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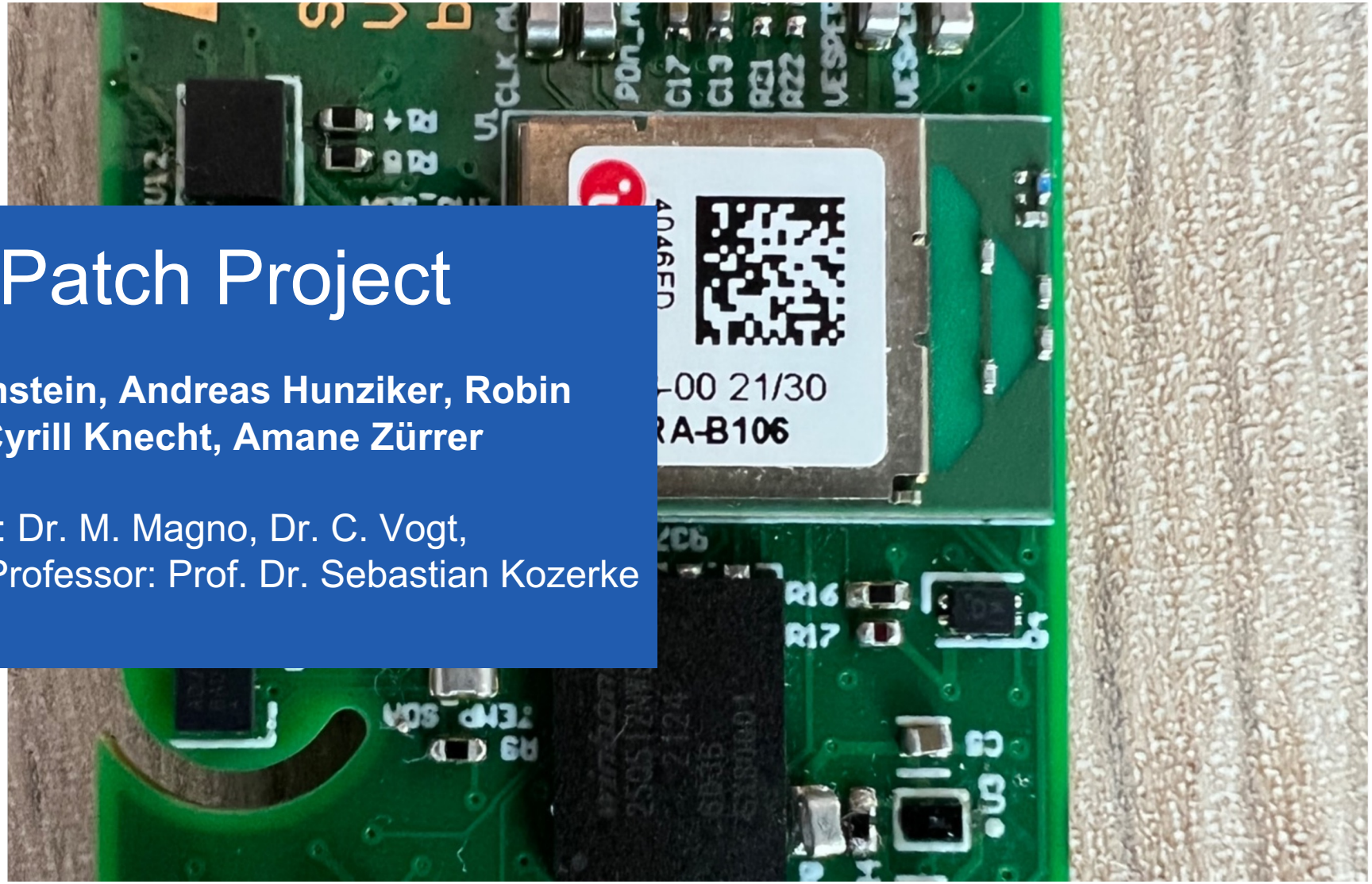
D-ITET



SmartPatch Project

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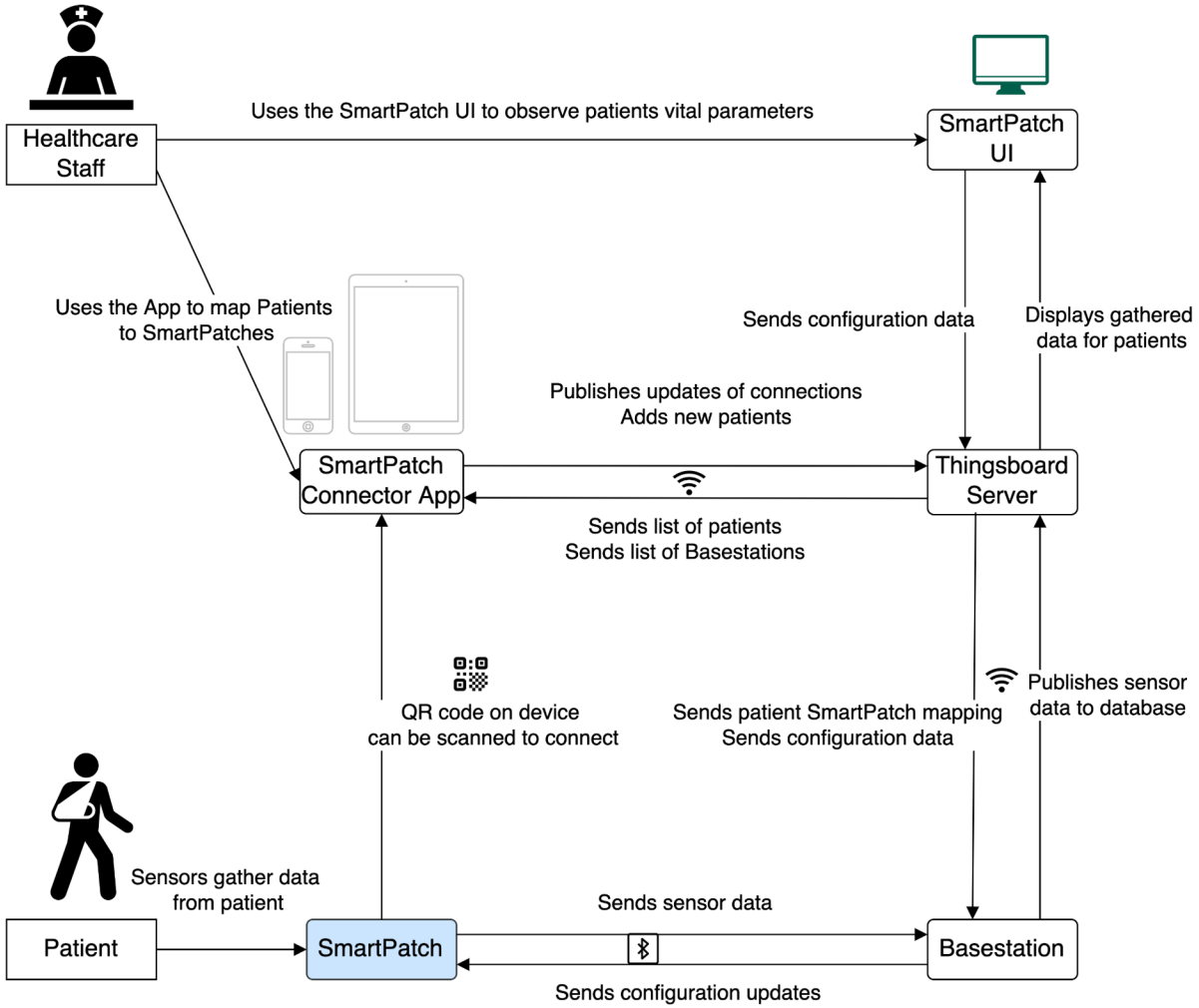
Supervisors: Dr. M. Magno, Dr. C. Vogt,
S. Cortesi, Professor: Prof. Dr. Sebastian Kozerke
18.01.2022

CENTER FOR PROJECT-BASED LEARNING

Introduction to general concept



Schematic Overview of the SmartPatch System

Contents

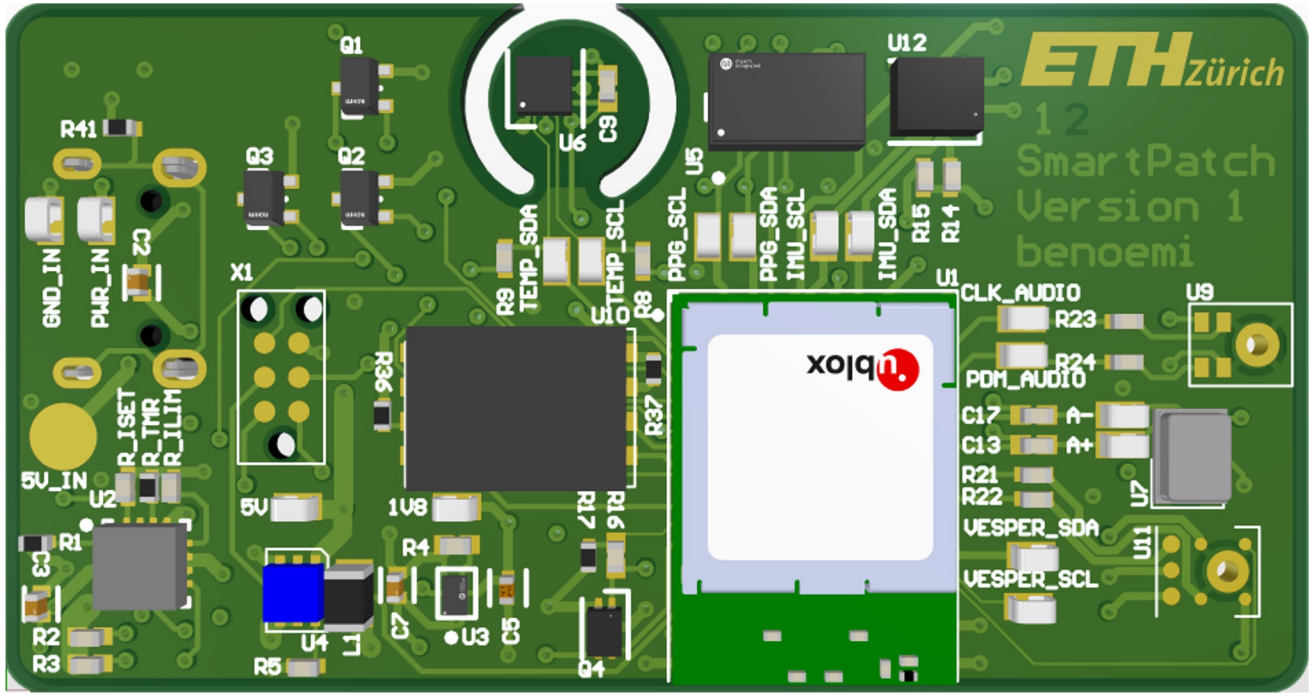
Goals

- SmartPatch can reliably and accurately measure
  - Heartrate
  - Blood Oxygen Saturation
  - Body Skin Temperature
  - Orientation and Movement
  - Audio Recording
  - Indoor Localisation
- Wireless streaming of data to Basestation using Bluetooth Low Energy
- High efficiency
- Basestation can receive and manage data from the patch via BLE
- GUI to show the data
- Resistant to environment of deployment
  - Highly hygienic
  - Easily sterilizable

Hardware

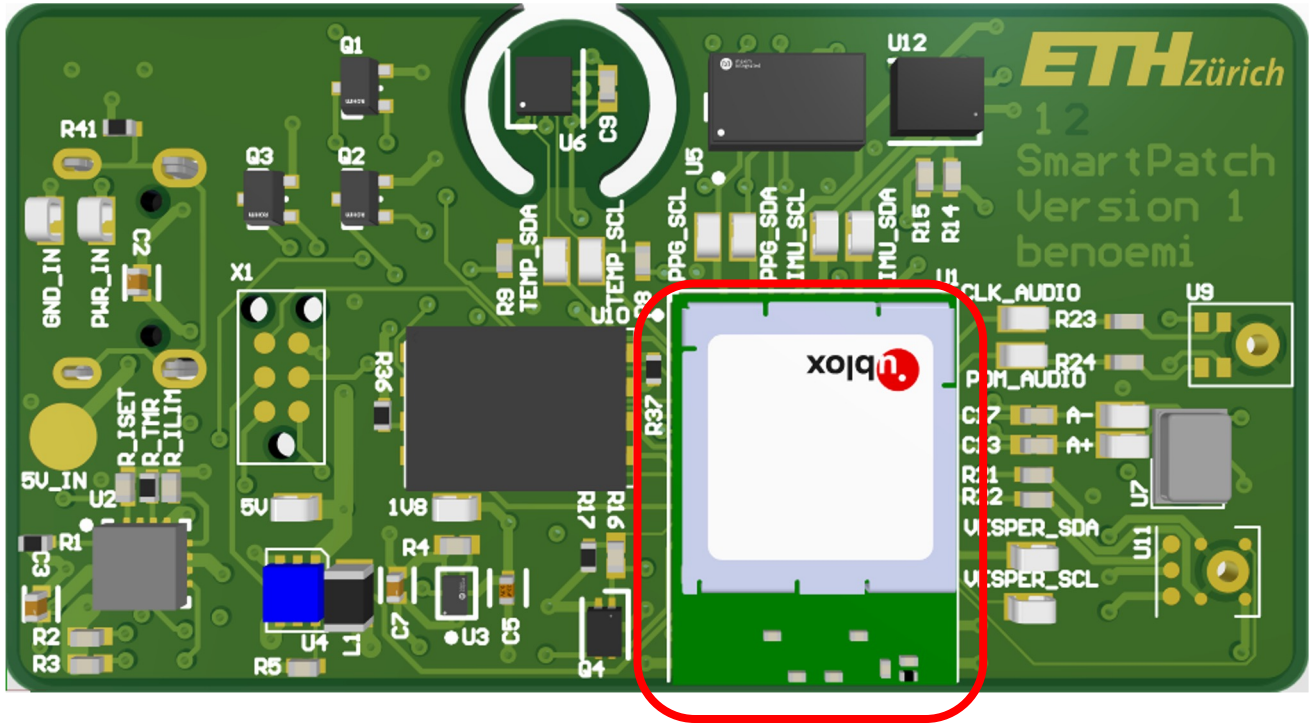
PCB Version 1

- Size: 48mmx26mm
- 4 layers
- 1mm thick
- Designed as Development Board
  - Easy Acess
  - Bigger distances between components
  - Testpoints
  - LEDs



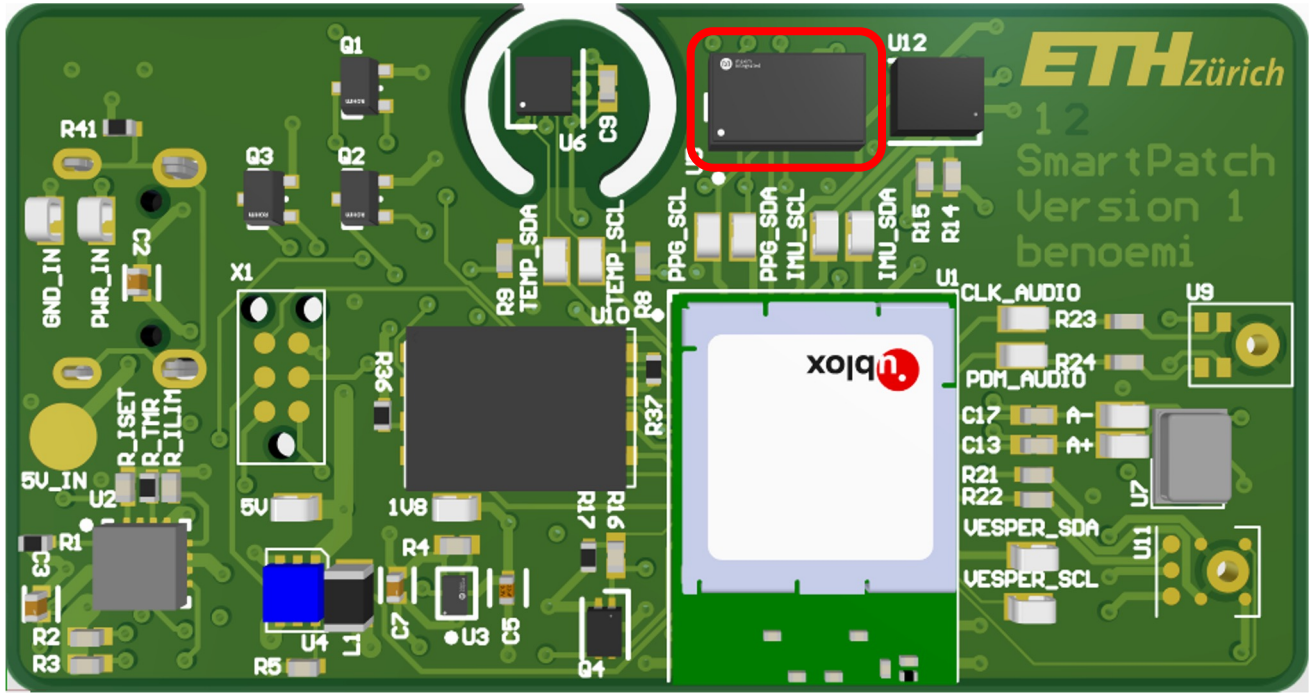
Components - MCU

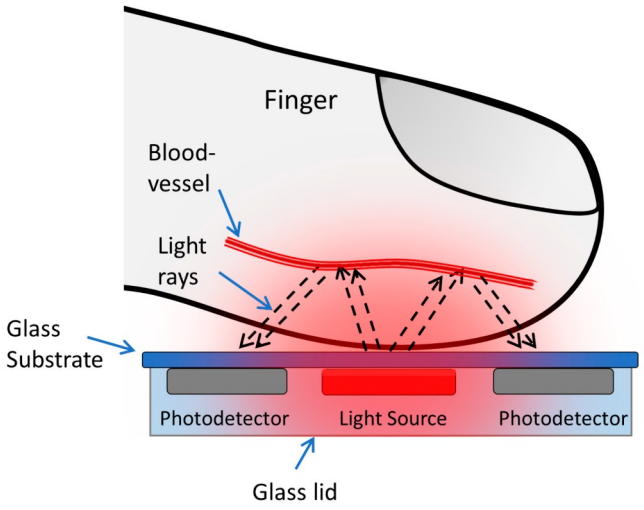
- Nora-B106 from UBlox
- Nordic nRF5340 chip
  - Two ARM Cortex-M33 processor cores
- One core for high performance application
- Second core for low power and efficiency
  - Network core
- Integrated Flash and RAM
- Bluetooth v5.2 (Bluetooth Low Energy)
- 42 GPIO pins
  - UART
  - QSPI, SPI
  - I2C
  - PDM
  - USB
  - PWM
  - AD converter



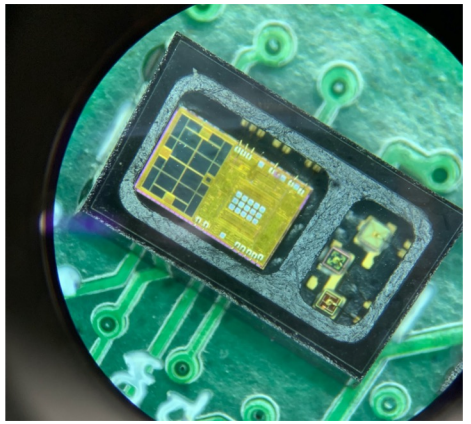
Components - PPG Sensor

- MAX30101
- Heart-Rate Monitor and Pulse Oximeter Sensor
- Ultra Low Power
- PPG Principles:
  - Light Source illuminates tissue
  - Photodiode measures intensity of reflected light
  - Can identify changes in blood volume



