The tongue can be used to operate a computer and control a mouse cursor.



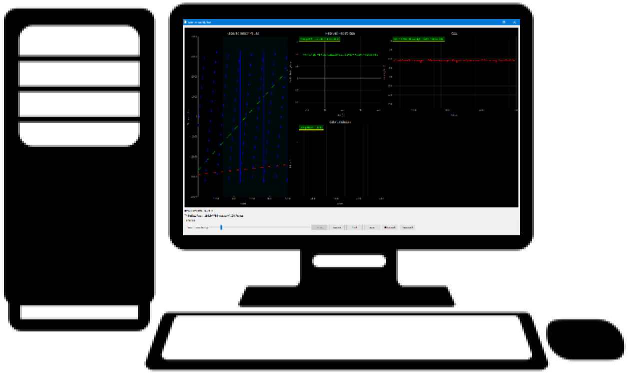


Introduction and Motivation

Objective of this work: Implement a wireless link from inside the mouth cavity and present a method for qualifying the link quality.



Wireless



State of the art

State of the art

Passive : RFTattoo [3]

-Sense the stretch of the skin.

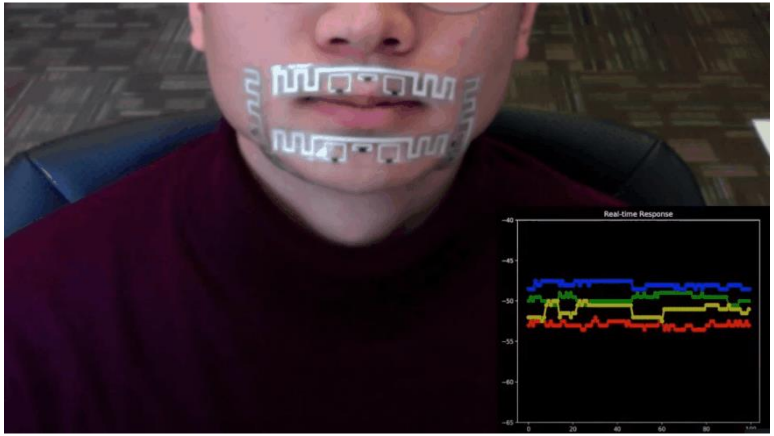
-1 mm stretch of the antenna results in 8 MHz resonance frequency shift.

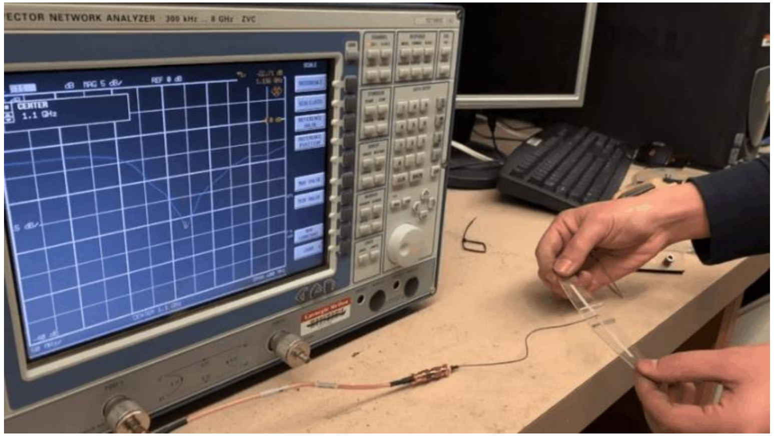
-Maximal detectable stretch in the ISM band (902 -928 MHz) is 3,25 mm

-Battery free

-Limited communication range of 2,5 m

-Slow with 4 Hz data acquisition





State of the art

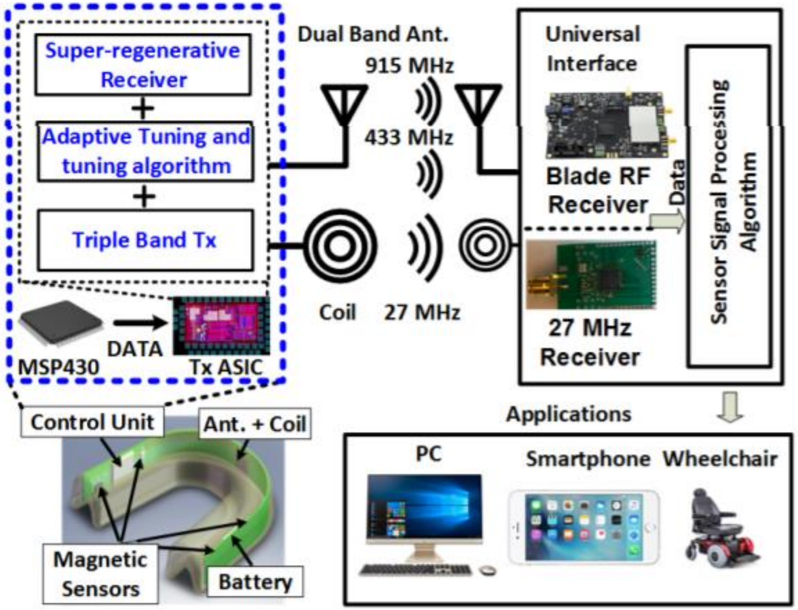
Active : iTDS [4]

-Automated impedance matching with custom Tx ASIC solution.

-3 operating bands (27 MHz, 433 MHz, and 915 MHz) that are automatically switched to mitigate external RF interference.

-103 cm operating range

-Complex Design , robust against interference and antenna detuning.



Theory

Theory
Propagation of electromagnetic waves in a lossy medium

An electromagnetic waves propagating through a lossy medium is attenuated due to:

- Ohmic losses due to conduction and displacement currents
- Reflection at the interfaces

Carrier Frequency (MHz)	Conductivity (σ, S/m)	Relative permittivity (ε_r)	Attenuation coefficient (α, Np/m)	Attenuation per cm (dB)
27	$0.70^{*}/0.03^{**}$	120/10	7.60/1.07	0.33/0.06
433.9	1.00/0.05	60/5	23.1/3.73	1.00/0.16
2480	2.50/0.09	50/4.2	65.5/8.07	2.85/0.35

* Muscle/** Fat

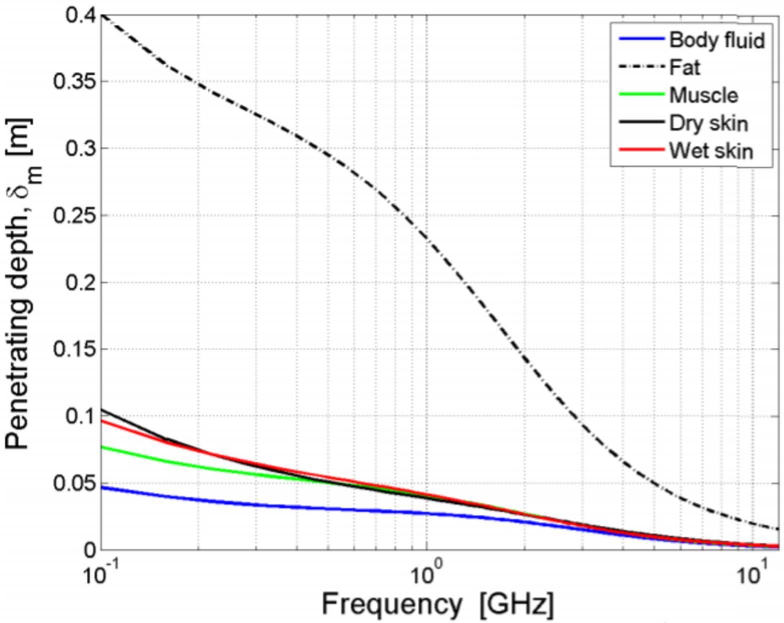
Attenuation characteristics of tissues
Source[6]

Theory
Propagation of electromagnetic waves in a lossy medium

The penetration depth δ of a material describes the depth at which the amplitude of a penetrating wave has decayed by a factor of 1/e of its initial value.

