Development of a Low-Cost, Low-Power, Photoacoustic Based Nitrogen Dioxide (NO2) Sensor Network for Air Pollution Measurements

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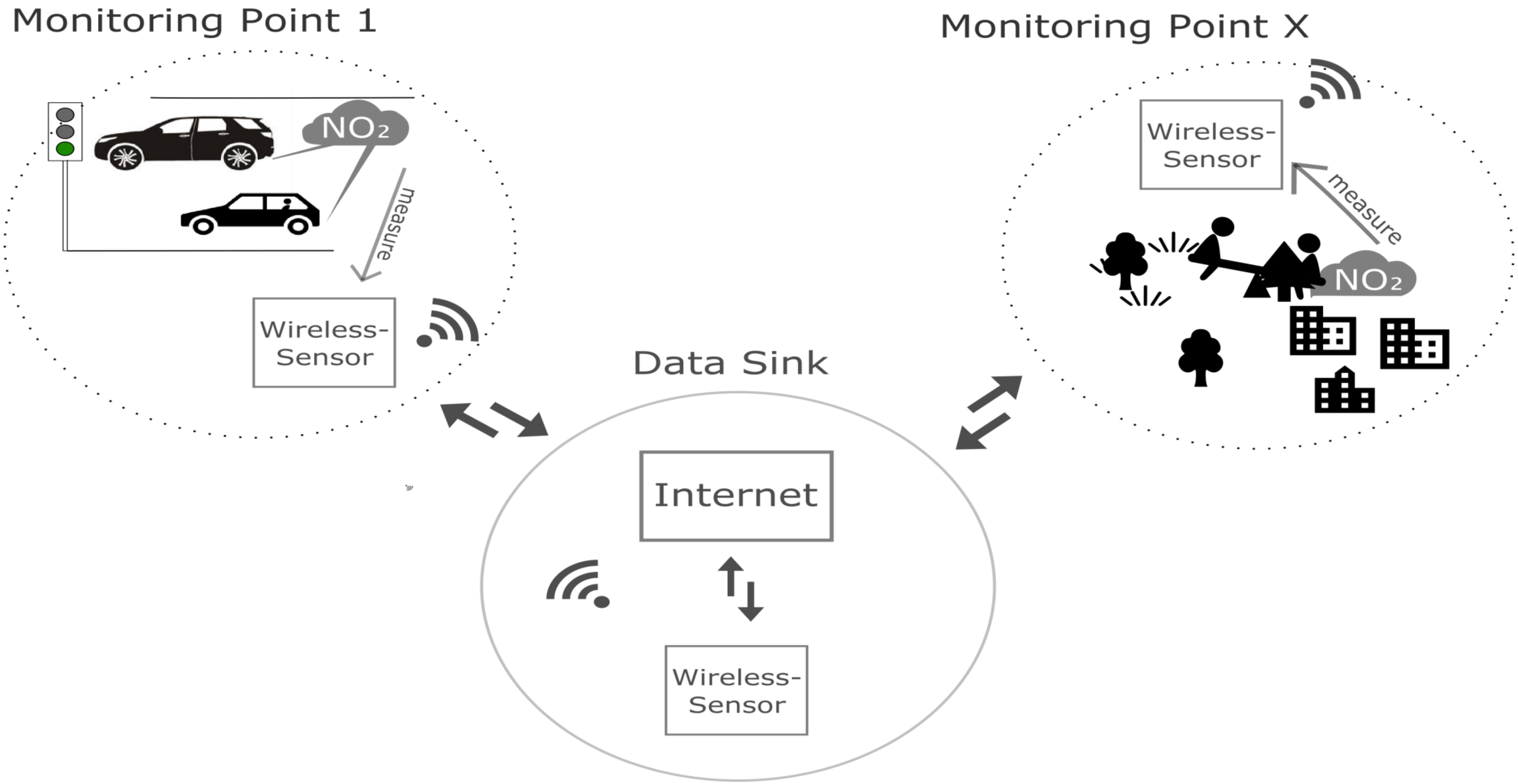
Motivation