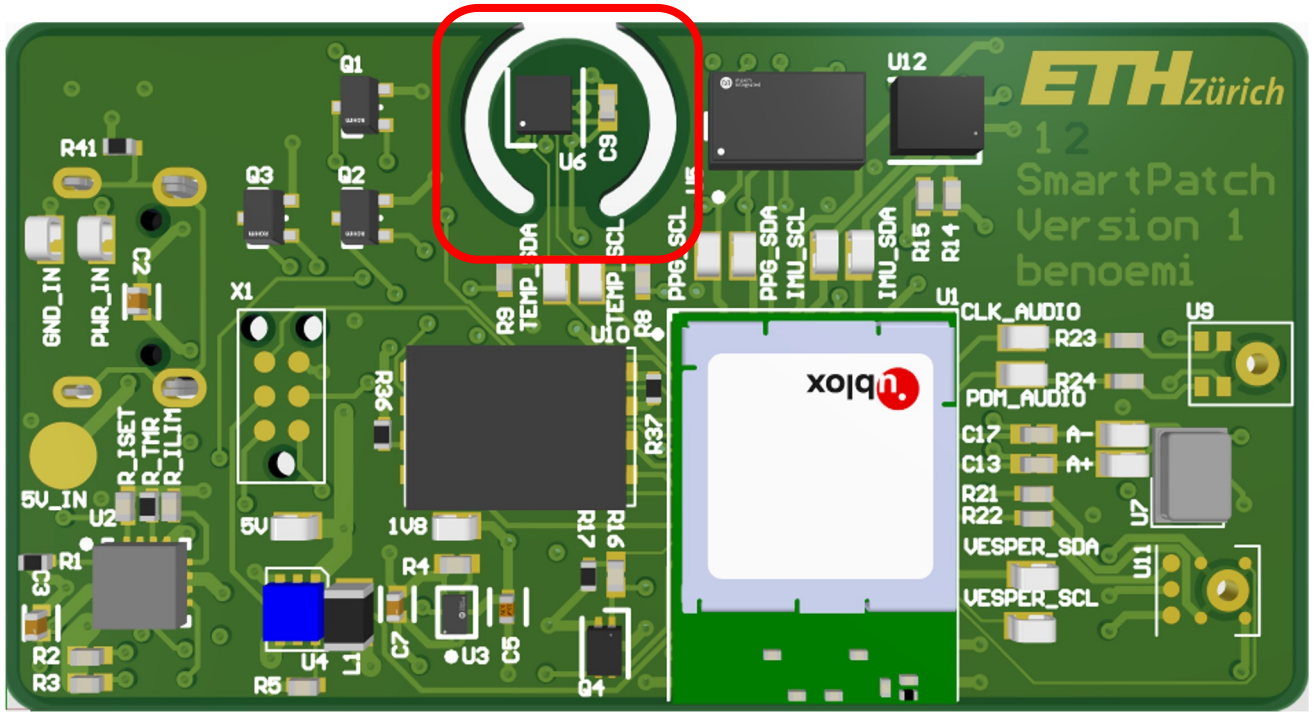


Source: https://priteshpawar.com/mobile-apps-to-measure-oxygen-levels/myth-buster/priteshpawar/



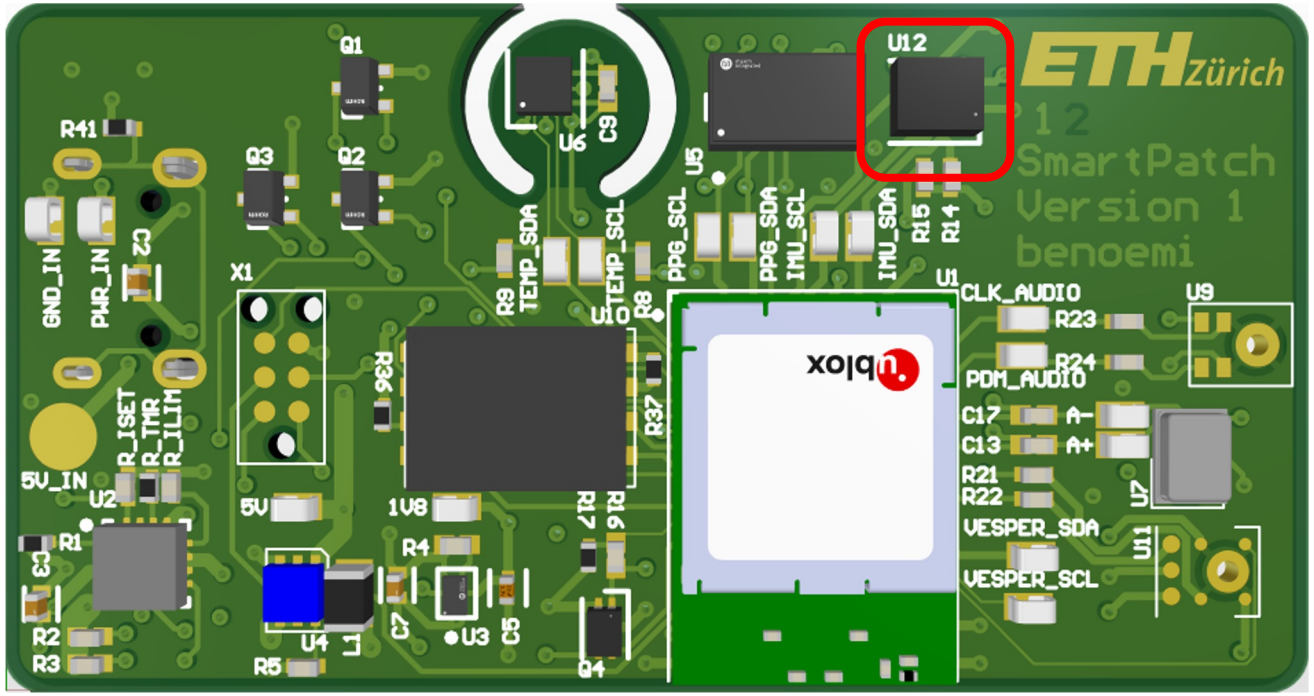
Components - Temperature Sensor

- MAX30208
- Measures skin temperature
- Ultra Low Power
- PCB designed for good readings
  - No power-planes under sensor
  - PCB cutout around sensor



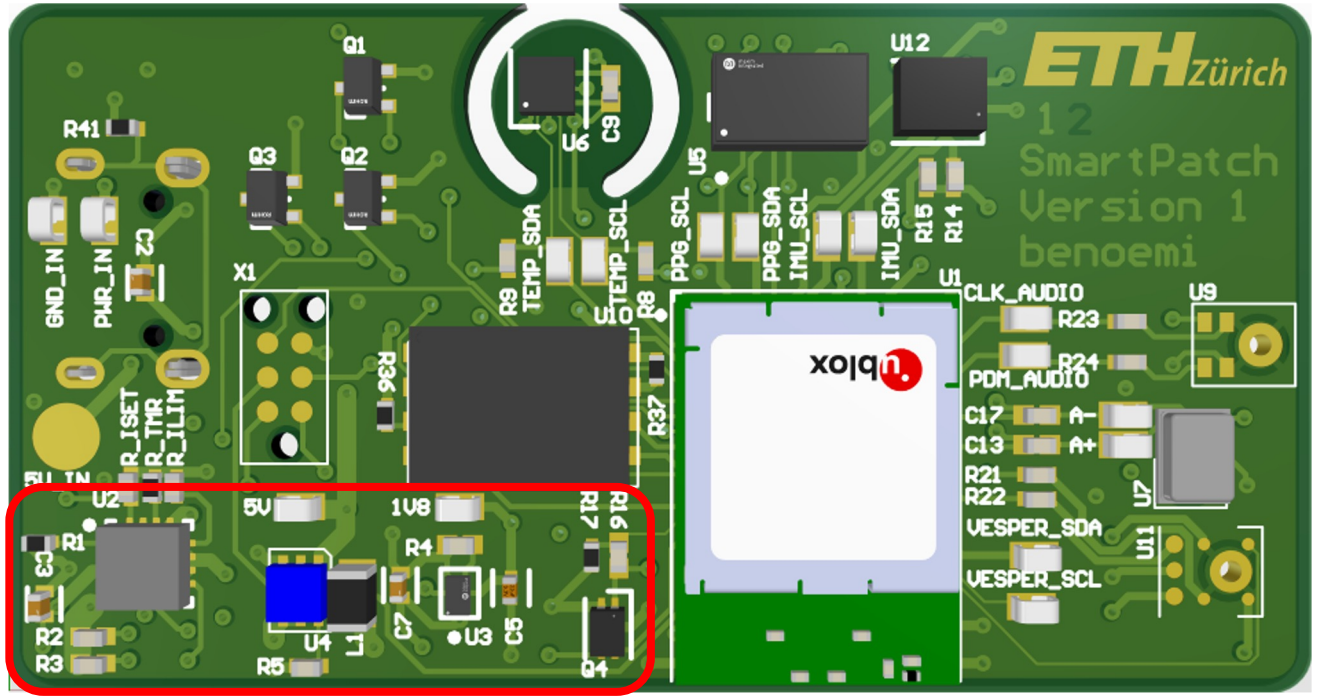
Components - IMU

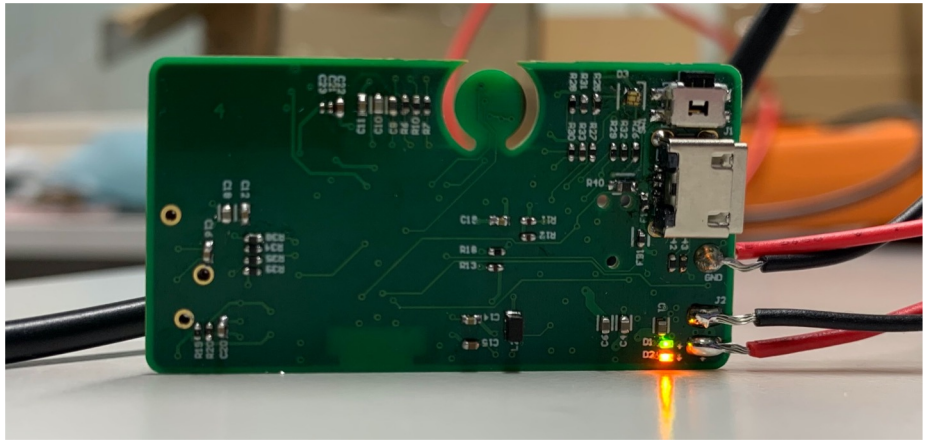
- LSM6DSV16X
- Accelerometer and Gyroscope
- Integrated Machine Learning Core
- Standard Interrupts
- Step detector and counter
- Uses:
  - General assessment of patient wellbeing
  - Patient mobility
  - Fall detection



Components - Battery and Power Management

- Battery should last 2-3 days till dressing change is required
- 1S LiPo Battery, 300mAh
- Battery Voltage can be sampled from MCU through a switch
- Battery Charging IC (BQ2407x)
- Buck and Boost converter to convert Battery Voltage to 1.8V and 5V (very high efficiency)

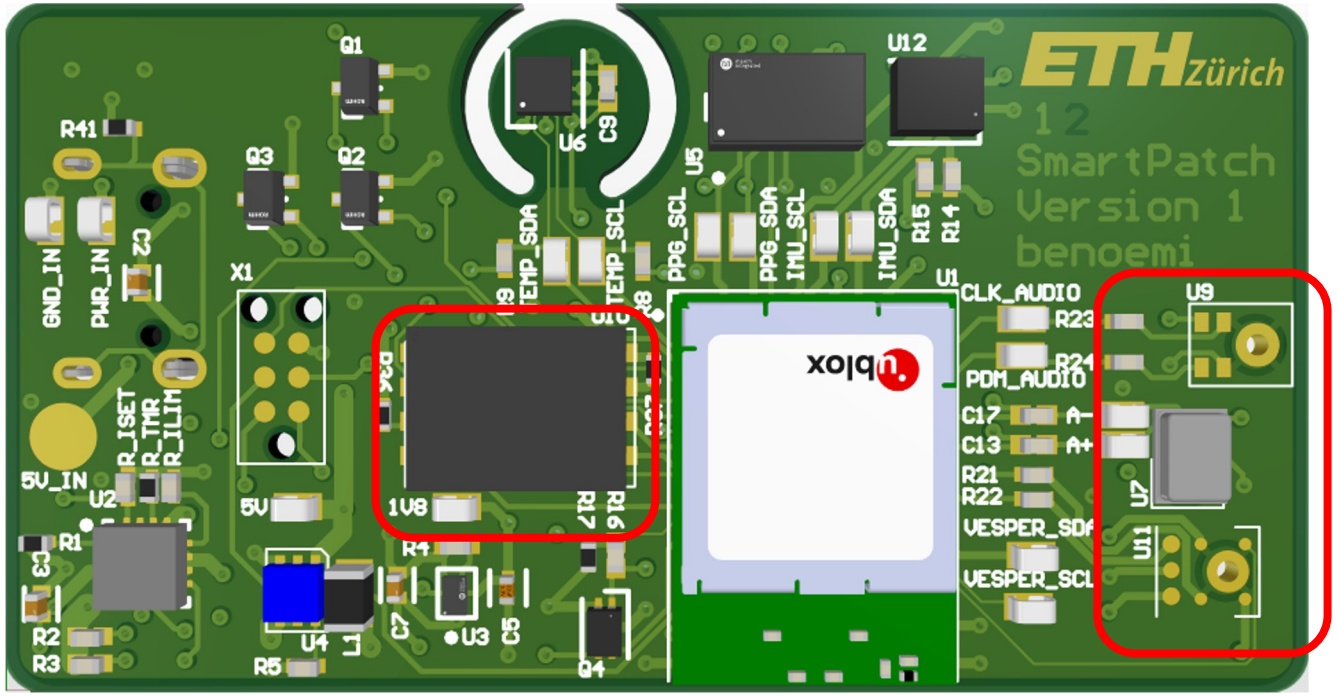




SmartPatch V1 with orange LED indicating charging status

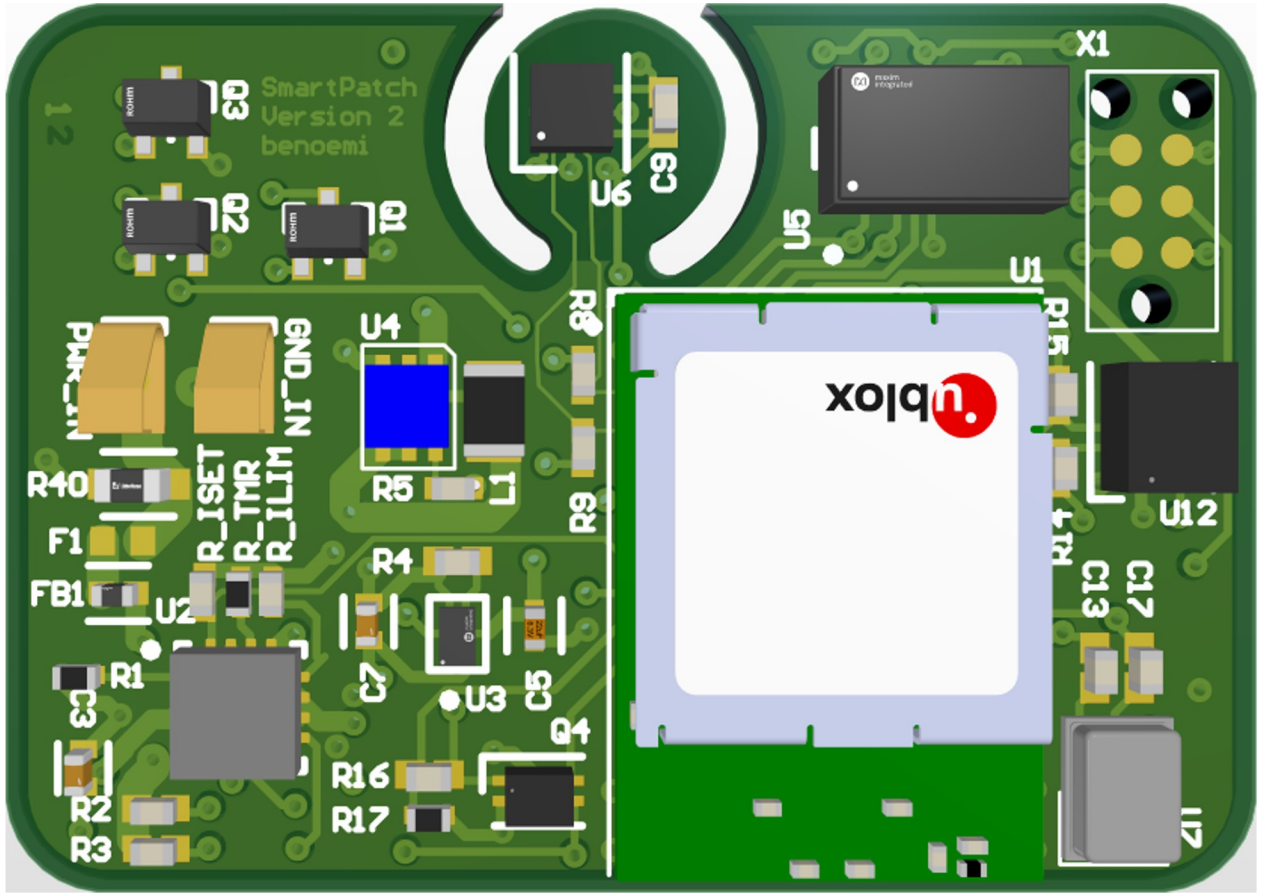
Components

- Microphones
  - Several mounted on V1 (Digital and Analogue)
- Flash Memory
  - Mainly for data from microphones
  - 512M bit
  - Communication via SPI
  - Winbond W25Q512NW



PCB Version 2

- Size: 31mmx20mm
  - Half the size of V1
- 4 layers
- 1mm thick
- Size limited by battery
- Pins for charging of battery
- Further improvements (could halve size again)
  - Custom battery
  - Smaller components (if not self-soldered)
  - Wireless programming

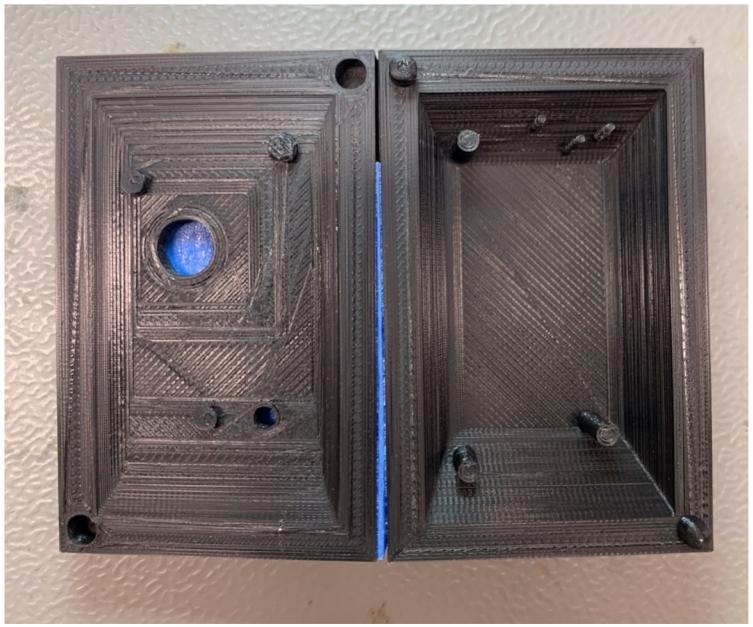


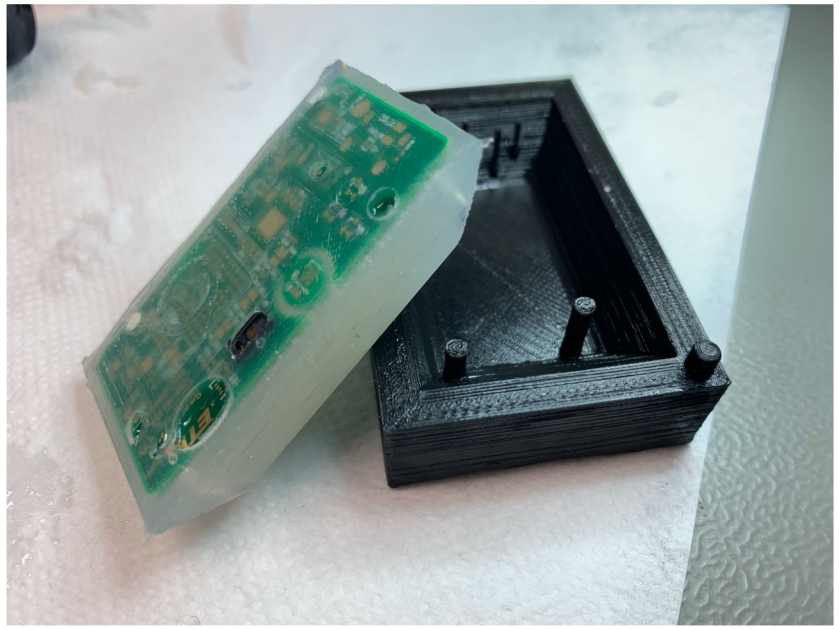
Final Housing

- Biocompatible Material
  - Polymer (PE or PVC)
  - Metal (Titanium)
  - Ceramic
  - Medical grade silicone
- Poured silicone
  - Soft
  - 3D printed mould
  - Mould designed for comfort, good signal acquisition and with internal battery