- The losses are due to conduction and displacement currents, as well as reflection at the interfaces.
- Higher attenuations occur at higher frequencies.
- However lower frequencies result in higher wavelengths and larger antennas.

→Tradeoff between size and range



Source[7]

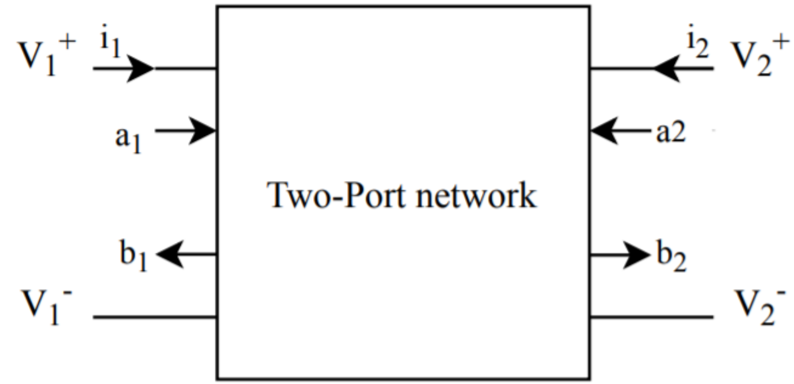
Theory
Scattering parameters

-The scattering parameters of an antenna provides a measure for the performance of an antenna.

-The reflection coefficient describes how well the antenna is matched to the transmission line.

-At the frequency band of operation, the S11 parameter should be as low as possible.

-The radiation power S21 describes the amount of power transferred from Port 1 to Port 2.

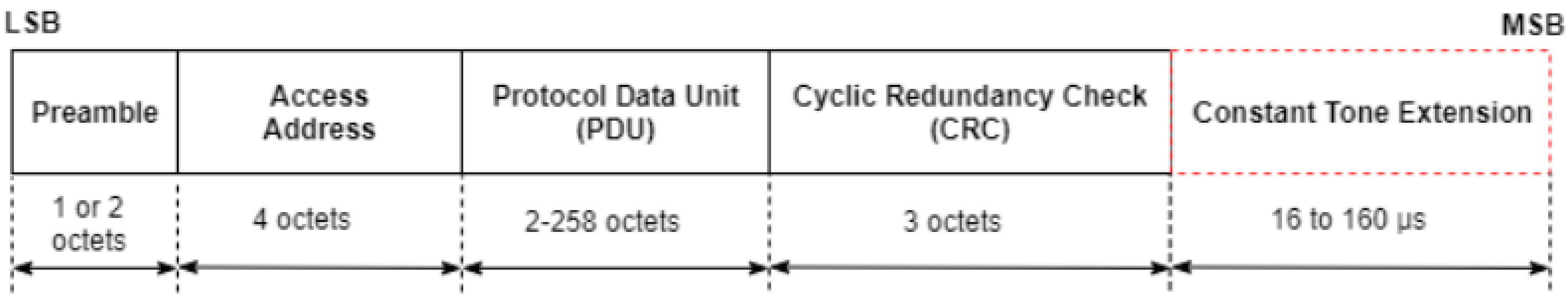


Theory
Bluetooth low energy 5 overview

-Channel Selection Algorithm (CSA) #2 reduces collisions from interference.

-Cyclic reduncancy check to detect communication errors.

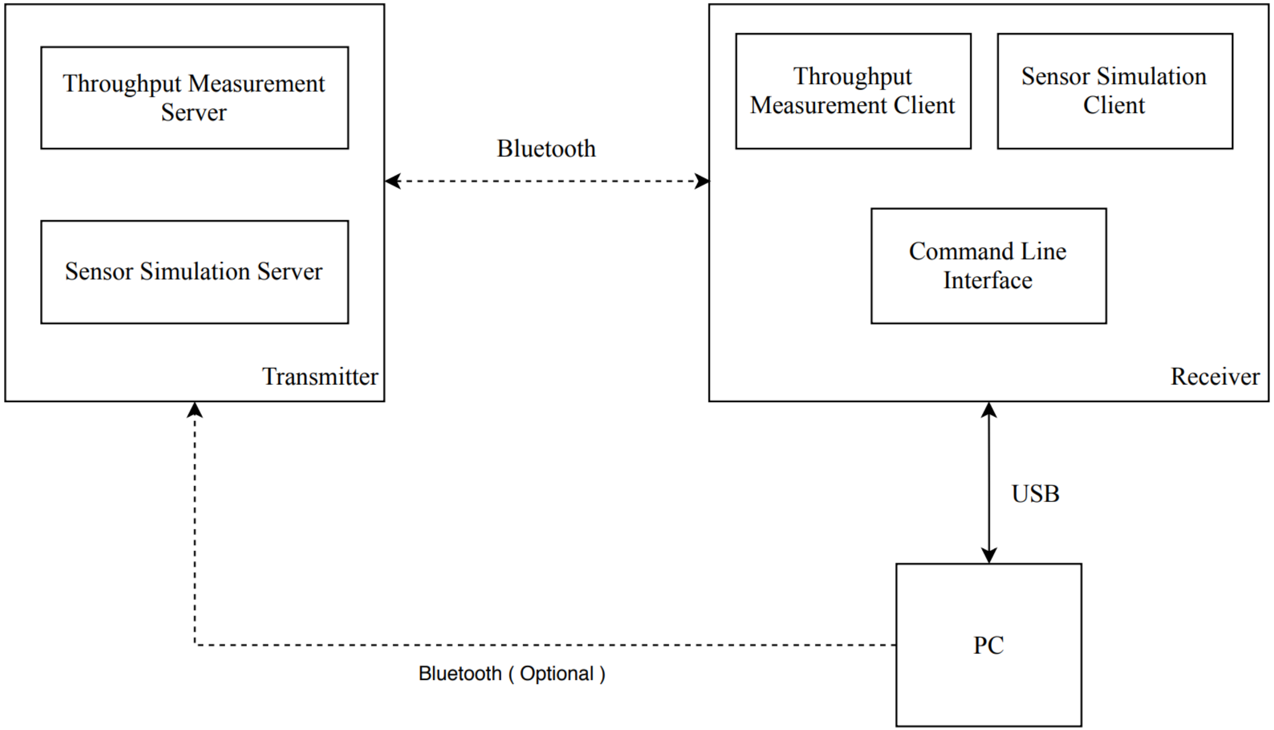
-Link-layer acknowledgements and retransmissions.



[5]

Implementation

System overview



Hardware selection

Transmitter : U-blox BMD-341-A-R – Cost : 12,38 €

- No external components needed
- UFL antenna connector : no restrictions for ground size plane and layout
- 14.8 mA @+8dBm, 4.8 mA @ +0dBm
- Size : 15 x 10,2 x 1,9 mm (MicroSD : 15 mm × 11 mm × 1 mm)
- Supports several protocols : BLE5, Zigbee, Thread, Proprietary 2,4GHz

Source

Antenna : Atom FXP75 – Cost : 7,09 €

- Smallest 2,4 GHz commercially available external antenna : 5,9 x 4,1x 0,24 mm
- Flexible mounting
- Easier to characterize
- Efficiency 45%

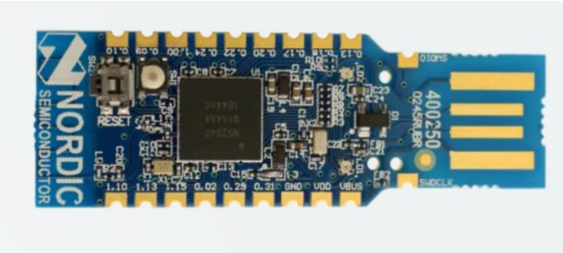
Source

Receiver

– Goal : support both embedded and custom receivers

Source

Source



Source

Embedded receiver : BLE compatible device

- Compatibility with a wide range of devices
- Supported connection parameters vary between devices
- Antenna typically embedded behind the screen : harder to adjust the position / orientation

Custom receiver : nRF52840-Dongle Cost : 8,81€

- Same SoC as the transmitter: faster development
- Flexible positioning
- Known connection parameters and capabilities
- Supports custom communication protocols

Pinout

Serial Wire Debug (SWD) Interface:

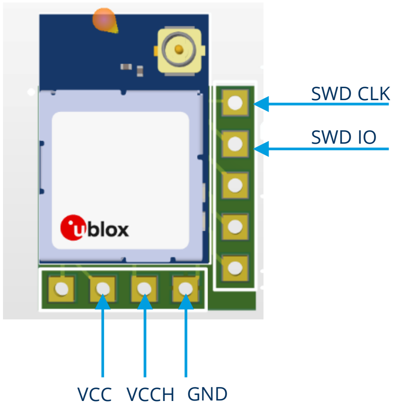
- Only 2 wires are required .
- Step by step debugging
- Used to programm the SoC using the NRF52DK debugger

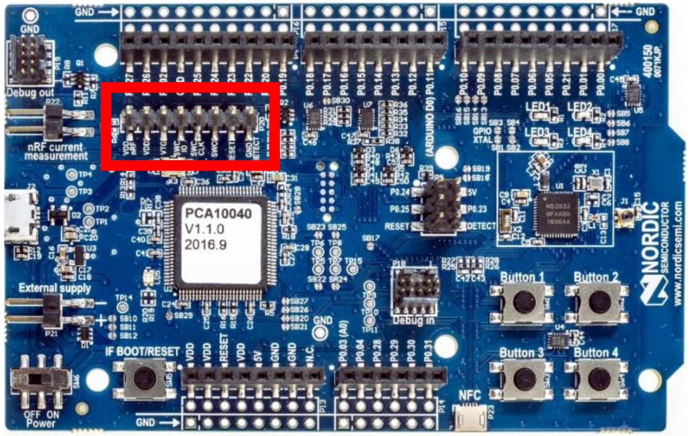
Power : VCC-VCCH

- **Low voltage mode**: VCC and VCCH connected to supply : 1,7-3,6V
- **High voltage mode**: VCCH connects to supply 2,5 -5,5 – VCC provides regulated 3V out to external devices

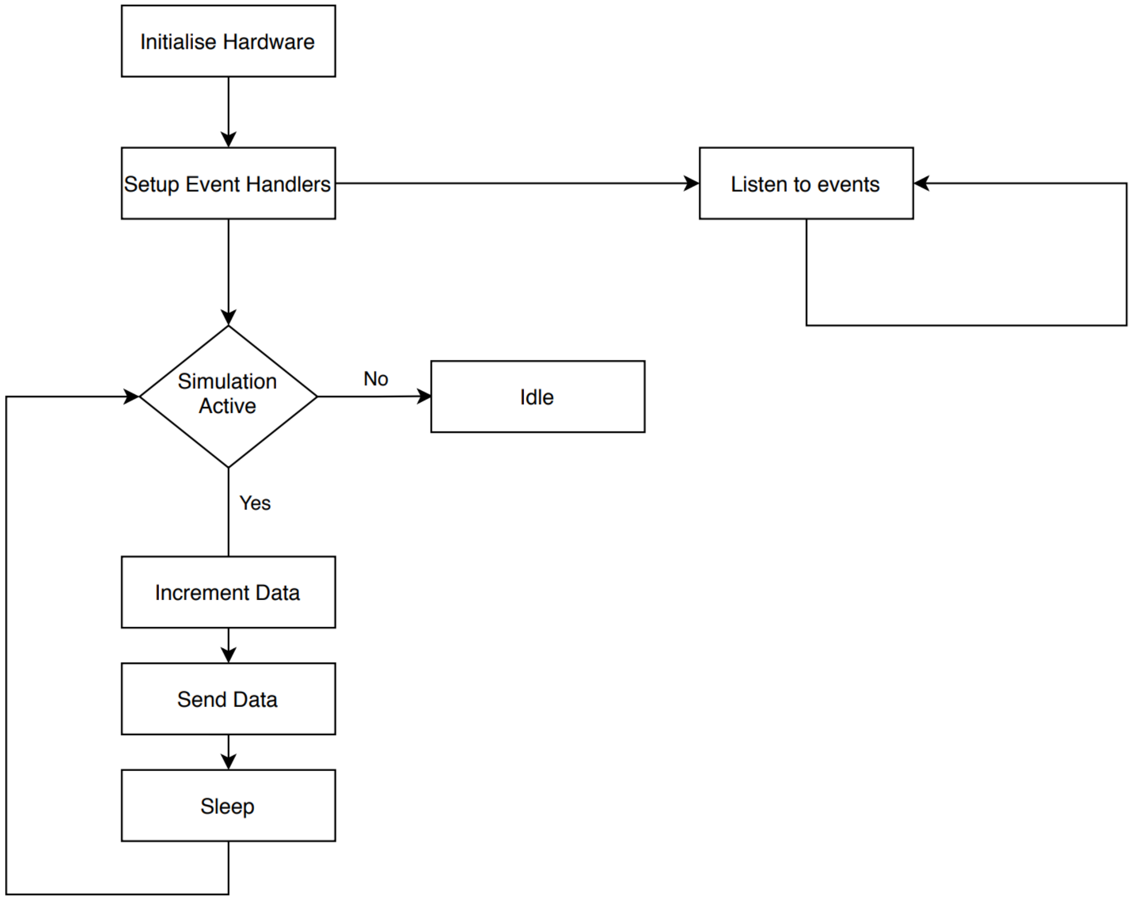
Exposed GPIOs : P0.17- P0.18 - P1.07- P1.08- P1.09 - P1.12

- Flexible pin assignement for digital interfaces (I2C,SPI,UART)