Housing Process

- Several mould iterations
  - fixation
  - pouring the silicone
  - size





Adhesive

- Silicone Based adhesive
  - Can irritate skin
- Medical Tape
  - Either not breathable or not waterproof
- Tegaderm
  - Waterproof
  - Breathable
  - Could be left on for 7 days
  - Used in hospital settings for wound dressings and as an adhesive to the skin for medical equipment
  - Easily applicable and removable
  - Cost effective

Source: https://www.walmart.com/ip/Adapt-Adhesive-Barrier-Spray-3-8-oz-7730-1-CI/46022501

Silicone Adhesive

Source: https://israelifirstaid.com/3m-transpore-medical-tape-2-5cm-x-9-1m/

Medical Tape

Source: 3M CH

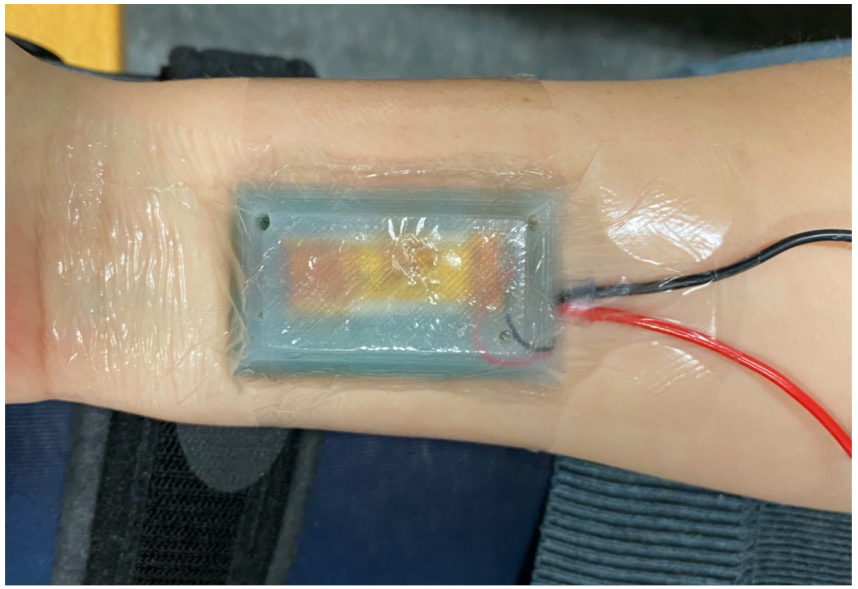
Tegaderm Roll

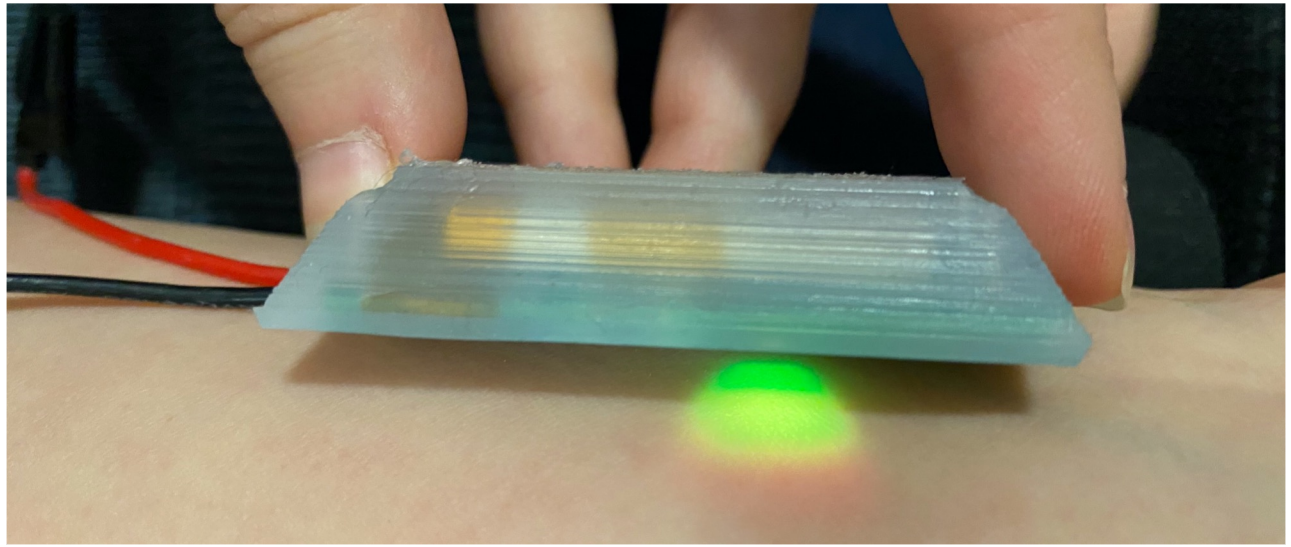
Source: 3M CH

Tegaderm Plaster

Conclusion

- Fully functional PCB
- Mould pleasant to wear
- Improvement potential:
  - PCB size (as in version two)
  - Custom battery
    - Flatter, to allow for more patient comfort and a less protruding patch
  - Further energy savings





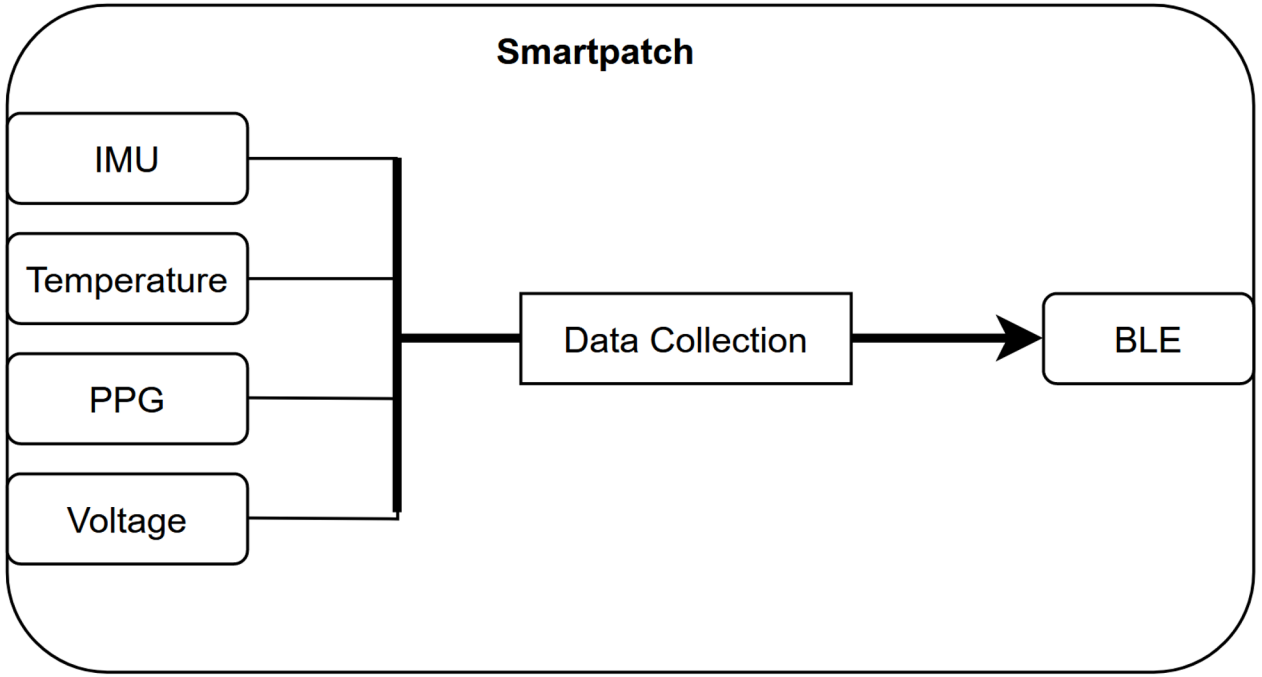
Firmware

Zephyr RTOS

- Open-source RTOS
- Support for Bluetooth Low Energy 5.2
- Power management
- Supports many different CPUs and SoCs
- Large number of available drivers

Firmware Architecture

- Thread to handle transmission of data
- Four threads collecting sensor data
  - IMU: 120 Hz
  - PPG: 100 Hz
  - Temperature: 1 Hz
  - Voltage: 1 Hz

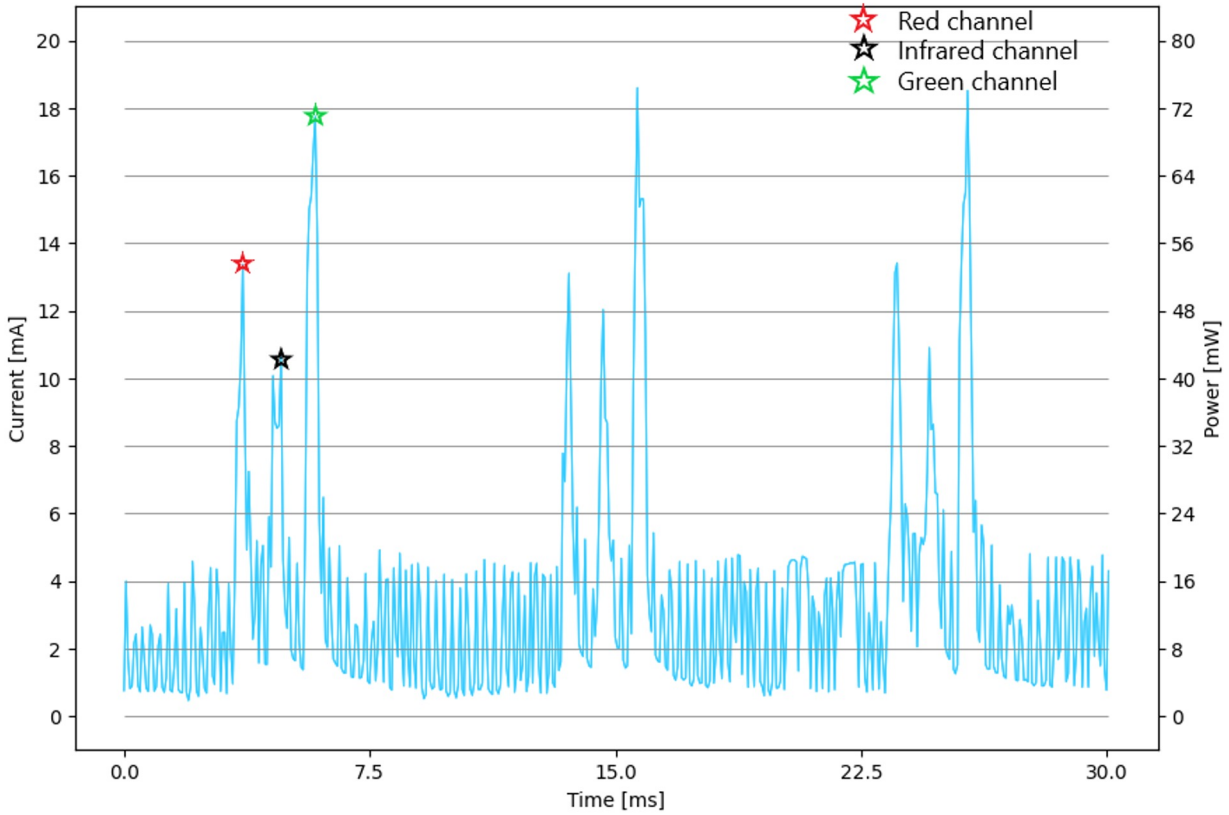


Power and energy

SmartPatch power measured for:

- Board and power supply
- All threads running
- PPG LEDs
- Bluetooth transmissions

Power analyzer
(Keysight N6705C)

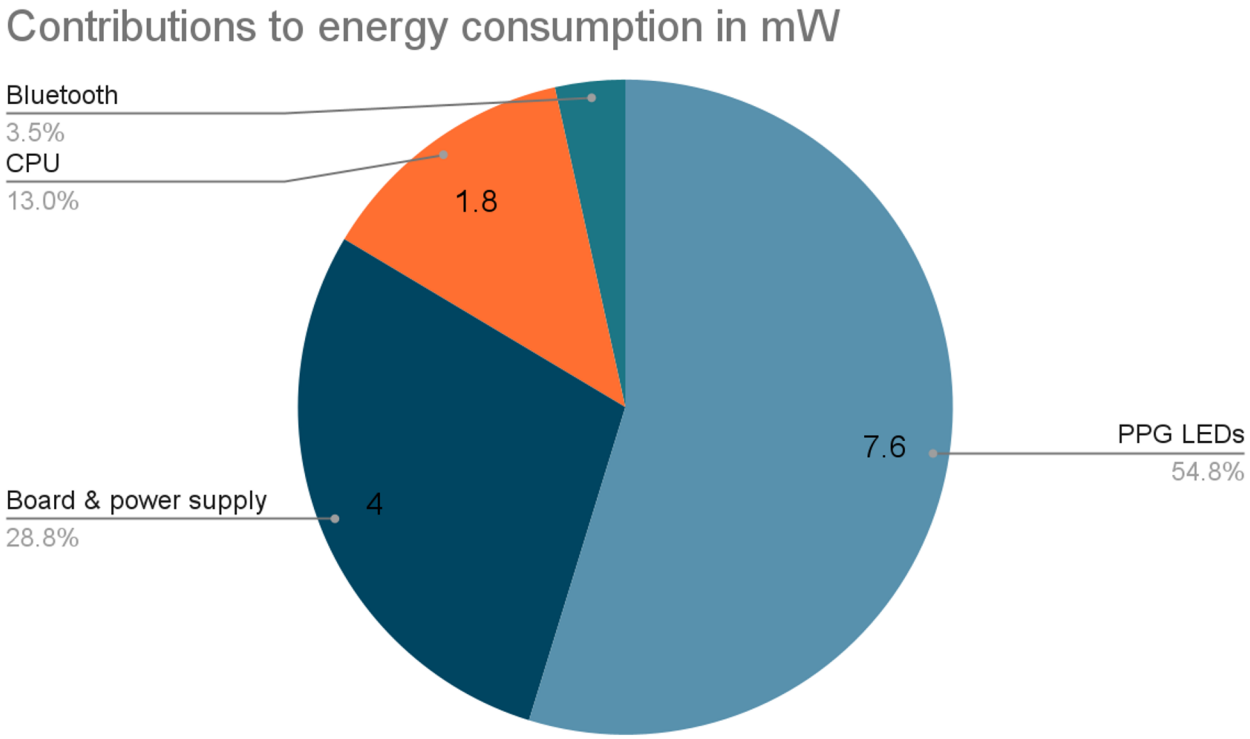


Power trace of a running SmartPatch with active PPG LEDs

Power and energy - Summary

SmartPatch power measured for:

- Board and power supply:
  - 4 mW (1.1 mA at 3.6 V)
- PPG LEDs:
  - 7.6 mW (2.1 mA at 3.6 V)
- CPU activity:
  - 1.8 mW (0.51 mA at 3.6 V)
- Bluetooth transmissions:
  - 0.48 mW (0.13 mA at 3.6 V)



Final consumption: 13.5 mW (3.75mA at 3.6 V)

- Can last for about three days with the current battery (1S, 300 mAh)

Power and energy - CPU utilization

- CPU utilization is about 5%

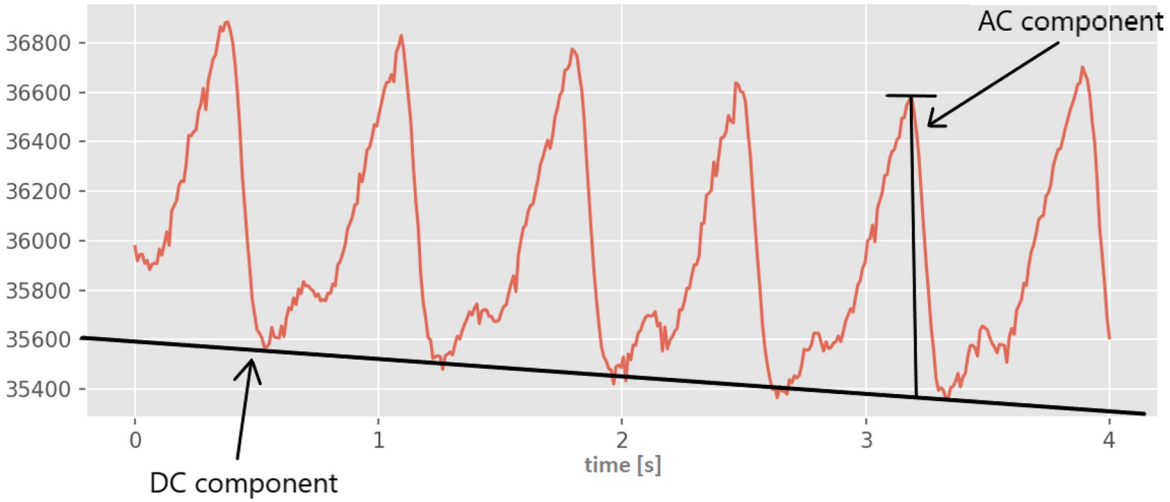
```
[00:02:00.110,748] <inf> thread_analyzer: Thread analyze:
[00:02:00.110,931] <inf> thread_analyzer:  BT RX                : STACK: unused 864 usage 160 / 1024 (15 %); CPU: 0 %
[00:02:00.111,053] <inf> thread_analyzer:  BT TX                : STACK: unused 776 usage 248 / 1024 (24 %); CPU: 0 %
[00:02:00.111,175] <inf> thread_analyzer:  vbatt_id             : STACK: unused 848 usage 176 / 1024 (17 %); CPU: 0 %
[00:02:00.111,297] <inf> thread_analyzer:  thread_analyzer      : STACK: unused 784 usage 240 / 1024 (23 %); CPU: 0 %
[00:02:00.111,358] <inf> thread_analyzer:  pulse_oximetry_id    : STACK: unused 436 usage 588 / 1024 (57 %); CPU: 0 %
[00:02:00.112,335] <inf> thread_analyzer:  onboard_processing_id: STACK: unused 7664 usage 528 / 8192 (6 %); CPU: 1 %
[00:02:00.112,426] <inf> thread_analyzer:  imu_id                : STACK: unused 388 usage 636 / 1024 (62 %); CPU: 1 %
[00:02:00.112,518] <inf> thread_analyzer:  body_temp_id          : STACK: unused 596 usage 428 / 1024 (41 %); CPU: 0 %
[00:02:00.112,976] <inf> thread_analyzer:  ble_id                : STACK: unused 3220 usage 876 / 4096 (21 %); CPU: 0 %
[00:02:00.113,220] <inf> thread_analyzer:  ipm_work_q            : STACK: unused 1748 usage 300 / 2048 (14 %); CPU: 0 %
[00:02:00.113,403] <inf> thread_analyzer:  sysworkq              : STACK: unused 1256 usage 792 / 2048 (38 %); CPU: 0 %
[00:02:00.113,433] <inf> thread_analyzer:  logging               : STACK: unused 72 usage 696 / 768 (90 %); CPU: 0 %
[00:02:00.113,464] <inf> thread_analyzer:  idle 00               : STACK: unused 248 usage 72 / 320 (22 %); CPU: 95 %
[00:02:00.113,677] <inf> thread_analyzer:  main                  : STACK: unused 1604 usage 444 / 2048 (21 %); CPU: 0 %
```

Processing

Processing

- Sort received data and apply conversions
- Heart rate
  - Own implementation (FFT)
  - Heartpy kit (peak detection)
- Blood oxygen levels
  - Own implementation
- Respiratory rate
  - Heartpy kit

Raw PPG signal



Heartpy: shorturl.at/jzPU7

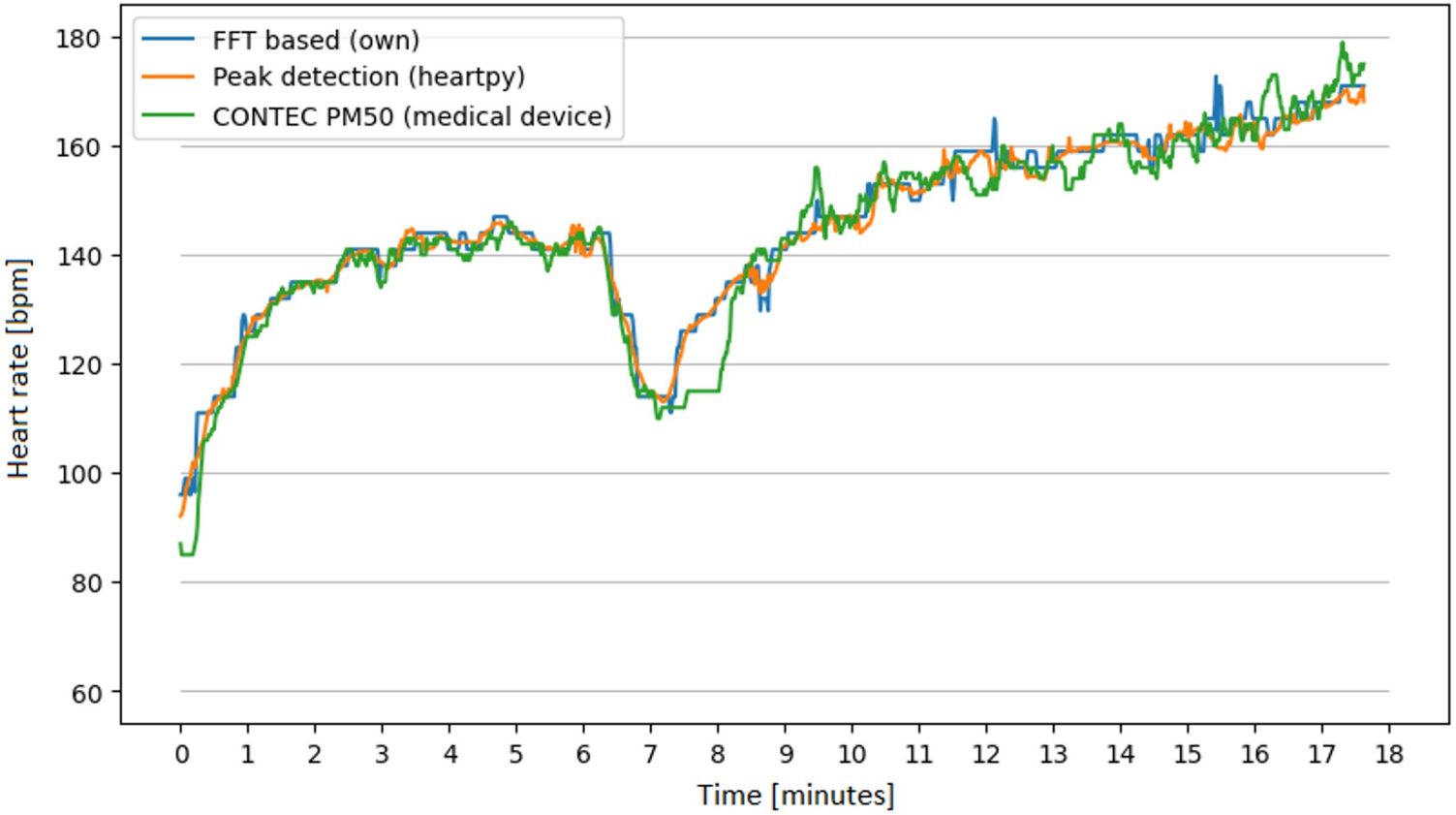
Experimental setup

- Heart rate
  - Comparison against CONTEC PM50 (Gima)
- Blood oxygen levels
  - Comparison against CONTEC PM50 (Gima)
- Respiration rate
  - Reference values by counting breaths

Evaluation - Heart rate

RMS deviations:

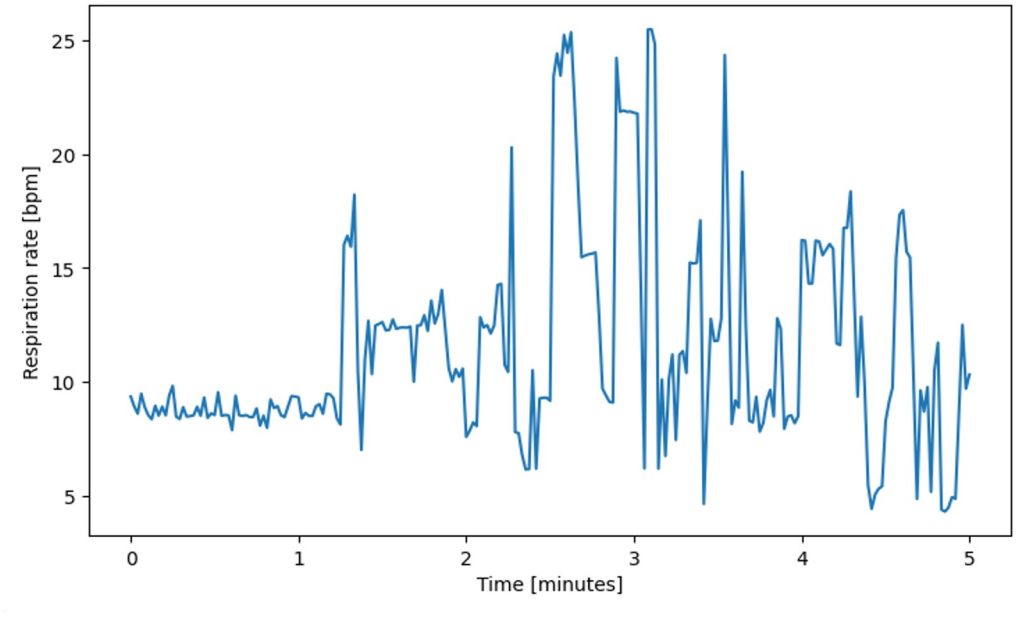
- FFT vs. heartpy:
  - 2.27 bpm (1.6%)
- FFT vs. reference:
  - 4.70 bpm (3.3%)
- Heartpy vs. reference:
  - 4.39 bpm (3.0%)



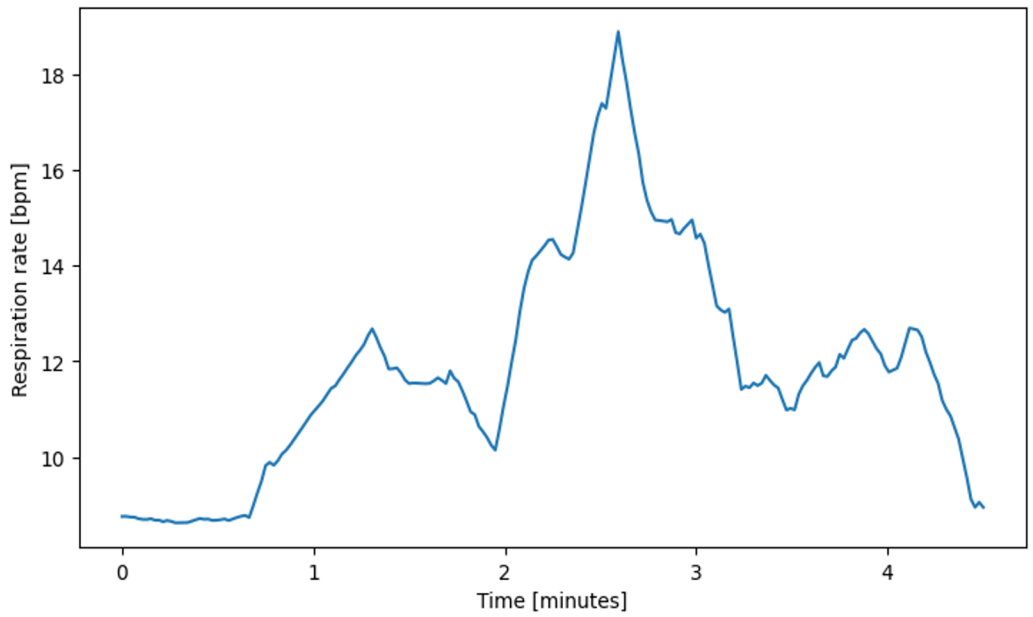
Heart rate of an active test subject taken at the forehead

Evaluation - Respiration rate

- Raw output very noisy
- Correlation visible after averaging



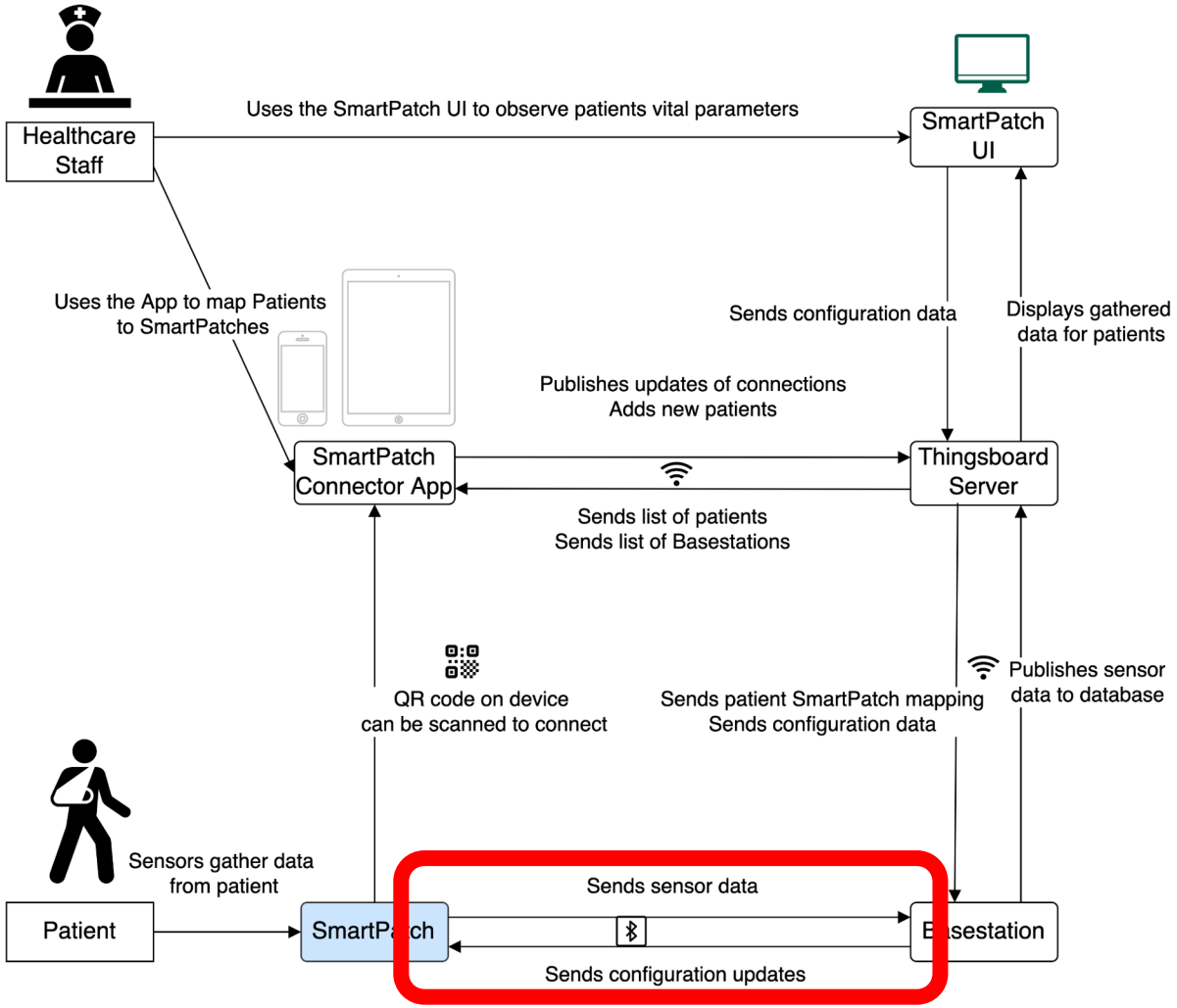
(raw output)



(after averaging)

BLE Connection

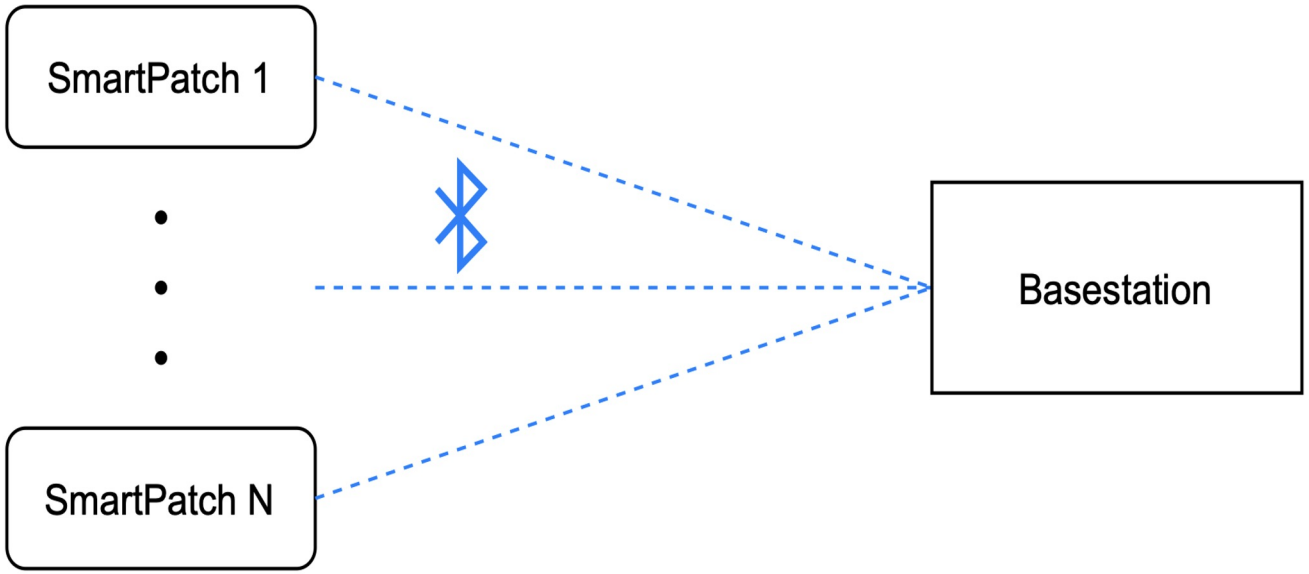
BLE Connection in Context



Schematic Overview of the SmartPatch System

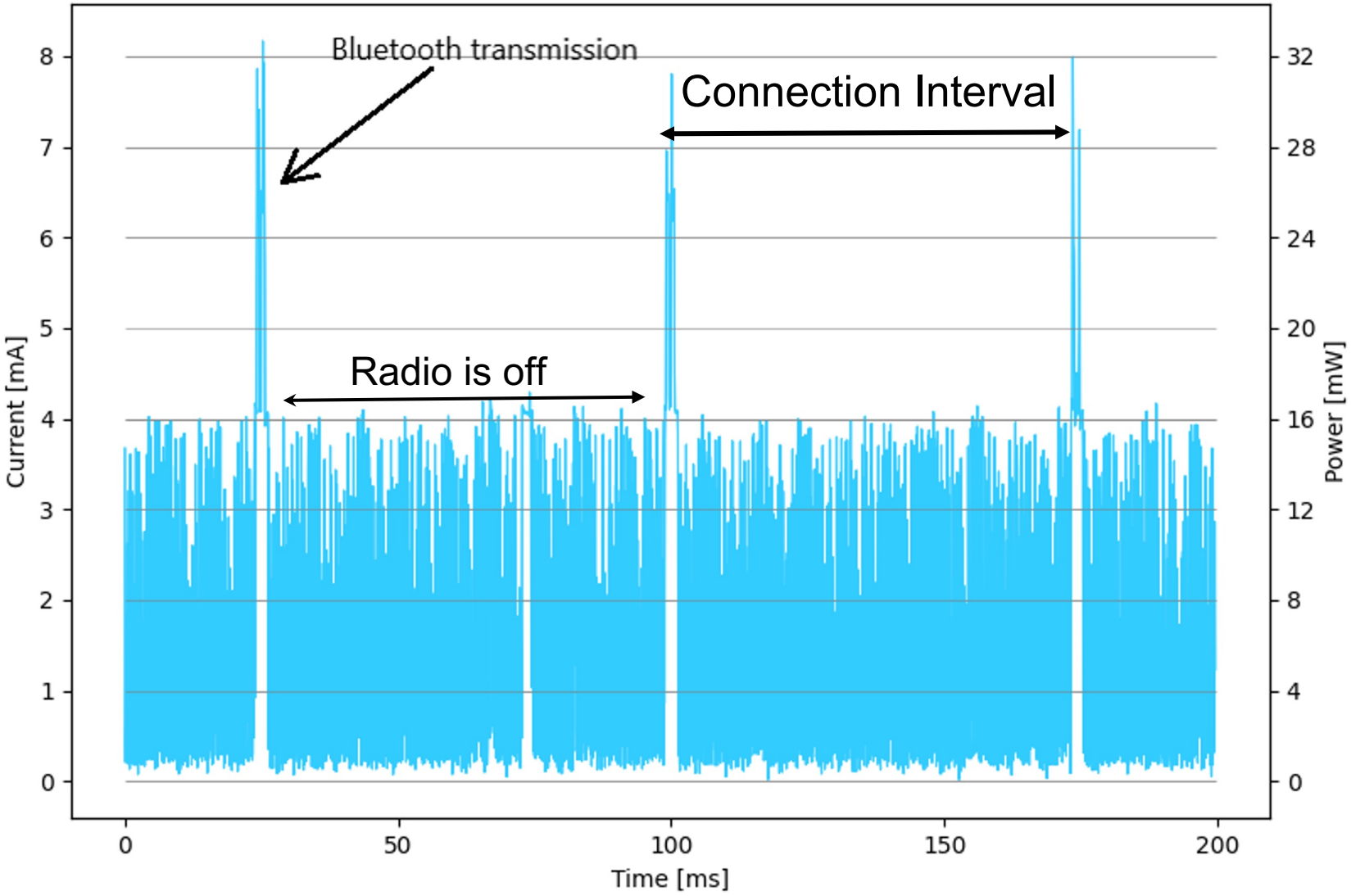
Goals

- Exchange data over Bluetooth Low Energy (BLE)
- Characterise and optimise throughput
- Compatible with indoor localisation
- Connect multiple devices



Connection Interval

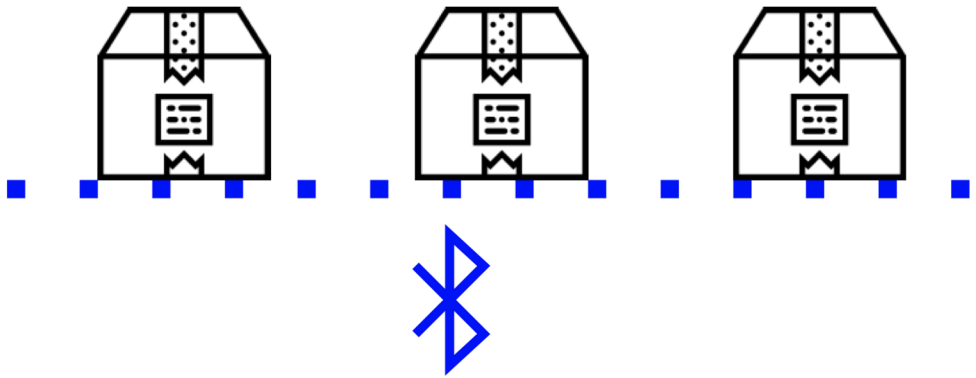
- Time between two connection events
- 7.5 ms - 32 s
- Configurable
- Smartpatch: 70 ms