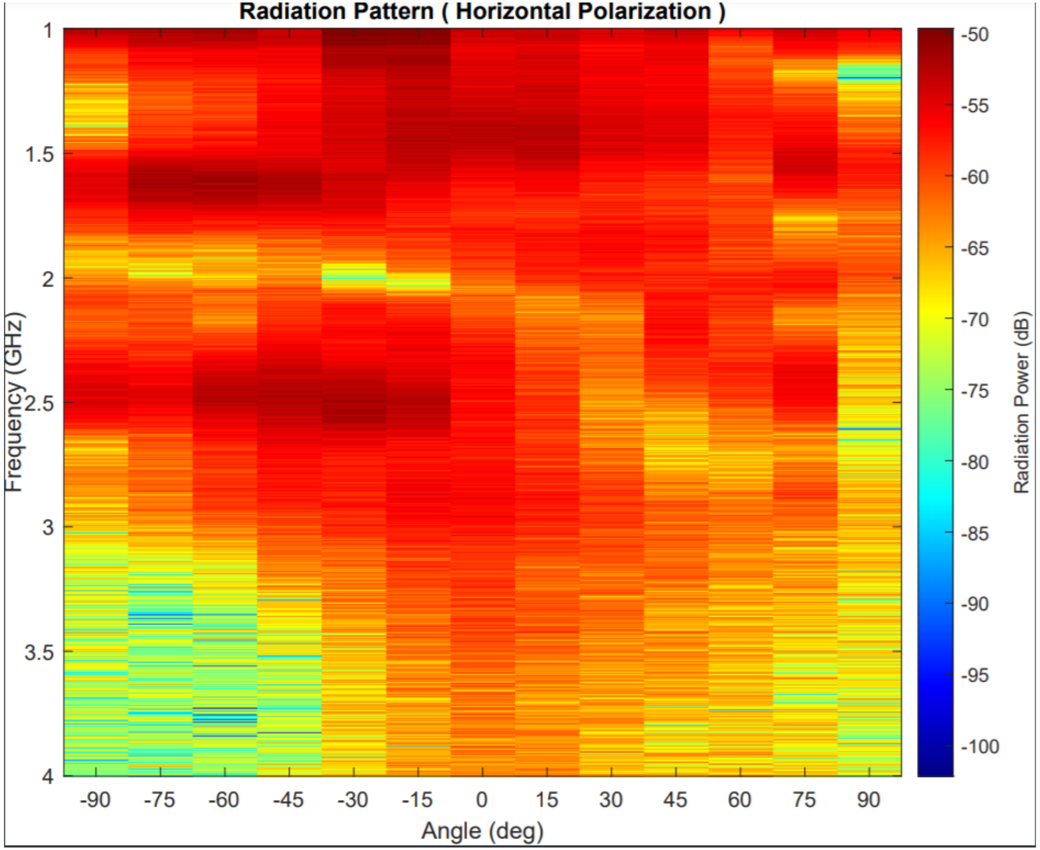


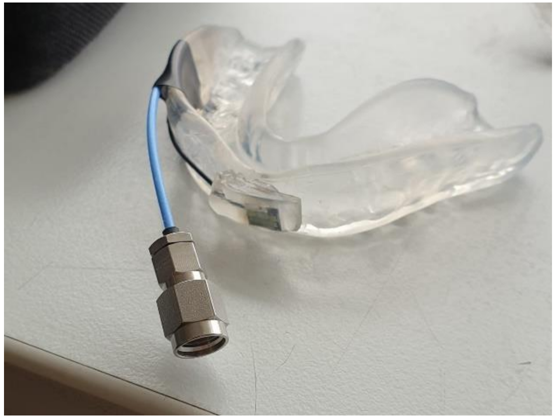
Main loop

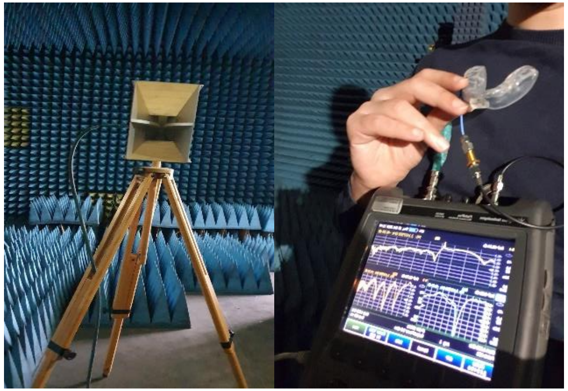

Initialise Hardware
Setup Event Handlers
Listen to events
Simulation Active
No
Idle
Yes
Increment Data
Send Data
Sleep