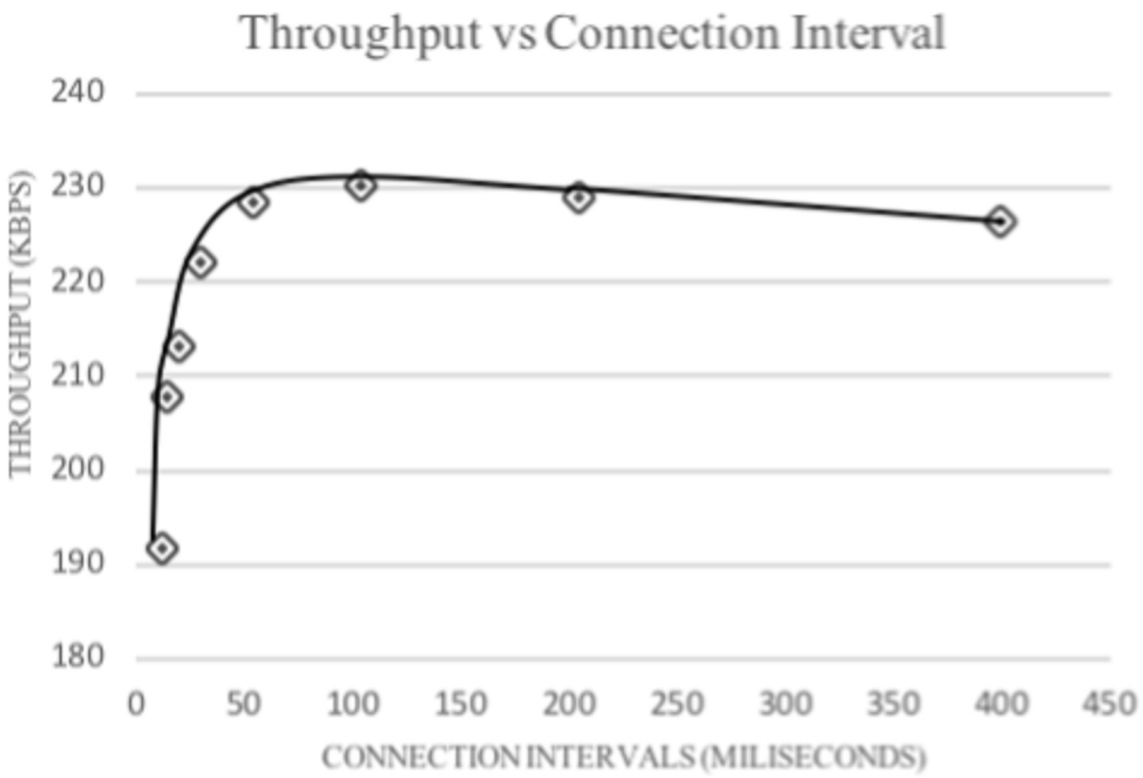
source: A. Zürrer, “Smartpatch project firmware and data processing,” January 2022, unpublished

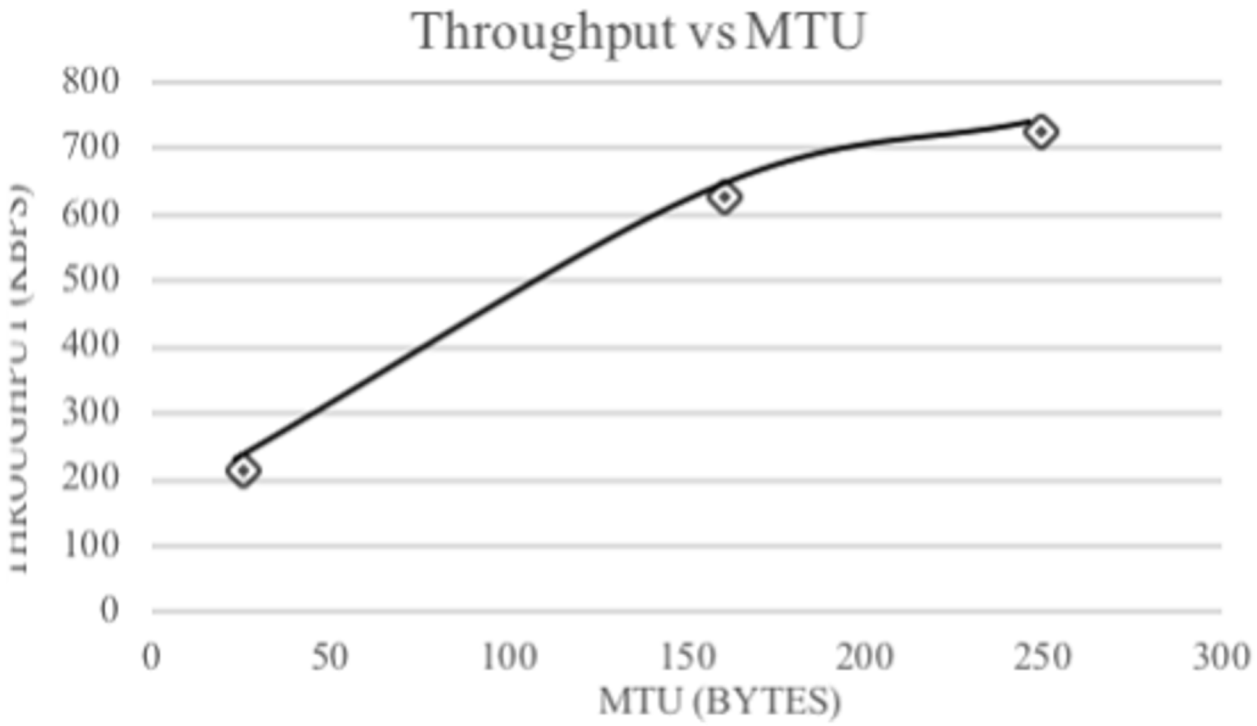
Maximum Transmission Unit (MTU)

- Size of the largest protocol data unit (PDU)
- 27 - 251 bytes
- Configurable
- Data length extension necessary



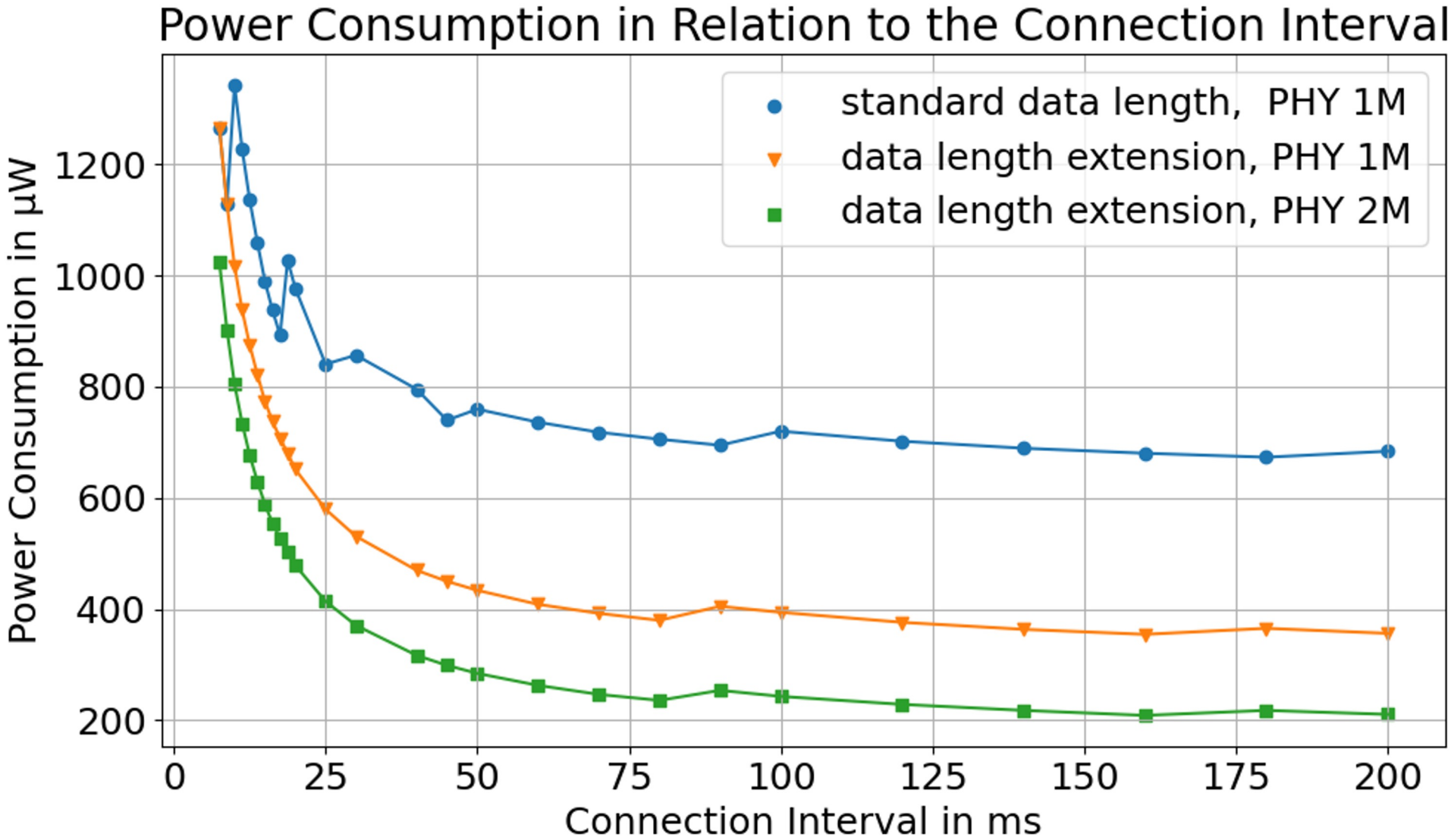
Importance of Connection Interval and MTU





source: M. Marawaha, P. Jha, R. Razdan, J. Dukes, S. Sheehan and E. O Nuallain, "Performance evaluation of bluetooth low energy communication,"

Importance of Connection Interval and DLE



source: Nordic Semiconductors, Online Power Profiler for BLE, https://bit.ly/3qy17ue, settings: chip=nRF5340, voltage=1.8, role=connection(peripheral), TX payload per event adjusted such that TX LL throughput >= 24 kbps.

Components of BLE Connection

SmartPatch

Zephyr™ C

BLE

Basestation

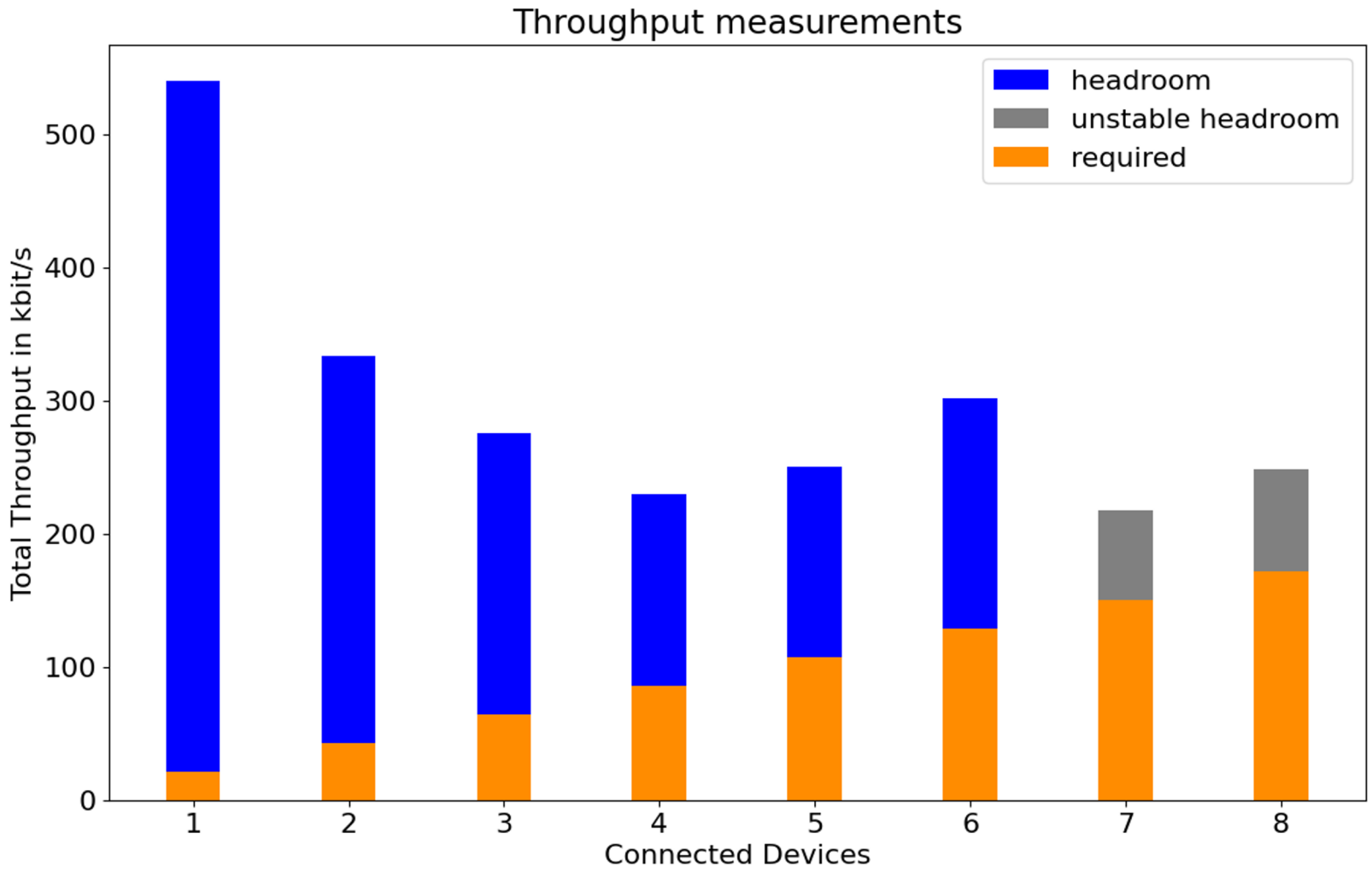
Bleak

Raspberry Pi

sources: zephyrproject.org, .nordicsemi.com/Products/nRF5340, bit.ly/3nvuSKk, bleak.readthedocs.io, raspberrypi.com, python.org

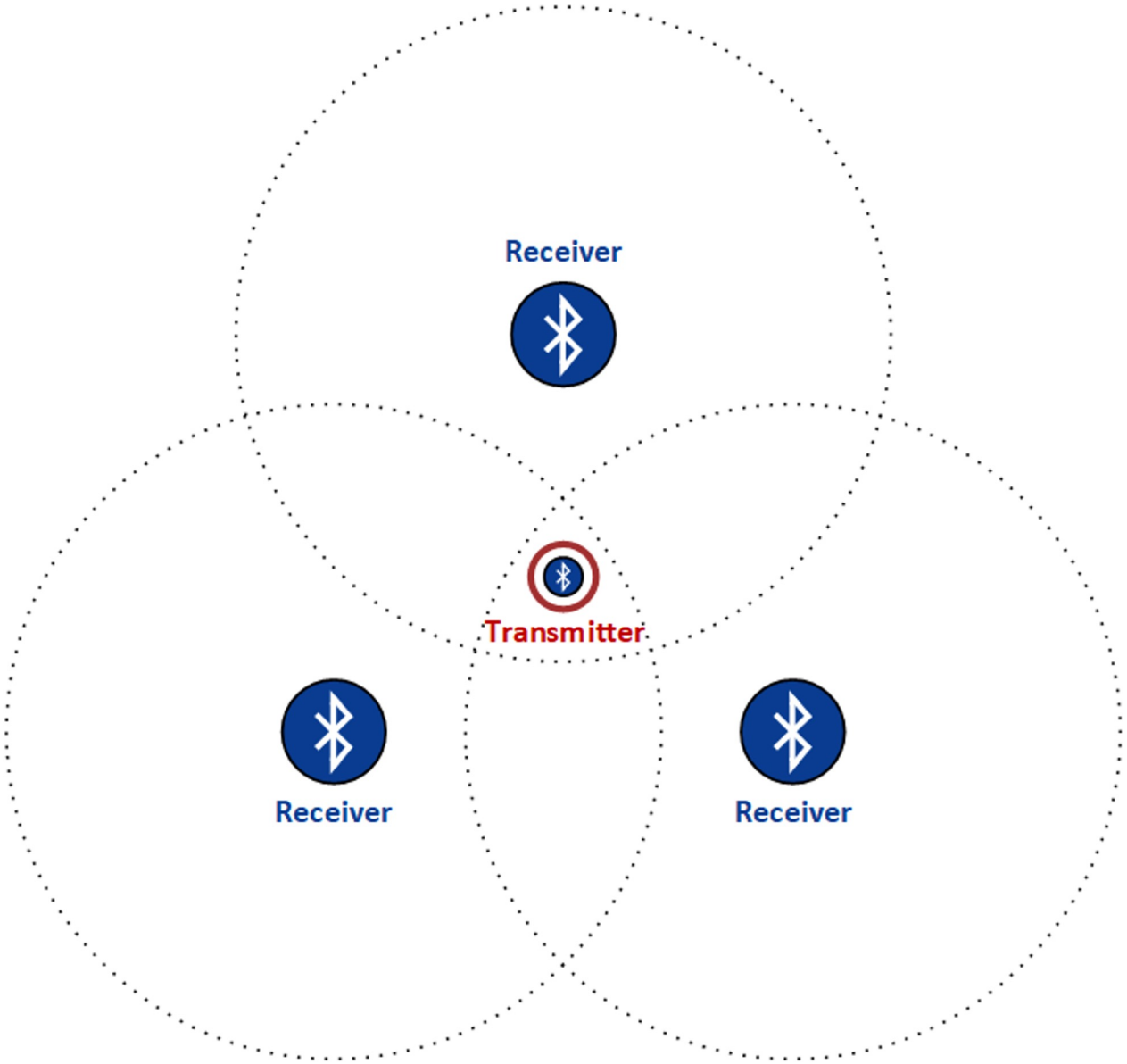
Results

- Throughput is sufficient
- Minimal headroom shown
- Eight devices connectable
- System compatible with indoor localisation

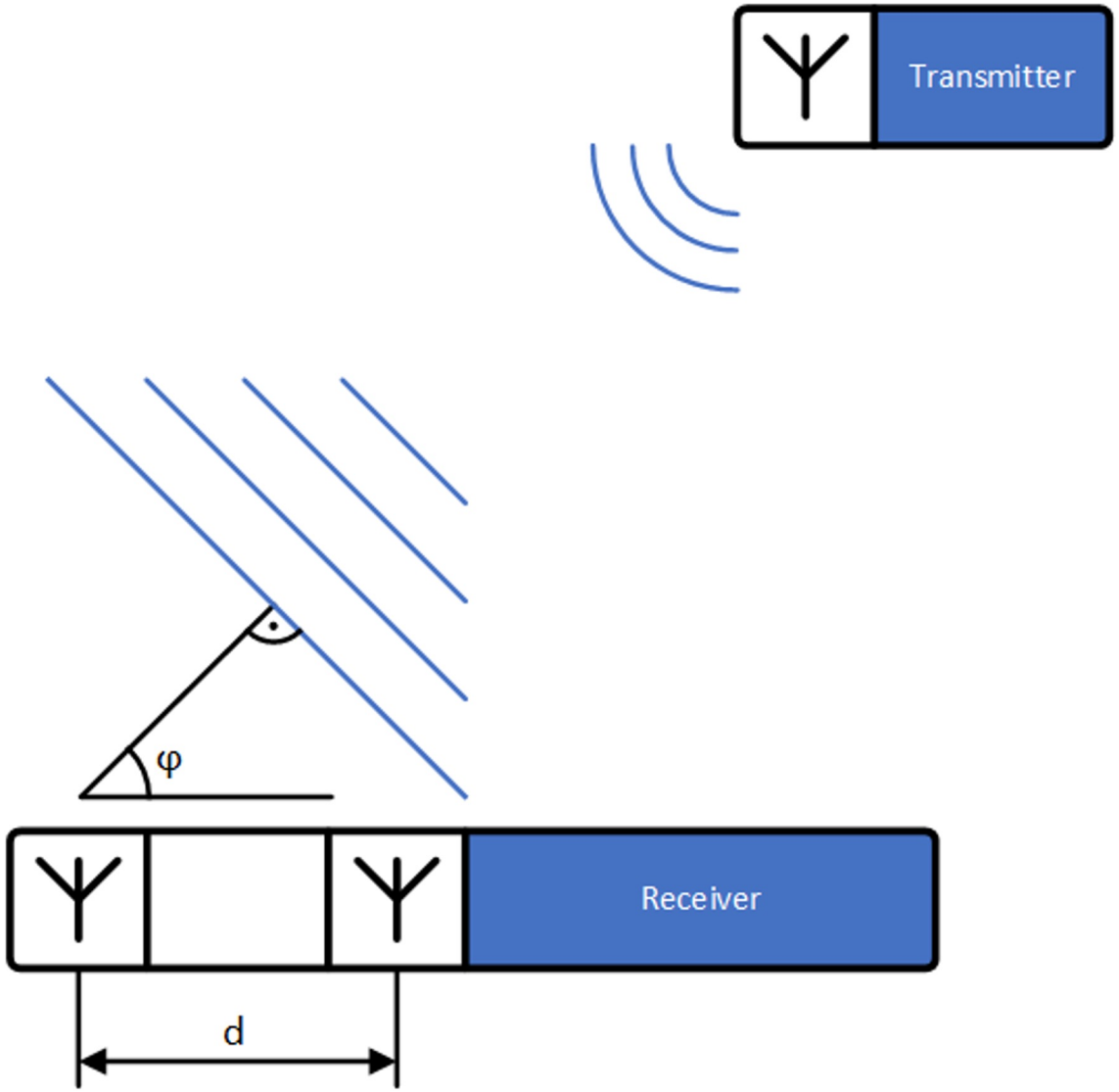


Indoor Localisation

Bluetooth Indoor Localization

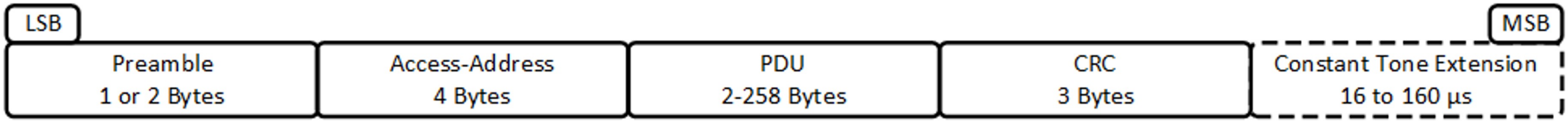


Angle of Arrival (AoA)

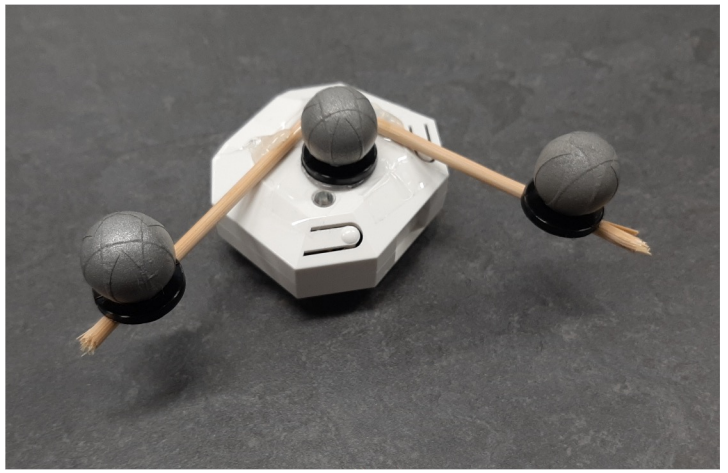


$$\varphi = arccos\left(\frac{\psi\lambda}{2\pi d}\right)$$

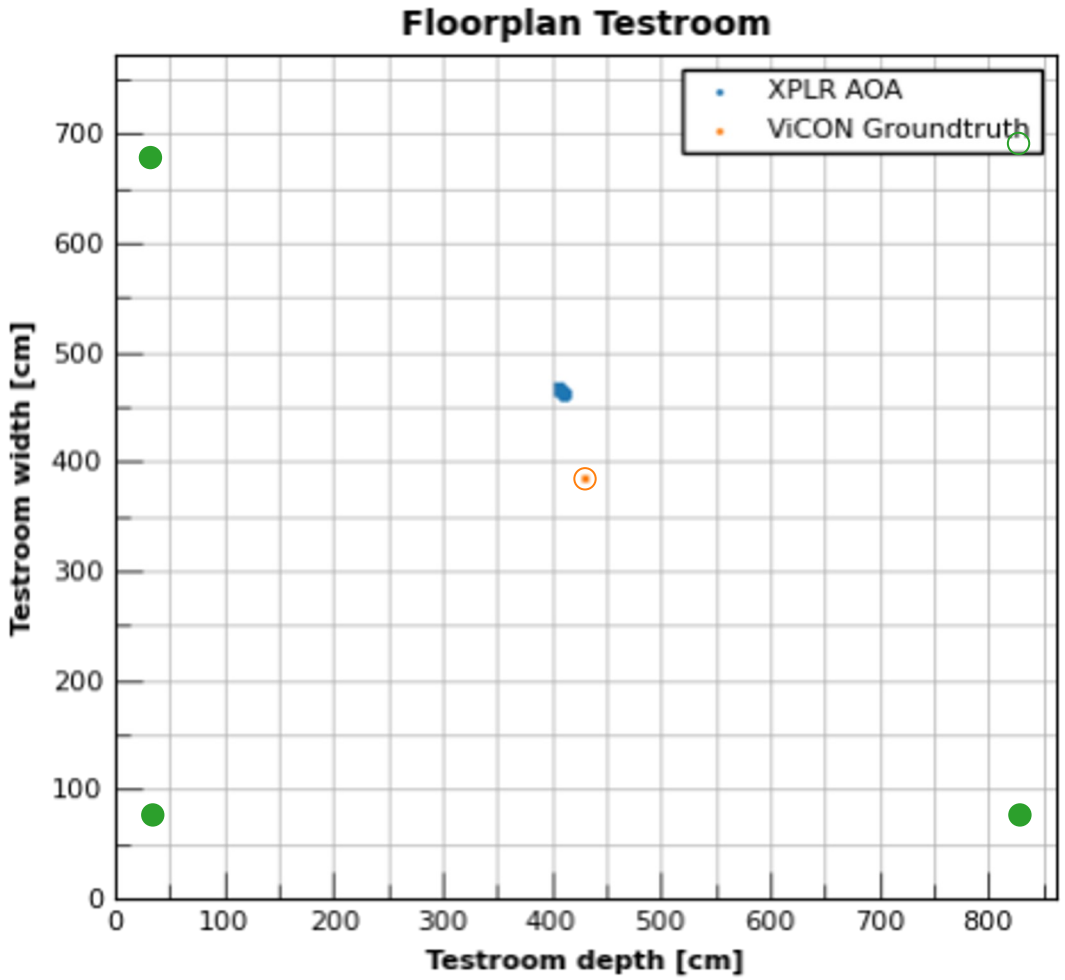
Constant Tone Extension



XPLR-AOA Evaluation Kit



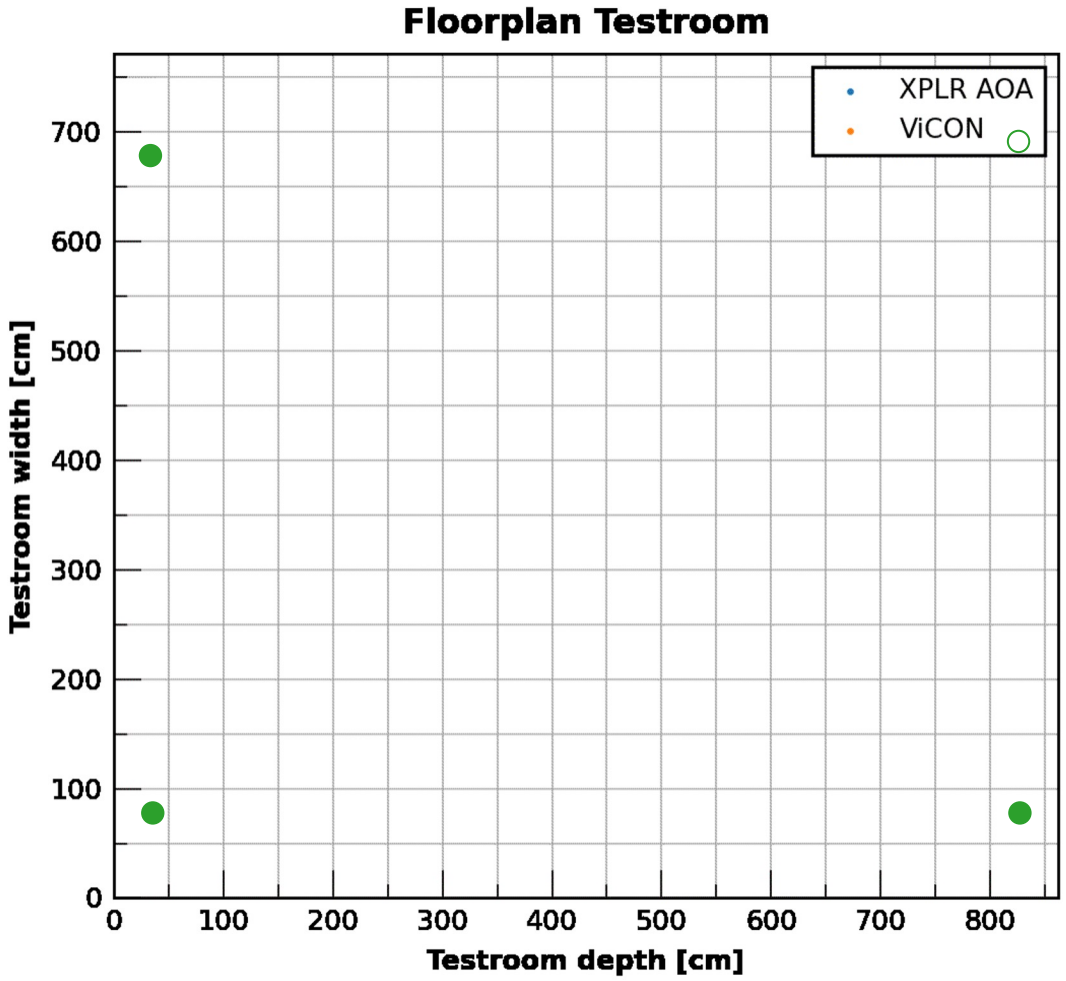
Static Performance of XPLR-AOA



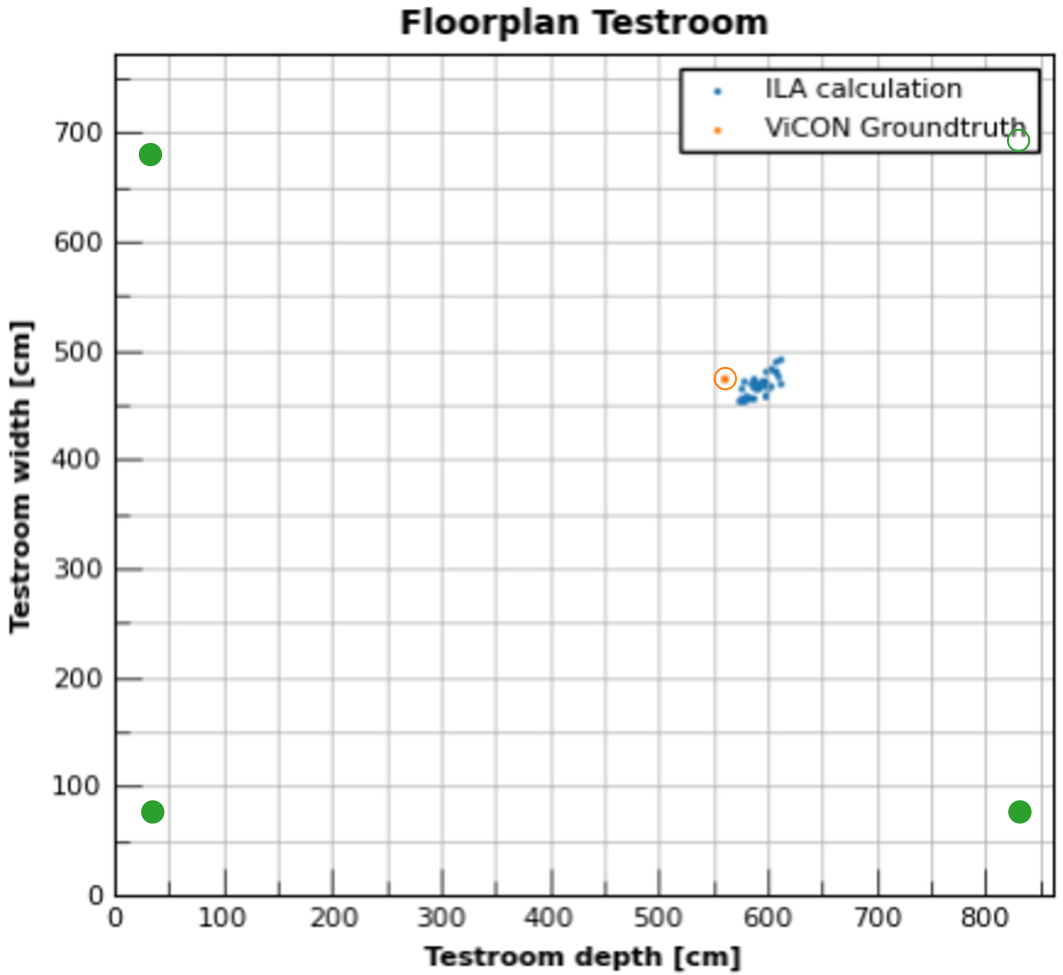
Accuracy / Precision per coordinate

- $\Delta x = 26cm$ / $\sigma_x = 2cm$
- $\Delta y = 83cm$ / $\sigma_y = 2cm$
- $\Delta z = 23cm$ / $\sigma_z = 4cm$

Dynamic Performance of XPLR-AOA



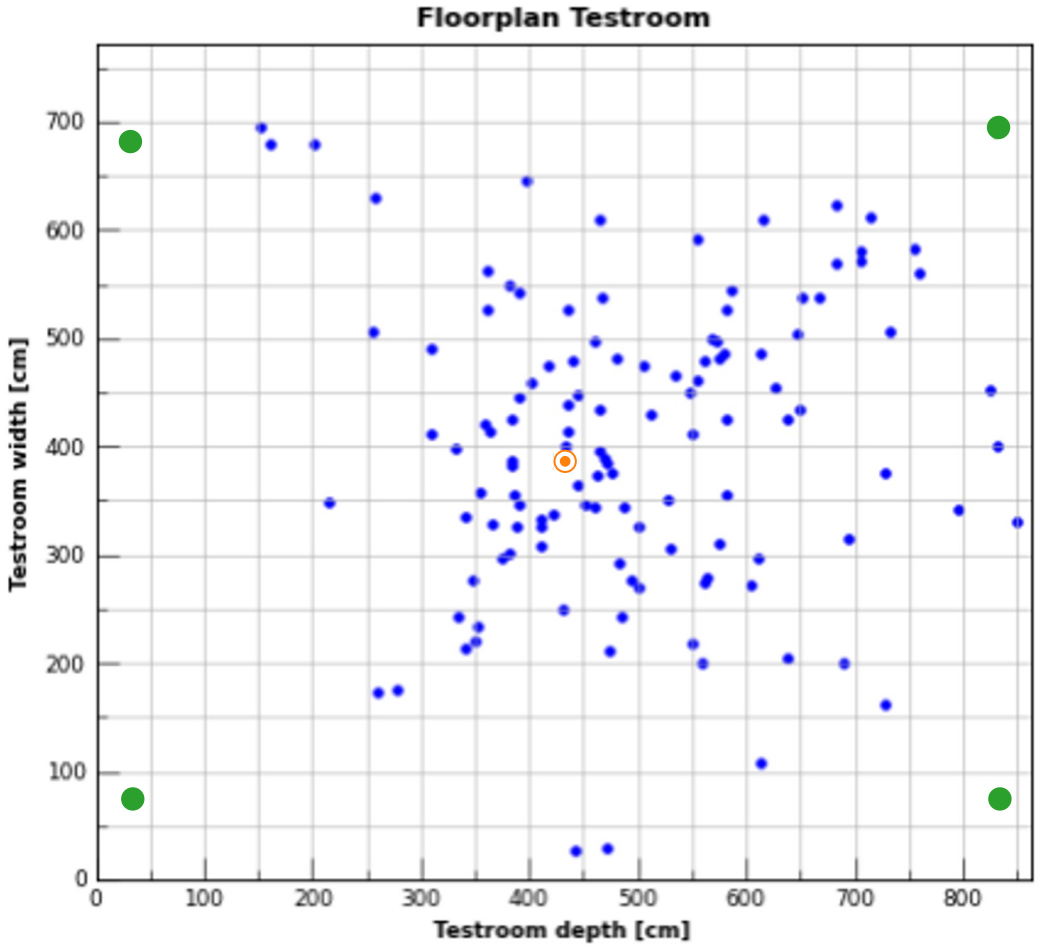
Static Performance of Developed Triangulation



Accuracy / Precision per coordinate

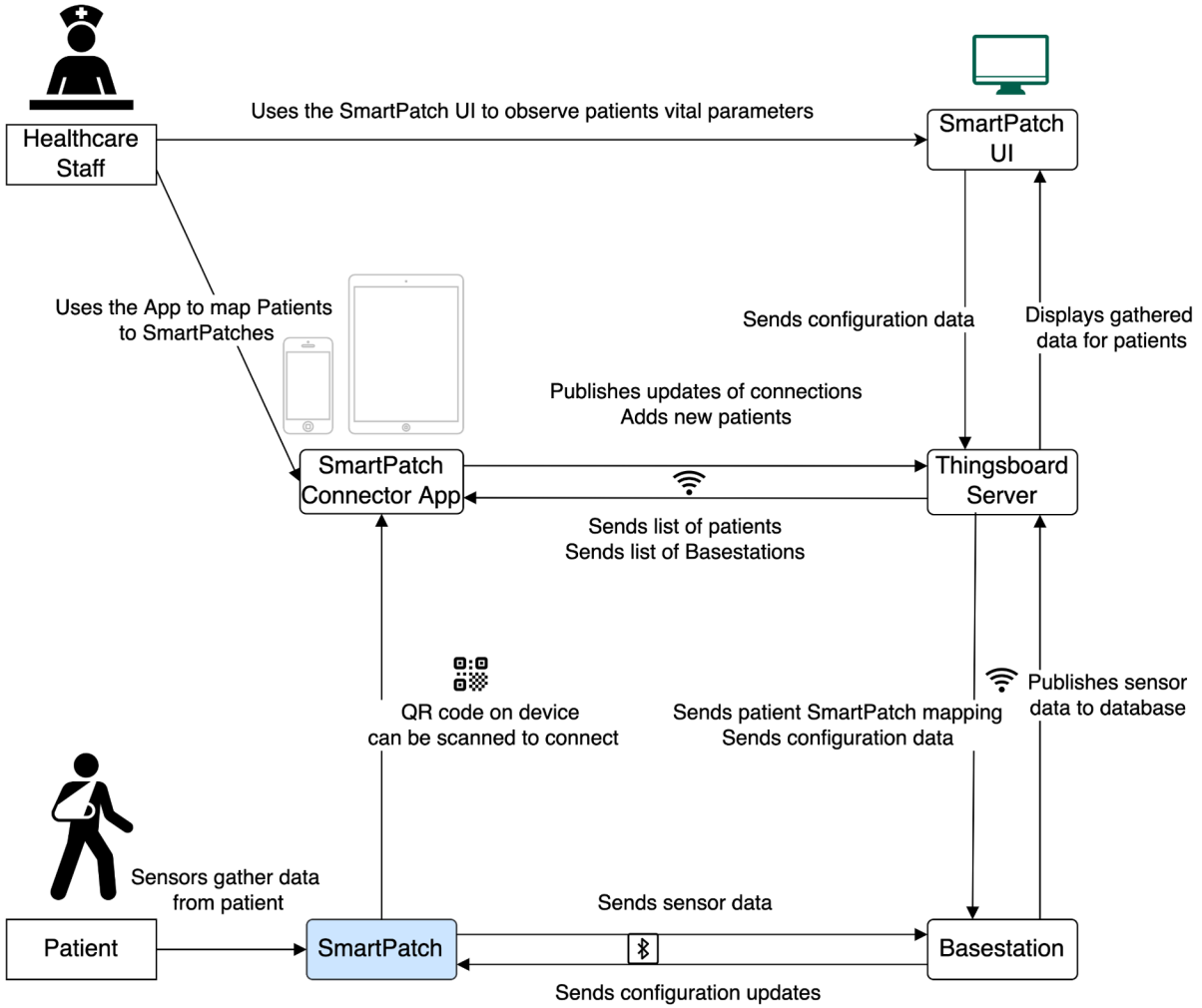
- $\Delta x = 30cm$ / $\sigma_x = 4cm$
- $\Delta y = 8cm$ / $\sigma_y = 4cm$
- $\Delta z = 39cm$ / $\sigma_z = 7cm$