Results

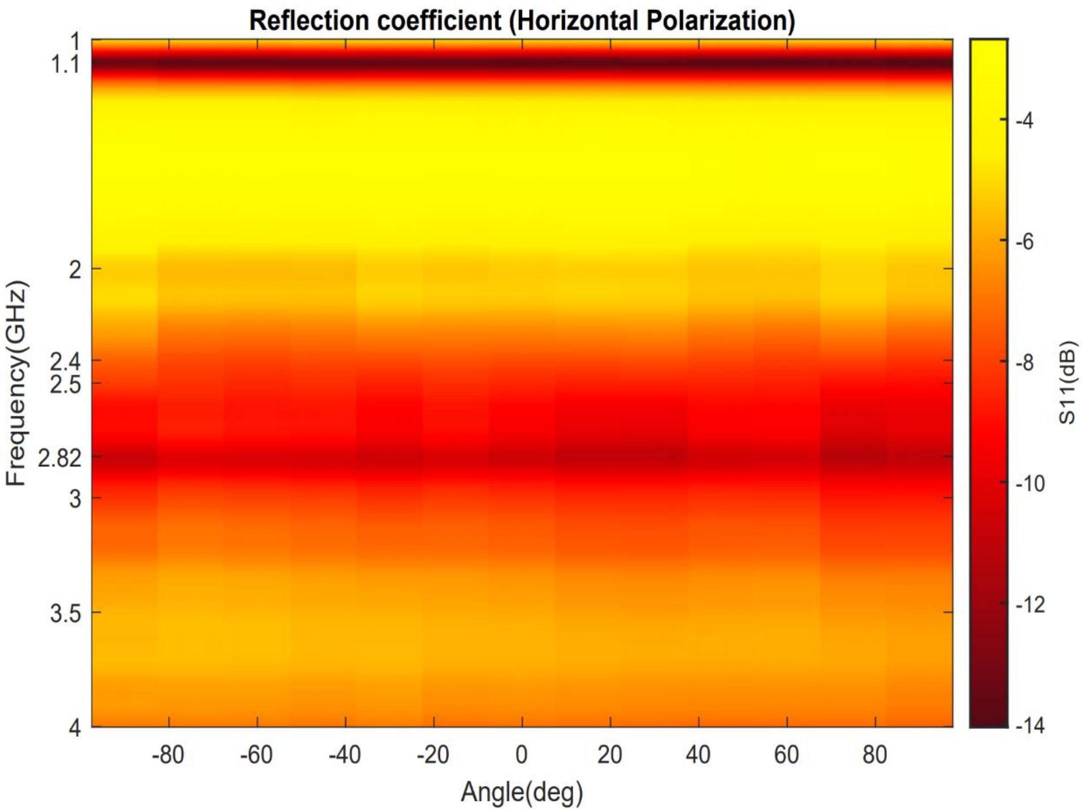
Radiation pattern - Antenna

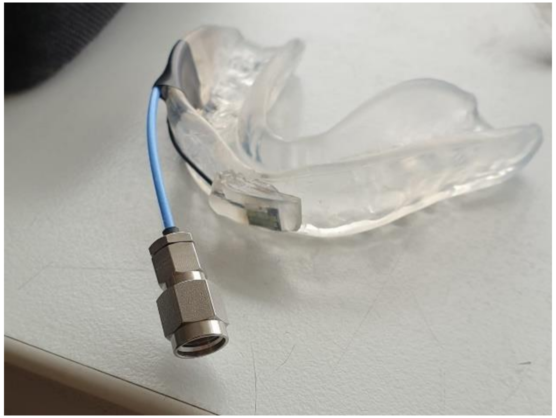


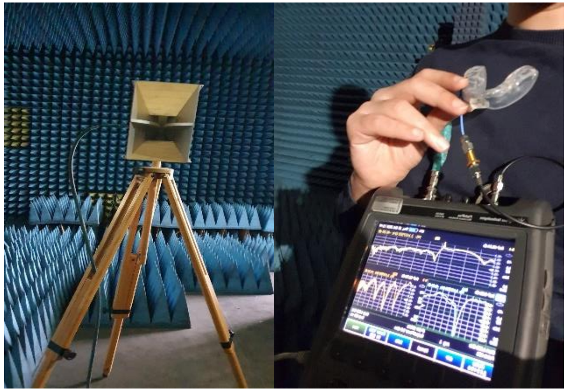




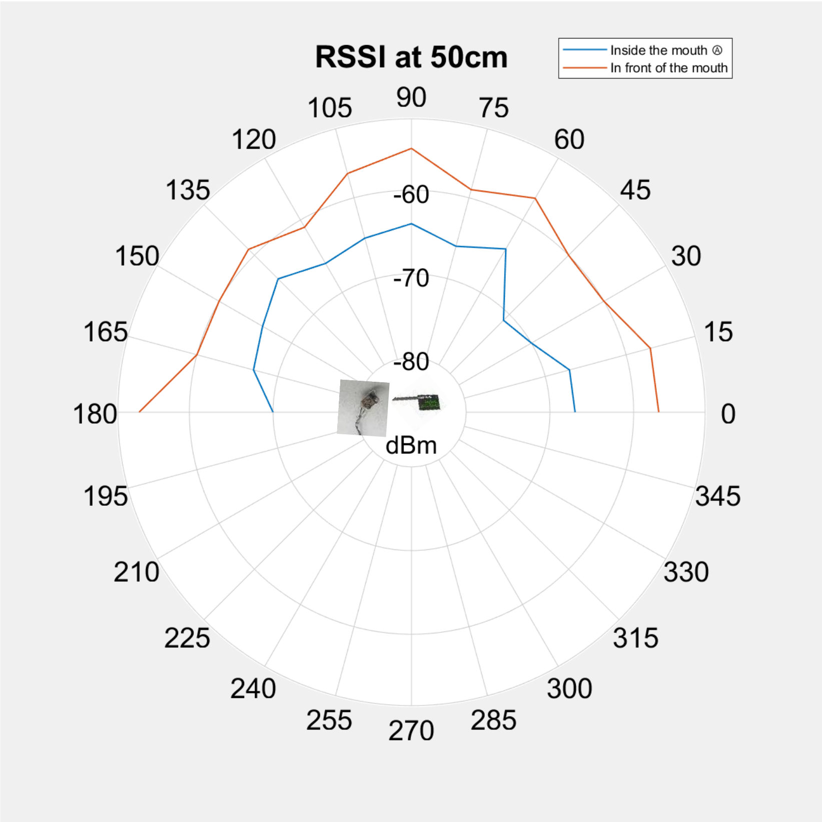
Reflection coefficient - Antenna

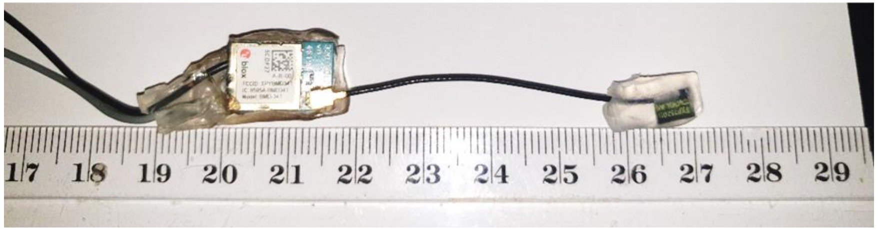


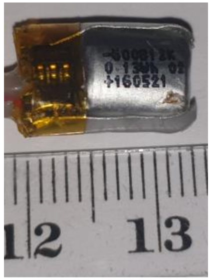




Radiation pattern – complete system





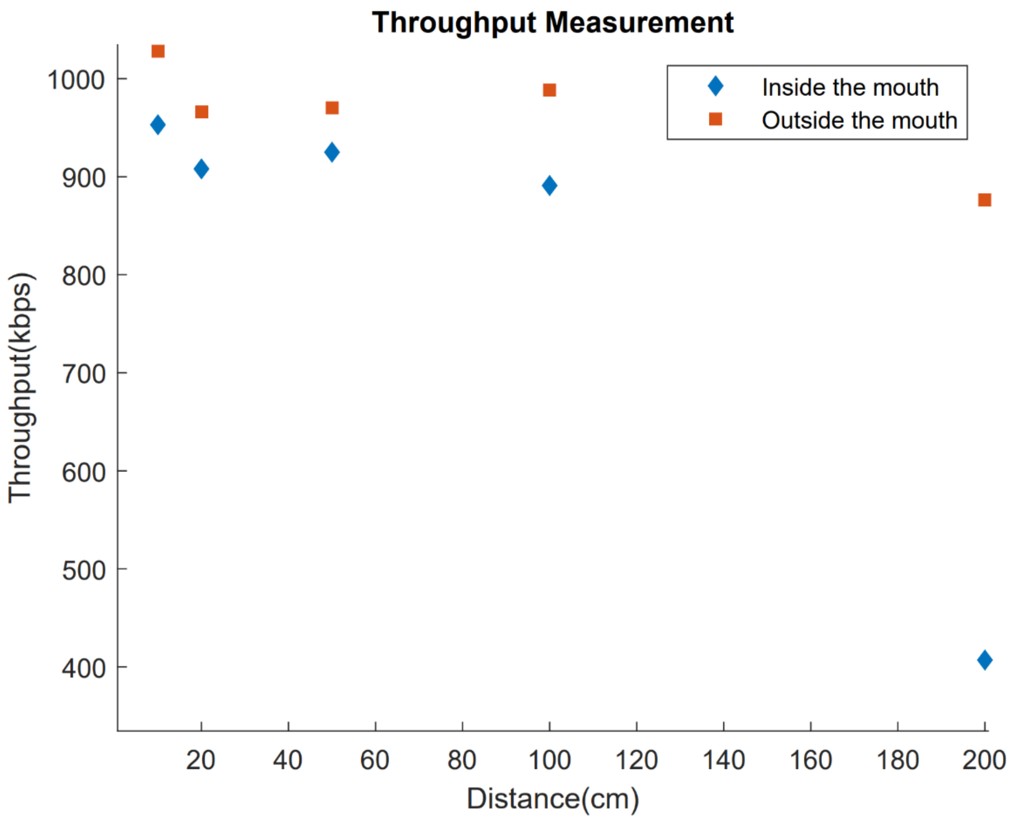


Power consumtion– complete system

Table 6.2: Peak current consumption - High Voltage mode

Test case	Link layer	Connection Inter-val[ms]	Update Rate [Hz]	Peak Cur-rent [mA]	Battery Life [Hours]
Maximal performance	2M	7.5	1120	9.3	3.14
Maximal range	Coded Phy	7.5	26	7.2	3.89
Balanced 1	2M	50	26	6.6	4.48
Maximal battery life	2M	400	26	6.6	4.48
Balanced 2	2M	7.5	100	6.9	3.93
Balanced 3	2M	7.5	400	7.0	3.93

Throughput – complete system



Summary and outlook

Summary and outlook

- Implementation adequate for intraoral assistive device at short ranges.
- Used components are certified off the shelve components, resulting in easier qualification process for the entire device.
- Modular implementation allows easier antenna swapping.
- Used SiP includes a DC-DC converter that can power external sensors thus alleviating the need for a dedicated power management unit.
- Latest Bluetooth protocol provides improved CSA algorithm resulting in better coexistence with other 2,4 GHz devices.
- Custom 2,4 GHz wireless protocols can be used to achieve a lower latency and higher data throughput.

Demo

Thank you for your attention

References

[1] H. P. Schwan, "Electrical properties of tissues and cell suspensions: mechanisms and models," *Proceedings of 16th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Baltimore, MD, USA, 1994, pp. A70-A71 vol.1.

[2] Principles and Applications of RF/Microwave in Healthcare and Biosensing ISBN: 978-0-12-802903-9

[3] Wang, Jingxian ; Pan, Chengfeng ; Jin, Haojian ; Singh, Vaibhav ; Jain, Yash ; Hong, Jason I. ; Majidi, Carmel ; Kumar, Swarun: RFID Tattoo: A Wireless Platform for Speech Recognition. In: Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 3 (2019), Dezember, Nr. 4. http://dx.doi.org/10.1145/3369812. – DOI 10.1145/3369812

[4] Kong, Fanpeng ; Ghovanloo, Maysam ; Durgin, Gregory D.: An Adaptive Impedance Matching Transmitter for a Wireless Intraoral Tongue-Controlled Assistive Technology. In: IEEE Transactions on Circuits and Systems II: Express Briefs 51 67 (2020), feb, Nr. 2, S. 240–244. http://dx.doi.org/10.1109/tcsii.2019. 2913623. – DOI 10.1109/tcsii.2019.2913623

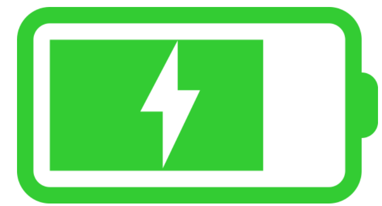
[5] Bluetooth Special Interest Group (SIG). "Bluetooth Core Specification." Version 5.1. https://www.bluetooth.com/.