SmartPatch Localization



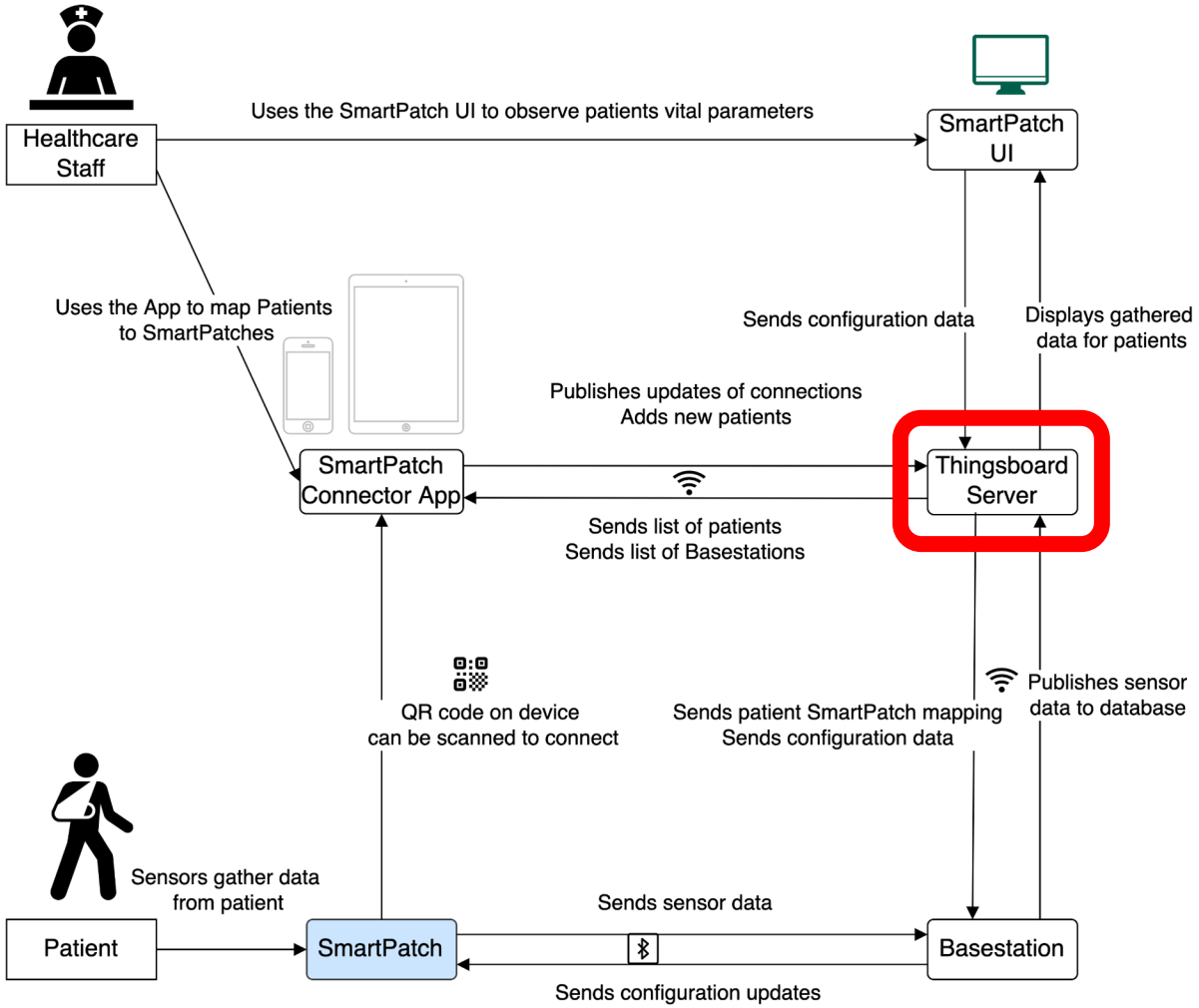
Full System

Concept



Schematic Overview of the SmartPatch System

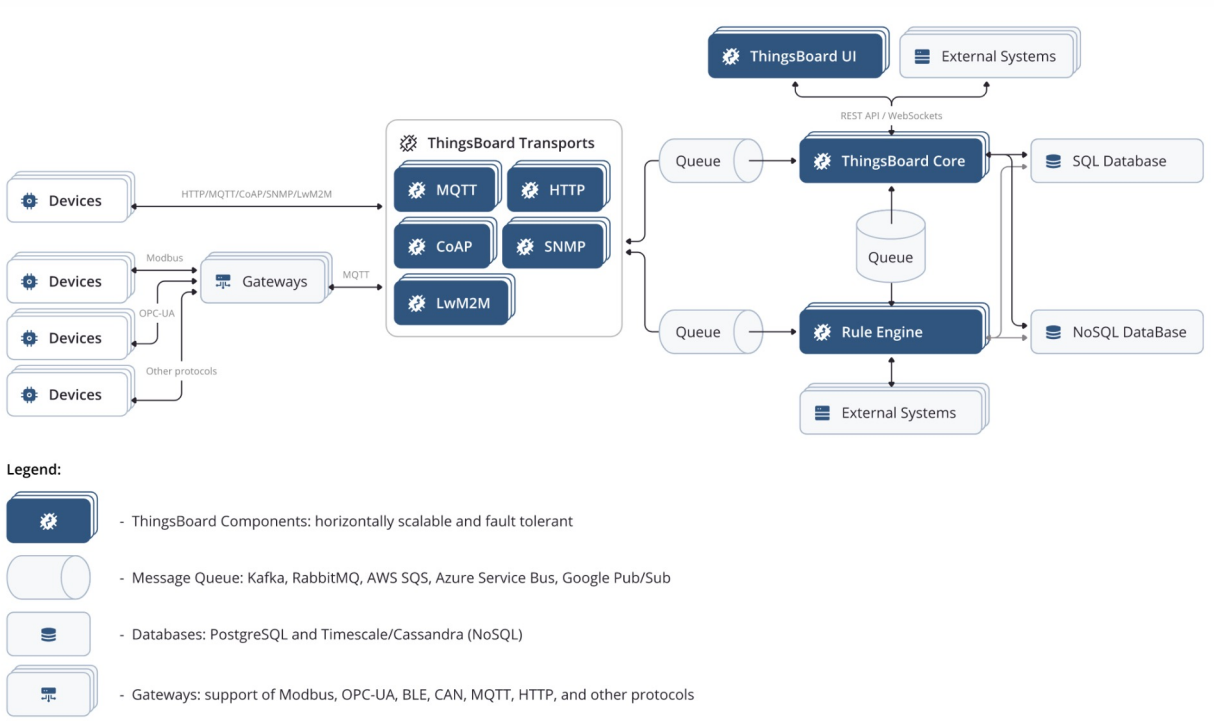
Thingsboard Server



Schematic Overview of the SmartPatch System

Thingsboard Server

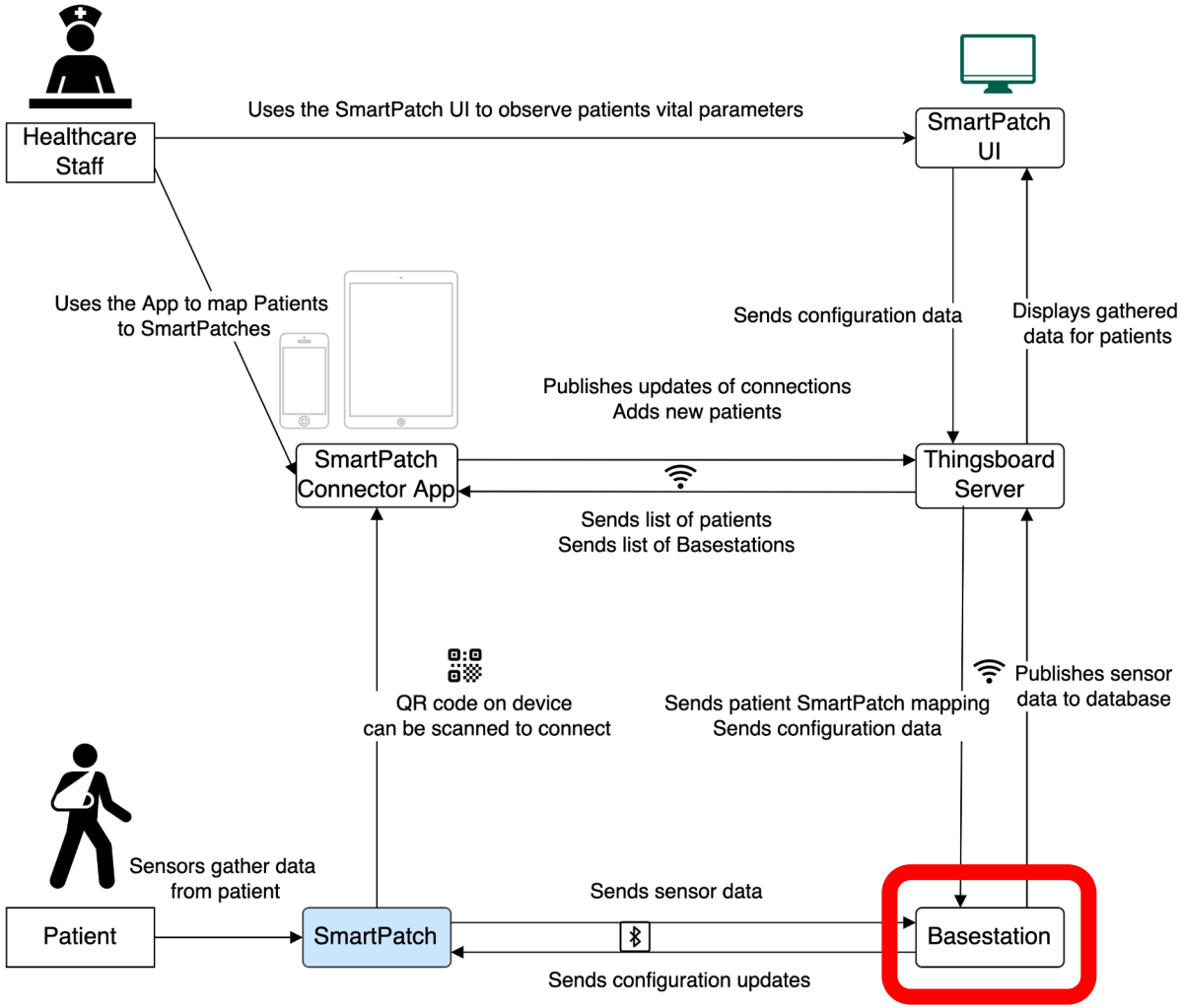
- Open-source IoT platform
- Features
  - Provides an MQTT broker
  - Provides a database
  - Provides an API
  - Provides the possibility to build a UI



Thingsboard Features Overview

Source: https://thingsboard.io/docs/getting-started-guides/what-is-thingsboard/

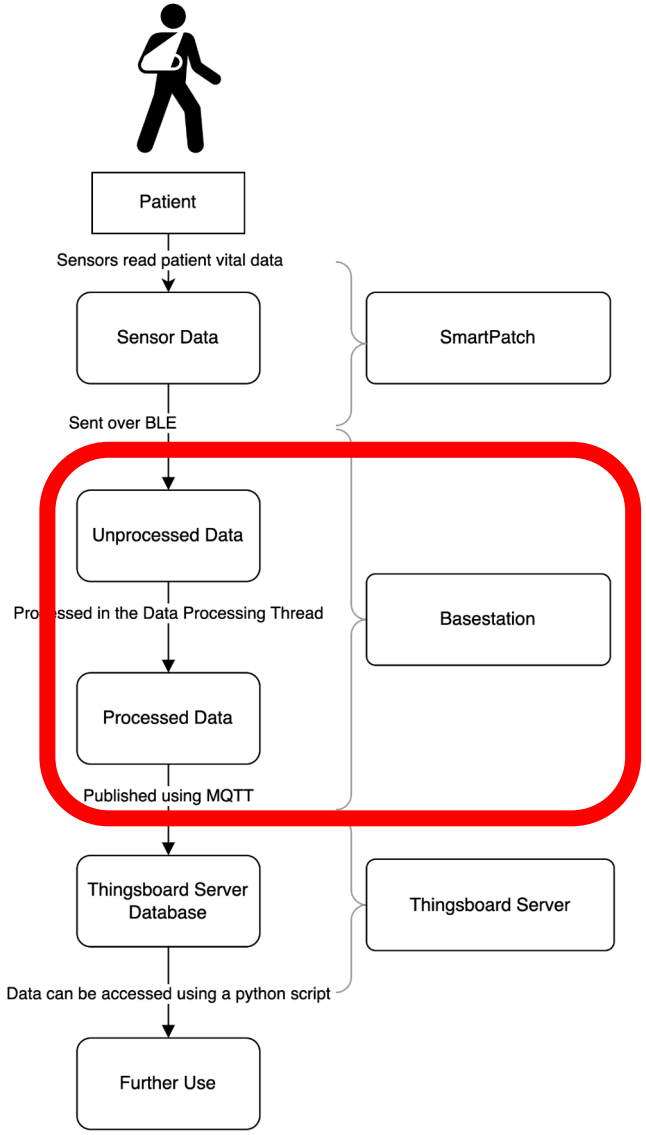
Basestation



Schematic Overview of the SmartPatch System

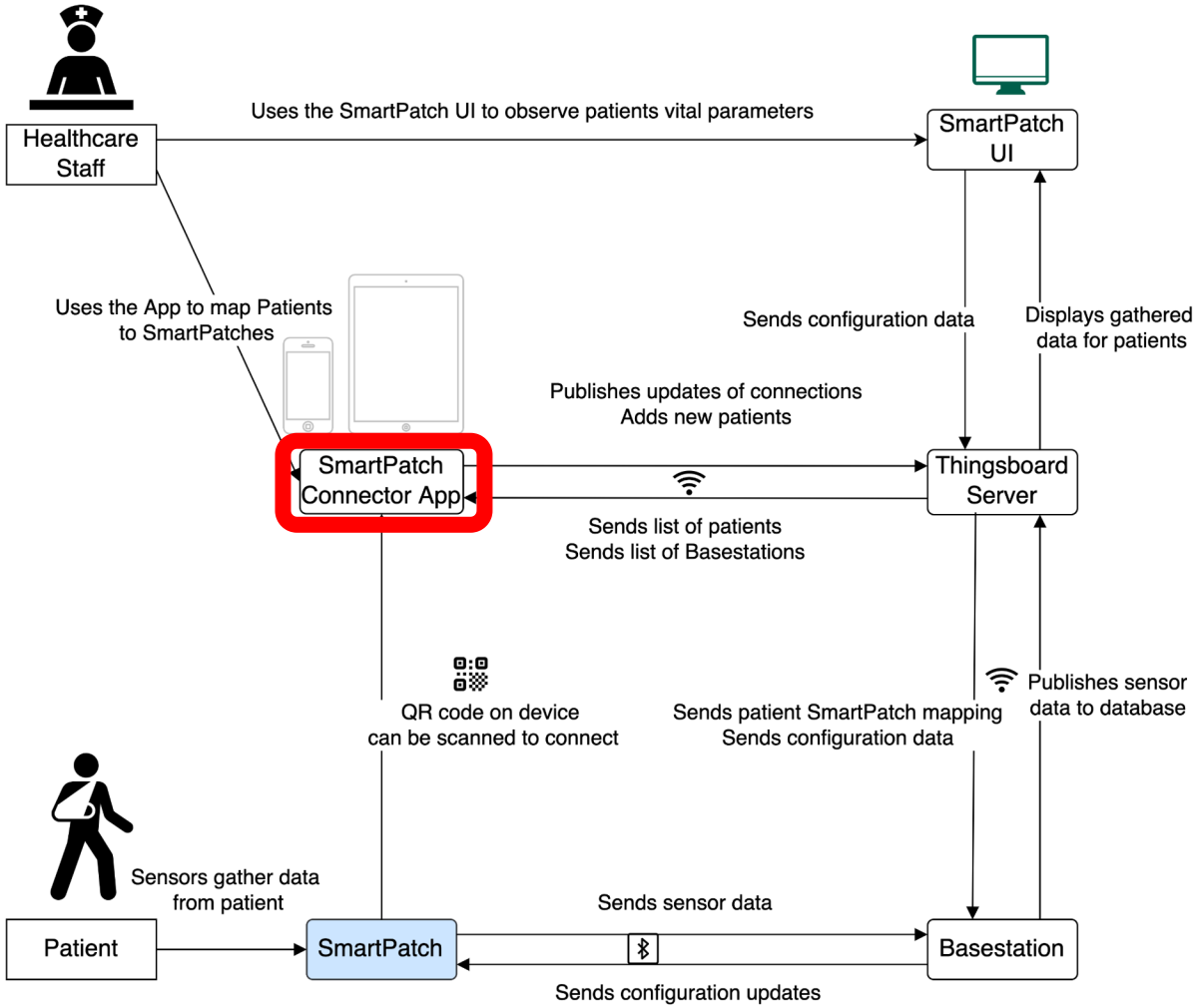
Basestation

- Get SmartPatch data over BLE
- Process raw data
- Publish it to Thingsboard server using MQTT
- Read updates from SmartPatch Connector App