[6] H. Park and M. Ghovanloo, "Wireless Communication of Intraoral Devices and Its Optimal Frequency Selection," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 12, pp. 3205-3215, Dec. 2014, doi: 10.1109/TMTT.2014.2365804.

Implementation

– Goal : support an adaptive operation mode for different usage scenarios

Source



Source

High performance mode :

- Faster data transmission : up to 1KHz
- Higher power consumtion
- Lower operating range < 1m

Usecase : Mouse pointing

Power saving mode :

- Slower data transmission < 10 Hz
- Low power consumtion
- Higher operating range > 2m

Usecase : Embedded gesture recognition

Problem

– Investigate the wireless connectivity of an intra oral device.

– Power requirements : operation with small sized batteries

– Size : mounting under the hardpalate / buccal shelf

– Range : operate a computer less than 1m away.

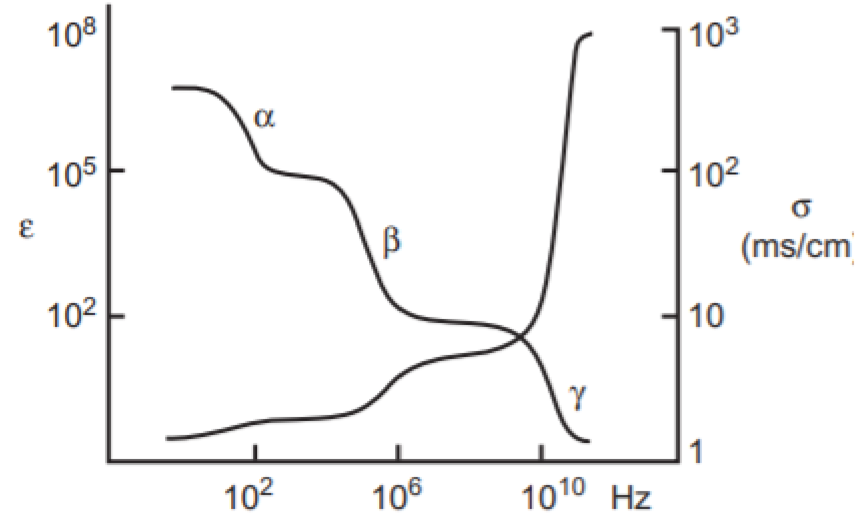
Structure :
Literature survey :
-Electromganetic waves as a carrier of information.
-Biological tissue models and interaction with electromagnetic waves.
-Electrical small Antennas.
-RF systems : components – parameters - Quality factor

Hardware survey :
-Antennas , tranceiver chips
Design
Experiment

Biological tissue properties

-Biological tissues display characteristics of both insulators and conductors.

-Dispersive permittivity and conductivity



Idealized dispersion of dielectric constant and conductivity of tissues and cell [1]

Biological tissue properties -2- Quelle [2] p57

- Relative complex permitttivity : $\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$

- attenuation constant : $$\alpha = \frac{\omega}{c}\sqrt{\frac{\varepsilon'}{2}}\sqrt{\sqrt{1+\tan\delta^2}-1}$$

- Phase constant $$\beta = \frac{\omega}{c}\sqrt{\frac{\varepsilon'}{2}}\sqrt{\sqrt{1+\tan\delta^2}+1}$$

- Plane wave wavelength $$\lambda = \frac{2\pi}{\beta} = \lambda_0\left[\sqrt{\frac{\varepsilon'}{2}}\sqrt{\sqrt{1+\tan\delta^2}+1}\right]^{-1}$$

- Loss tangent

Effects of antenna proximity to biological tissue

-The impedance of the antenna is changed.
-Impedance mismatch , s parameter

FREQUENCY-DEPENDENT ATTENUATION CHARACTERISTICS OF TISSUE [41]

Carrier Frequency (MHz)	Conductivity (σ, S/m)	Relative permittivity (ε_r)	Attenuation coefficient (α, Np/m)	Attenuation per cm (dB)
27	0.70*/0.03**	120/10	7.60/1.07	0.33/0.06
433.9	1.00/0.05	60/5	23.1/3.73	1.00/0.16
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* Muscle/** Fat

[41] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz," *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2251–2269, Nov. 1996.

Quelle : https://ieeexplore.ieee.org/document/6957600

RF quality metrics

– Definition:

Antenna : VSWR – Gain

– System : Received signal strength - Packet error rate.

Hardware considerations

– Integrated solutions : EYU , Würth , Anna-blox
 - Custom pcb :
- Frequency , receiver , position , antenna
- Experiment : program a bluetooth characteristic , send fake sensor data, measure PER and rssi , (compare with head tracking position,

Effects of biological tissue on RF performance

1 - propagation loss through oral tissue.

2 - Dielectric loading : surrounding tissue detunes an antenna requiring adaptive impedance matching , wideband antenna design and custom coating.

FREQUENCY-DEPENDENT ATTENUATION CHARACTERISTICS OF TISSUE [41]

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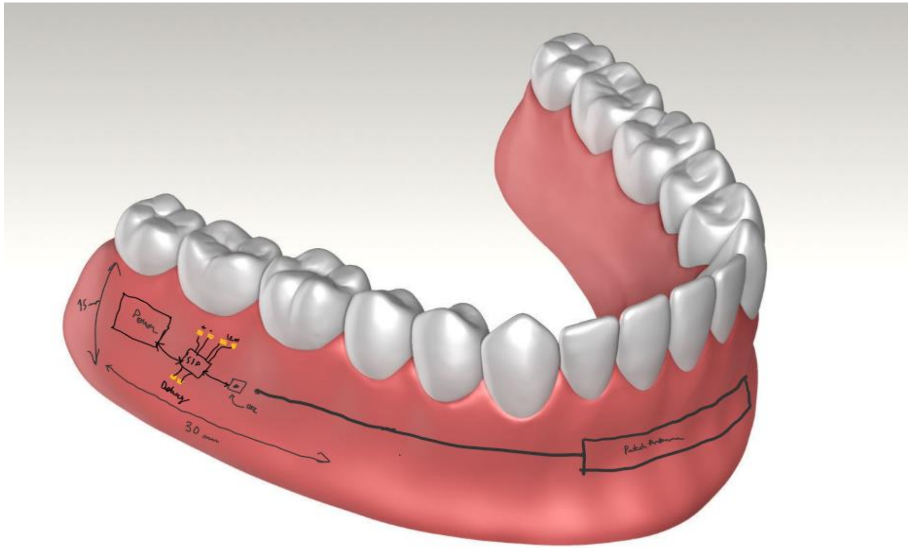
State of the art

- intra-oral
- Implantables
- small antennas, small batteries , low power sensoric
- Ultra low power rf solutions

Bluetooth low energy

– A custom PCB contains a wireless tranceiver SiP , impedance matching and a power management unit and exposes the following ports :

- UfL connector : to connect to an external antenna.
- I2C : to connect to an external sensor unit
- Power IN : to connect to an external Li-PO / Lithium Ion battery
- Power OUT : to power an external sensor unit.



- BLE : low energy consumption , easier implementation and testing.
- Sip : An Sip solution reduces the amount of externally needed components.
- Ufl connector : An external antenna has no ground plane size constraint allowing for a compact size. It also allows testing several antennas sizes and placements in the oral cavity.