System Data Pipeline

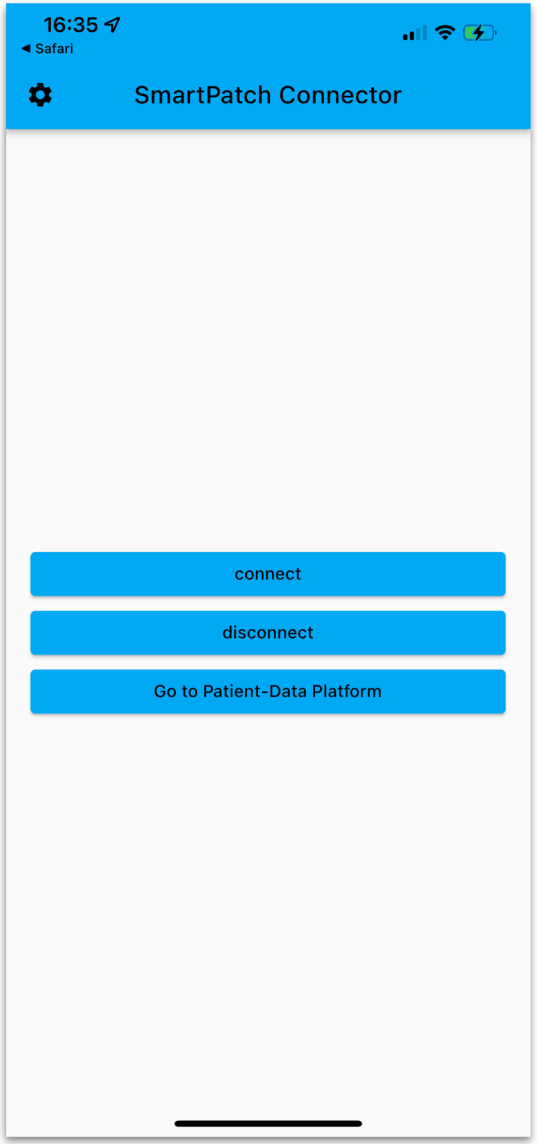
SmartPatch Connector App



Schematic Overview of the SmartPatch System

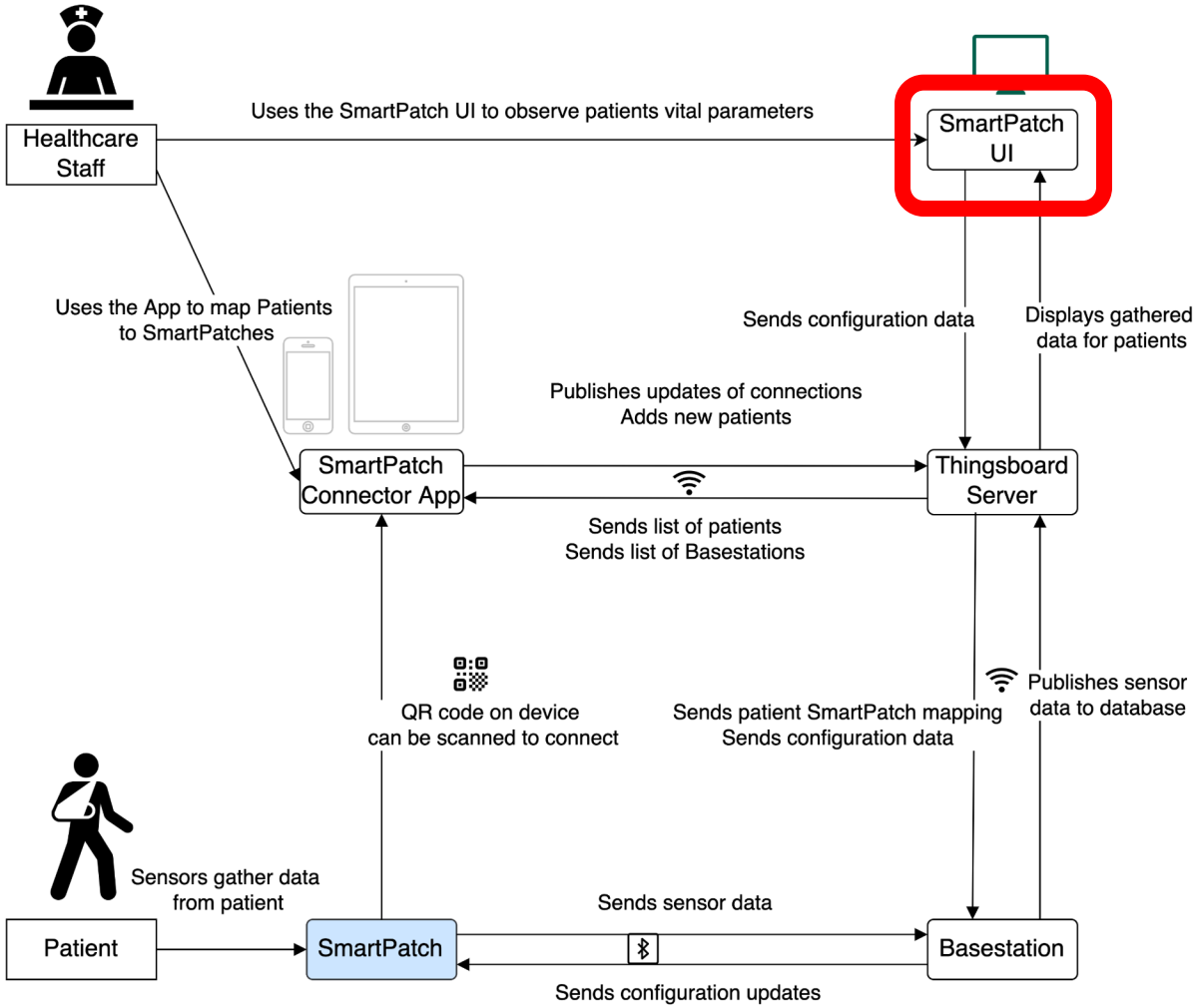
SmartPatch Connector App

- Map a patient to a SmartPatch
- Disconnect a patient from a SmartPatch
- Add a new patient to the database
- Access the SmartPatch UI



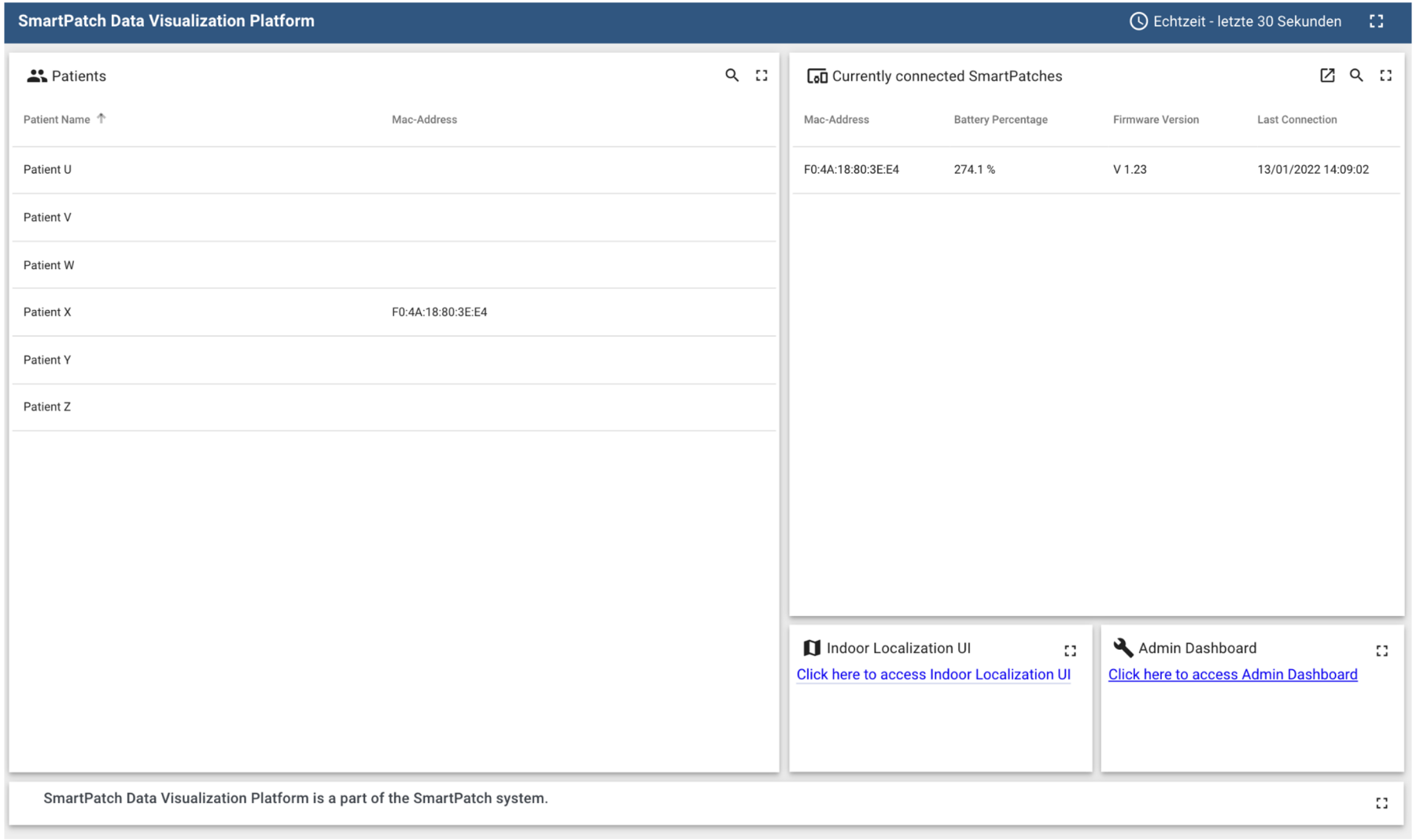
Connector App Home Page

SmartPatch UI



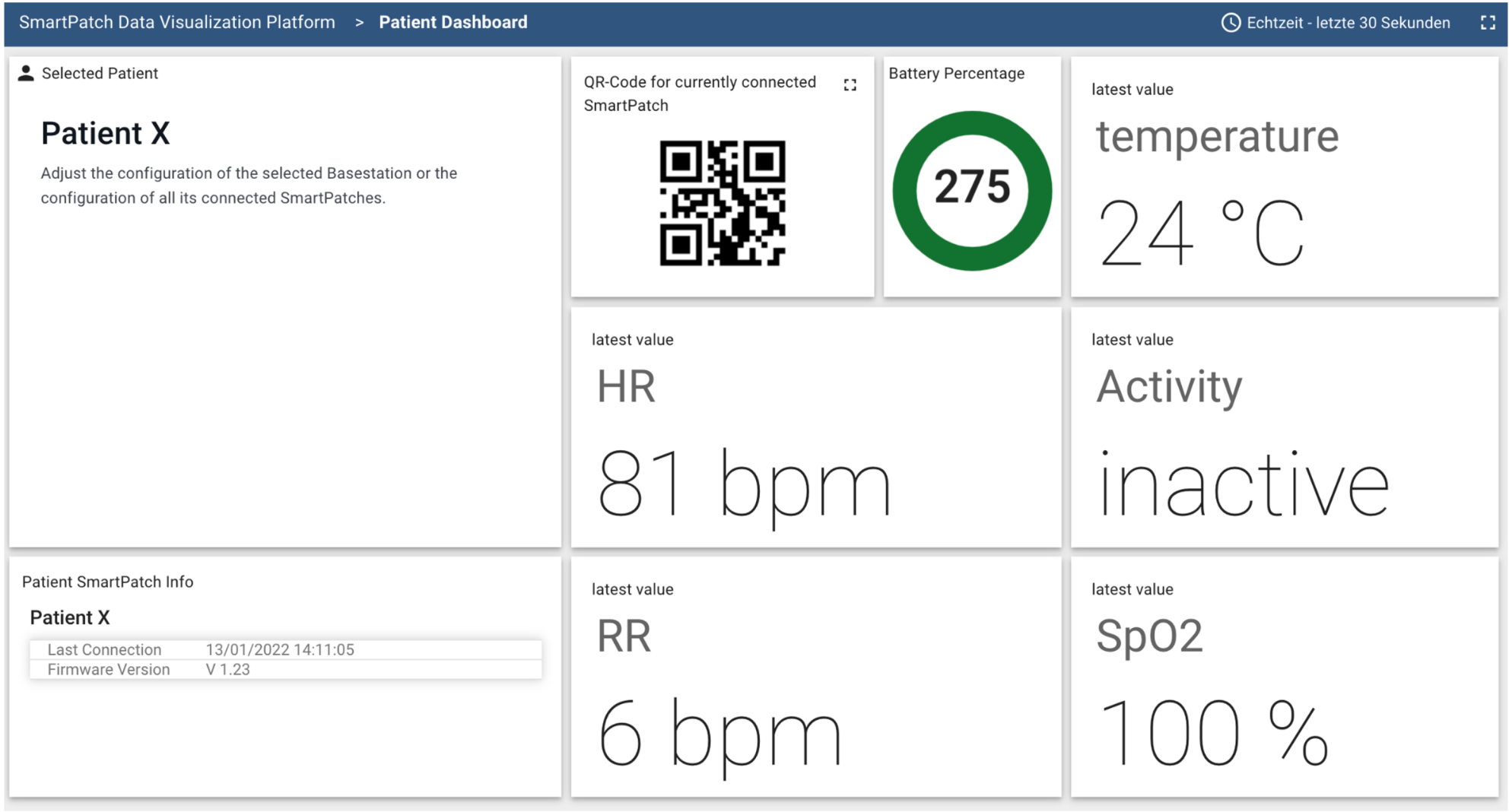
Schematic Overview of the SmartPatch System

SmartPatch UI



SmartPatch UI Home Page

SmartPatch UI



SmartPatch UI Patient Data Page

SmartPatch Project Achievements

- All goals met ✓
- System works → can be seen after presentation
- Test were successful with:
  - multiple Basestations
  - up to 6 SmartPatches at once
- Future work:
  - Testing and deployment in hospital environment

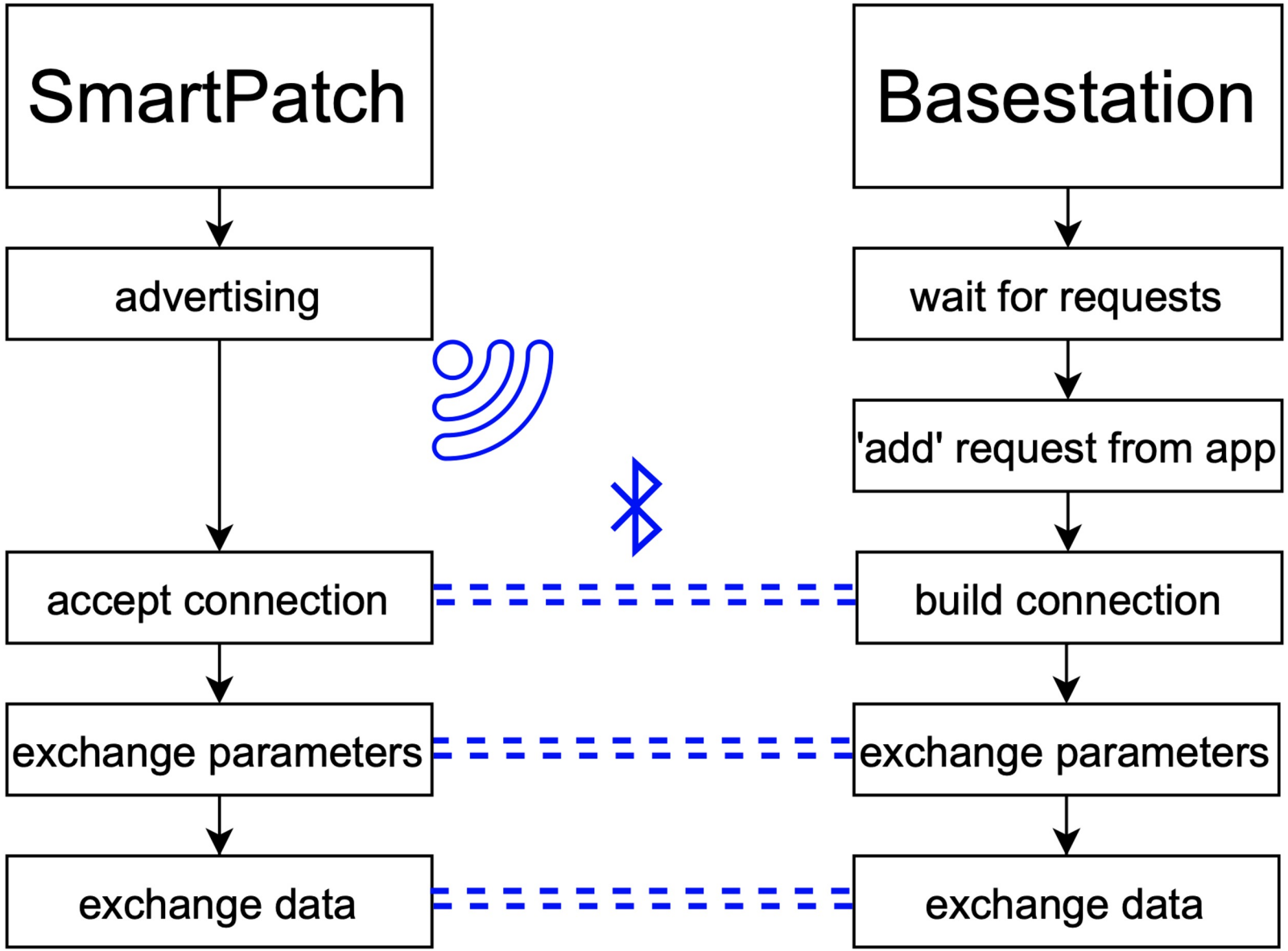
SmartPatch Logo

Source: https://smartpatch.pbl.ee.ethz.ch/site/

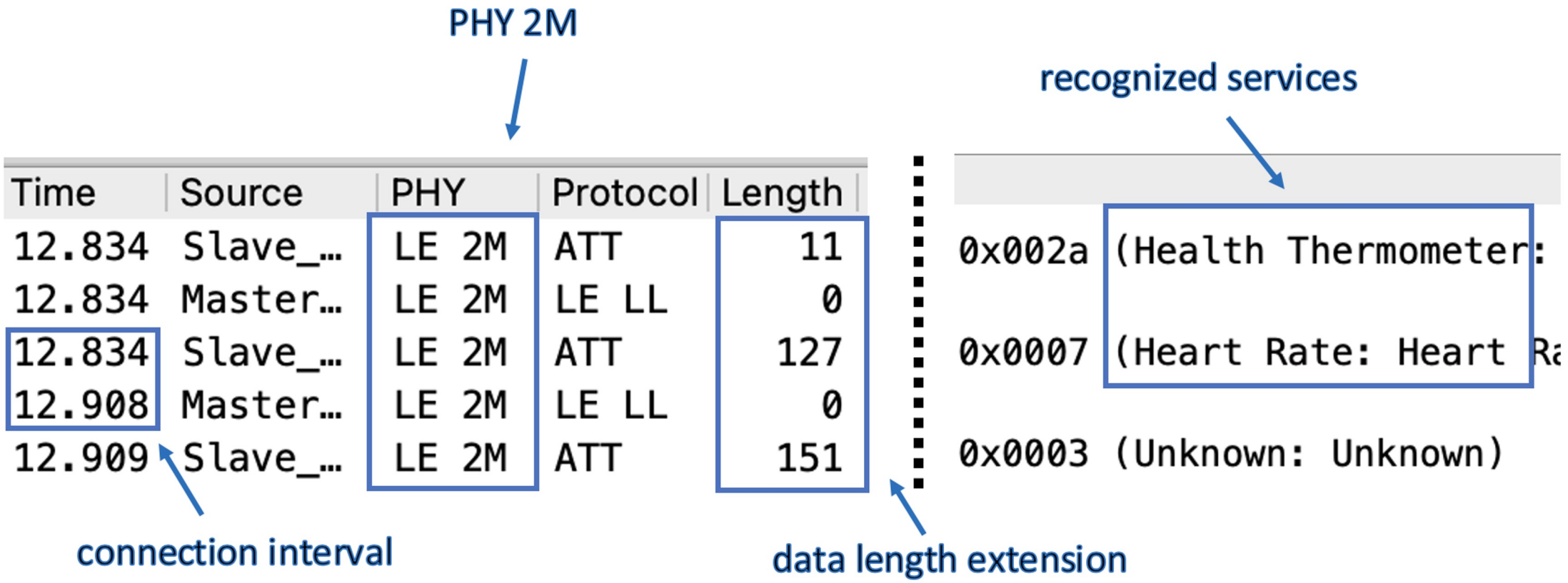
Thank You For Your Attention!

Additional material

Building BLE Connection



Results


PHY 2M
recognized services
Time
Source
PHY
Protocol
Length
12.834 Slave_… LE 2M ATT 11
12.834 Master… LE 2M LE LL 0
12.834 Slave_… LE 2M ATT 127
12.908 Master… LE 2M LE LL 0
12.909 Slave_… LE 2M ATT 151
0x002a (Health Thermometer:
0x0007 (Heart Rate: Heart Ra
0x0003 (Unknown: Unknown)
connection interval
data length extension

Advertisement