Open questions :

- **Custom antenna design resources.**
- **Test commercially available flexible antennas (**FXP75.07.0045B , PC17.07.0070A **)**

FXP74.07.0100A

Manufacturer	Taoglas
Gain	+4.0 dBi
Impedance	50 Ω
Size	47.0 x 7.0 x 0.1 mm
Type	Patch, Flexfilm
Connector	U.FL.
Cable length	100 mm
Comment	Should be attached to a plastic enclosure or part for best performance. For more info see antenna data sheet. Should not be mounted inside a metal enclosure. To be mounted on a U.FL connector.
Approval	RED, MIC, KCC, ANATEL, ACMA and ICASA

FXP75.07.0045B

Manufacturer	Taoglas
Gain	+2.5 dBi
Impedance	50 Ω
Size	5.9 x 4.1 x 0.24 mm
Type	Patch, Flexfilm
Connector	U.FL.
Cable length	45 mm
Comment	Should be attached to a plastic enclosure or part for best performance. For more info see antenna data sheet. Should not be mounted inside a metal enclosure. To be mounted on a U.FL connector.
Approval	FCC, IC, RED, MIC, NCC, KCC, ANATEL, ACMA and ICASA

PC17.07.0070A

Manufacturer	Taoglas
Gain	+1.0 dBi
Impedance	50 Ω
Size	24.0 x11.0x 0.8 mm
Type	Patch, PCB
Connector	U.FL.
Cable length	70 mm
Comment	Should be attached to a plastic enclosure or part for best performance. For more info see antenna data sheet. Should not be mounted inside a metal enclosure. To be mounted on a U.FL connector.
Approval	FCC, IC, RED, MIC, NCC, KCC, ANATEL, ACMA and ICASA

Open questions :

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- https://www.lairdconnect.com/rf-antennas/wifi-antennas/embedded-antennas/flexpifa-flexible-adhesive-backed-pifa-internal-antenna
- https://www.lairdconnect.com/rf-antennas/wifi-antennas/embedded-antennas/nanogreen-series-internal-antenna
- **Tunable :** http://datasheets.avx.com/ethertronics/AVX-E_1001932FT.pdf
- **Molex** https://www.molex.com/molex/products/part-detail/antennas/2069941100

NFC

– NFC power transfer is possible with miniature coils https://ieeexplore.ieee.org/document/8400620
- Power and data through same coil https://ieeexplore.ieee.org/document/7959373

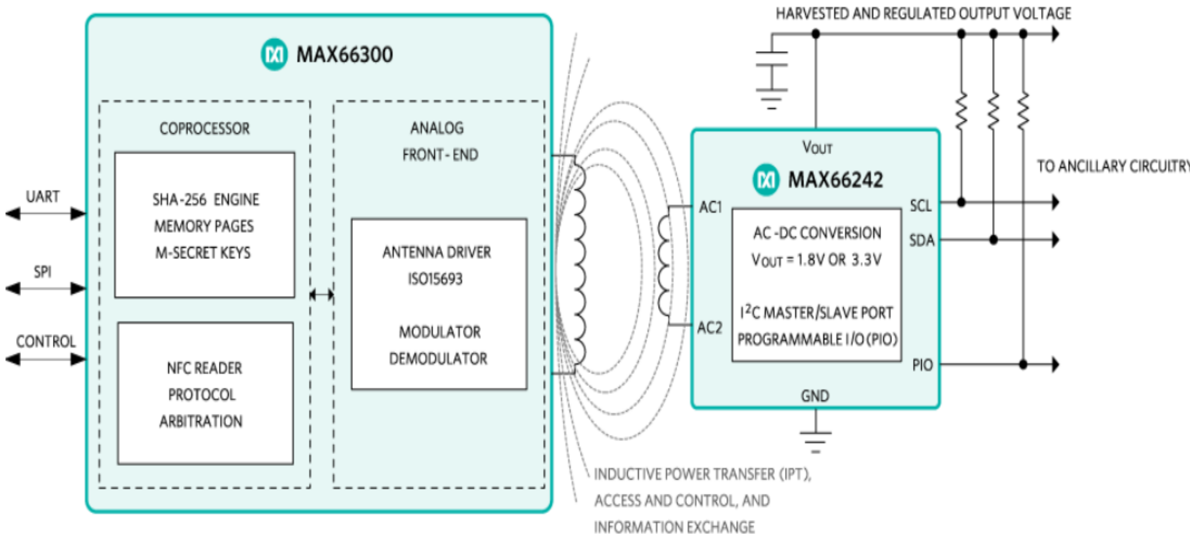


Figure 1. An NFC system consisting of the MAX66300 transceiver and the MAX66242 transponder. Ancillary circuitry is connected to the MAX66242 V_{OUT}, I^2C interface, and the PIO.

https://www.maximintegrated.com/en/design/technical-documents/app-notes/6/6725.html

NFC

https://www.mdpi.com/1424-8220/18/11/3746/pdf

-Headunit with cheek nfc coil.

-Mouth unit with nfc coil attached to inner cheek.

+ Battery less operation for low powered sensors inside the mouth (with nfc power harvesting).

+Robust wireless link (no interference , easy to connect , lowest propagation path loss)

-Low efficiency of wireless power transfer requires larger head unit batteries.

-Low data rate < 424 kbit/s

NFC

https://www.mdpi.com/1424-8220/18/11/3746/pdf

- CHIP antenna ground fläche
- -Antennen vergleich

Variant 2

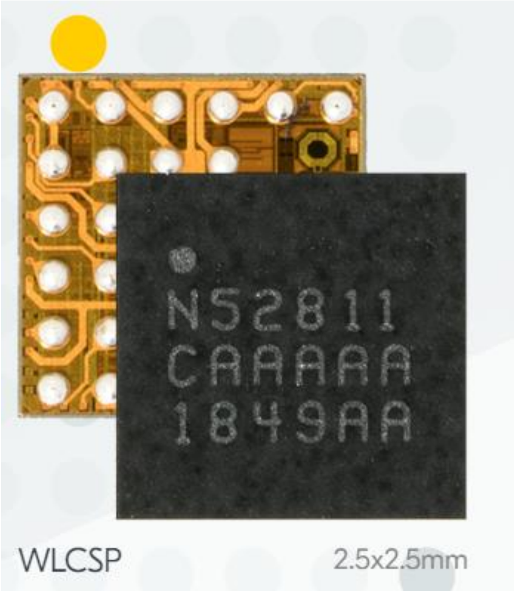
nRF52811

- Available reference design : 9 mm * 9 mm , 4 layers with DC-DC circuit.
- 4.6 mA in TX (0 dBm),
- 50Ω RF Pin , Proposed design : chip antenna , various ground plane sizes.
- TX current consumption @+0/8dBm : 6,4/16,4 dBm

Variant 3

nRF52811

- Available reference design : 9 mm * 9 mm , 4 layers with DC-DC circuit.
- 4.6 mA in TX (0 dBm),
- More flexible design : impedance matching , antenna selection.
- Proposed design : chip antenna , various ground plane sizes.



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Design
Experiment

Wireless history

– Investigate the wireless connectivity of an intra oral device.

– Power requirements : operation with small sized batteries

– Size : mounting under the hardpalate / buccal shelf

– Range : operate a computer less than 1m away.

Structure :
Literature survey :
-Electromganetic waves as a carrier of information.
-Biological tissue models and interaction with electromagnetic waves.
-Electrical small Antennas.
-RF systems.

State of the Art :
-
Hardware survey :
-Antennas , tranceiver chips
Design
Experiment

Biological tissue properties -2-

If we apply an alternating voltage : $V(t) = V0 \cos(\omega t)$ to the tissue model , a changing charge on the capacitor induces a displacement current : $Id = dQ/dt = - \omega CV0 \sin(\omega t)$

Total current : $I = GV + C\, dV/dt = (\sigma + i\, \omega\, \varepsilon)\, A\, .V/d$

Admittance $Y = I/V = (A/d)(\sigma + i\omega\varepsilon)$

With $\varepsilon = \varepsilon 0 * \varepsilon r$

A complex valued relative prermittivity is defined : $\varepsilon^* = \varepsilon r - i\sigma/\omega\varepsilon 0$

Experiment design

- Test a real world usage :

Total current : $I = GV + C\, dV/dt = (\sigma + i\, \omega\, \varepsilon)\, A\, .V/d$

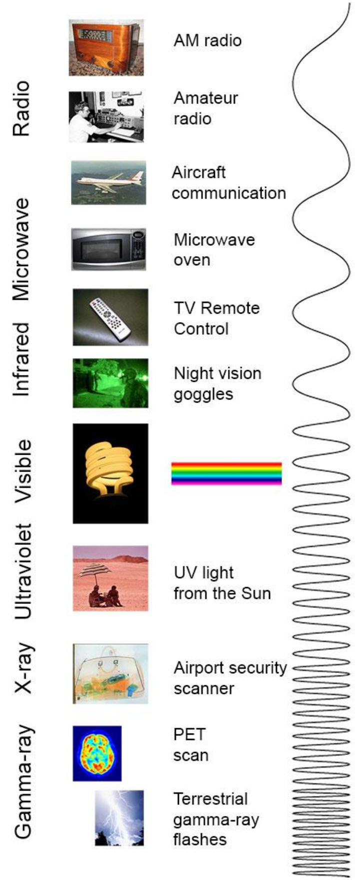
Admittance $Y = I/V = (A/d)(\sigma + i\omega\varepsilon)$

With $\varepsilon = \varepsilon_0 * \varepsilon_r$

A complex valued relative prermittivity is defined : $\varepsilon^* = \varepsilon_r - i\sigma/\omega\varepsilon_0$

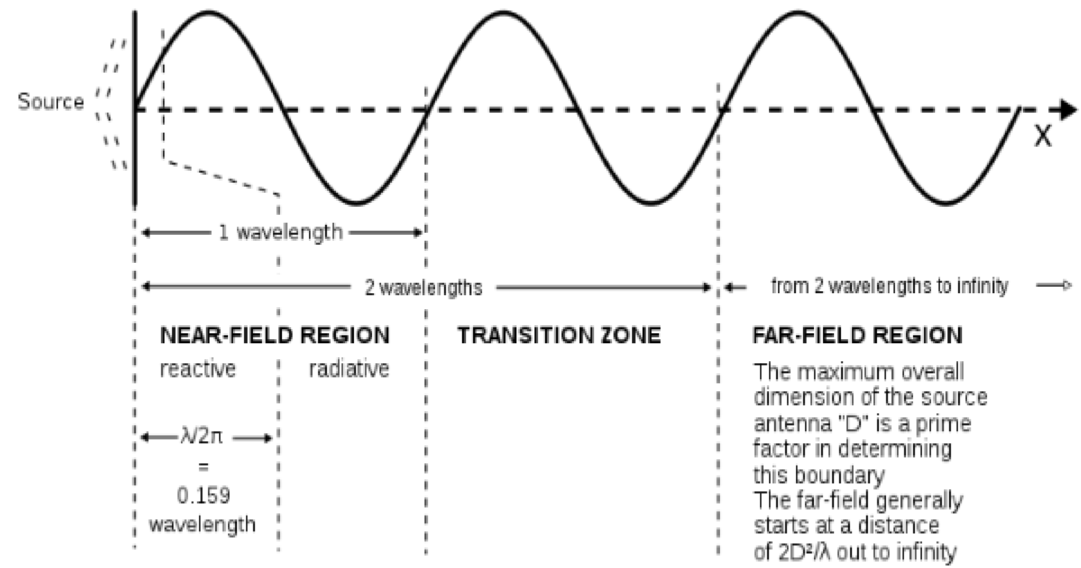
Biological tissue properties – 4

-Insulation effects



Electrically small antennas

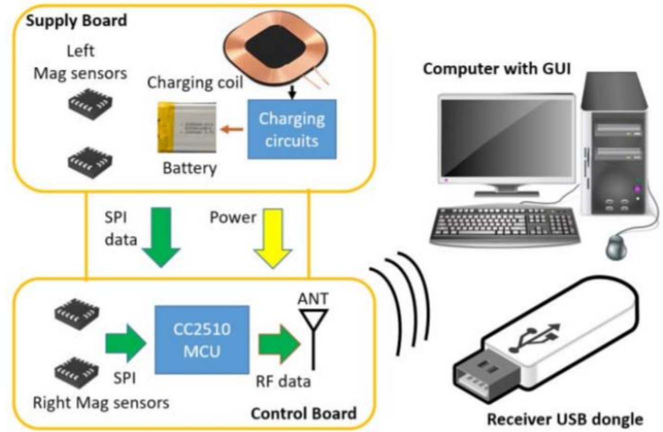
-Discovery :
-First experimental :



State of the Art

Kong2018
- Single band 2,4GHz.
- 3 Custom antennas were evaluated.
- Patch antenna showed a 0,5 % Packet error rate (PER) in worst case (closed mouth + 90° head orientation) at 1 m distance from Rx antenna.

-susceptible to interference due the crowded 2,4 GHz band (WiFi , Bluetooth …)



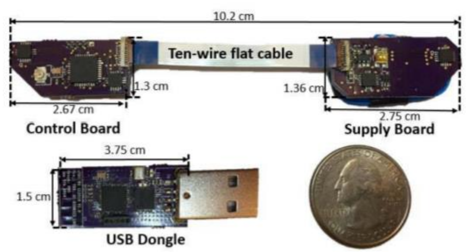
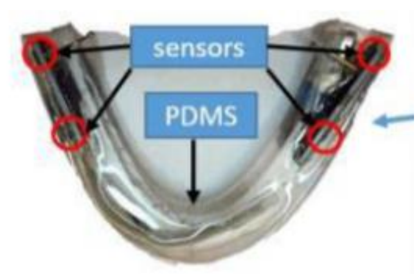


Fig. 3. iTDS system prototype with a control board, a supply board, and a USB dongle.



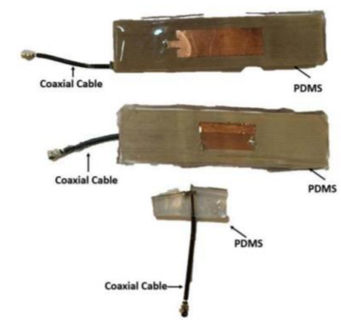


Fig. 8. Photograph of the three types of fabricated antennas from the top to the bottom with the PDMS coating material: the patch antenna, the PIFA, and the dipole antenna.

https://ieeexplore.ieee.org/document/8258970

State of the Art

Hangue Park ; Maysam Ghovanloo 2014

“Experimental results showed that 27 MHz has the smallest path loss in the near-field up to 39 cm separation between transmitter and receiver antennas. However, 433.9 MHz shows the best performance beyond 39 cm and offers a maximum operating distance of 123 cm with 0 dBm transmitter output power. These distances were obtained by a bit error rate test and verified by a link budget analysis and full functionality test of the iTDS with computer access.’

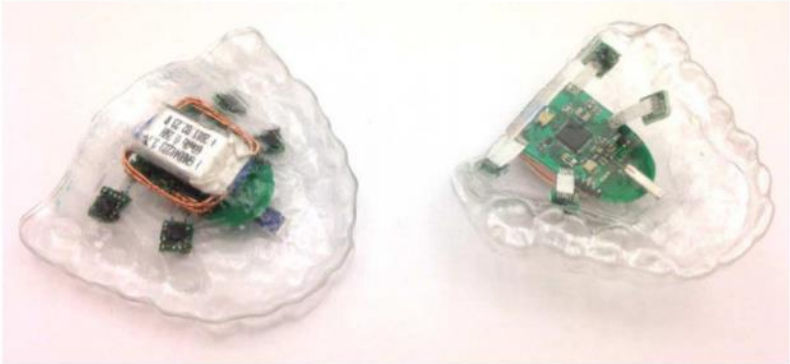


Fig. 4. Photos of the iTDS embedded in the Essix-type transparent dental retainer: (a) top side of 433.9 MHz iTDS and (b) bottom side of 2.48 GHz iTDS.

https://ieeexplore.ieee.org/document/6957600