Monitoring Point 1
NO2
measure
Wireless-
Sensor
Monitoring Point X
Wireless-
Sensor
measure
NO2
Data Sink
Internet
Wireless-
Sensor

Photoacoustic Effect

- Sensor principle based on the Photoacoustic Effect

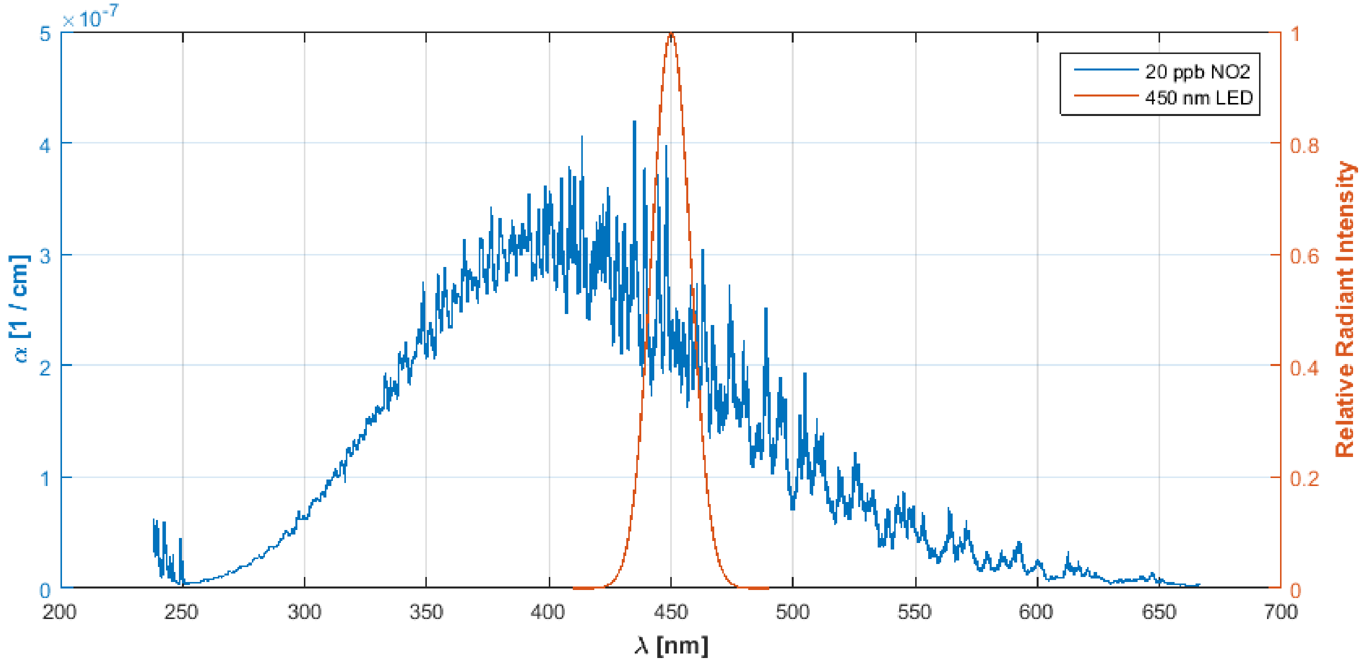
- Usage of photoacoustic cells
- $S(\lambda) = F \cdot \alpha(\lambda) \cdot P_0(\lambda)$ [1]

S ... *photoacoustic signal*
F ... *Properties of the applied environment (cell constant)*
α ... *absorption coeffficent of the gas*
P_0 ... *optical power of the light source*

[1] Christoph Haisch. "Photoacoustic spectroscopy for analytical measurements.
"In: Measurement Science and Technology 23 (1 2012). doi: 10.1088/0957-0233/23/1/012001.

Photoacoustic Spectroscopy

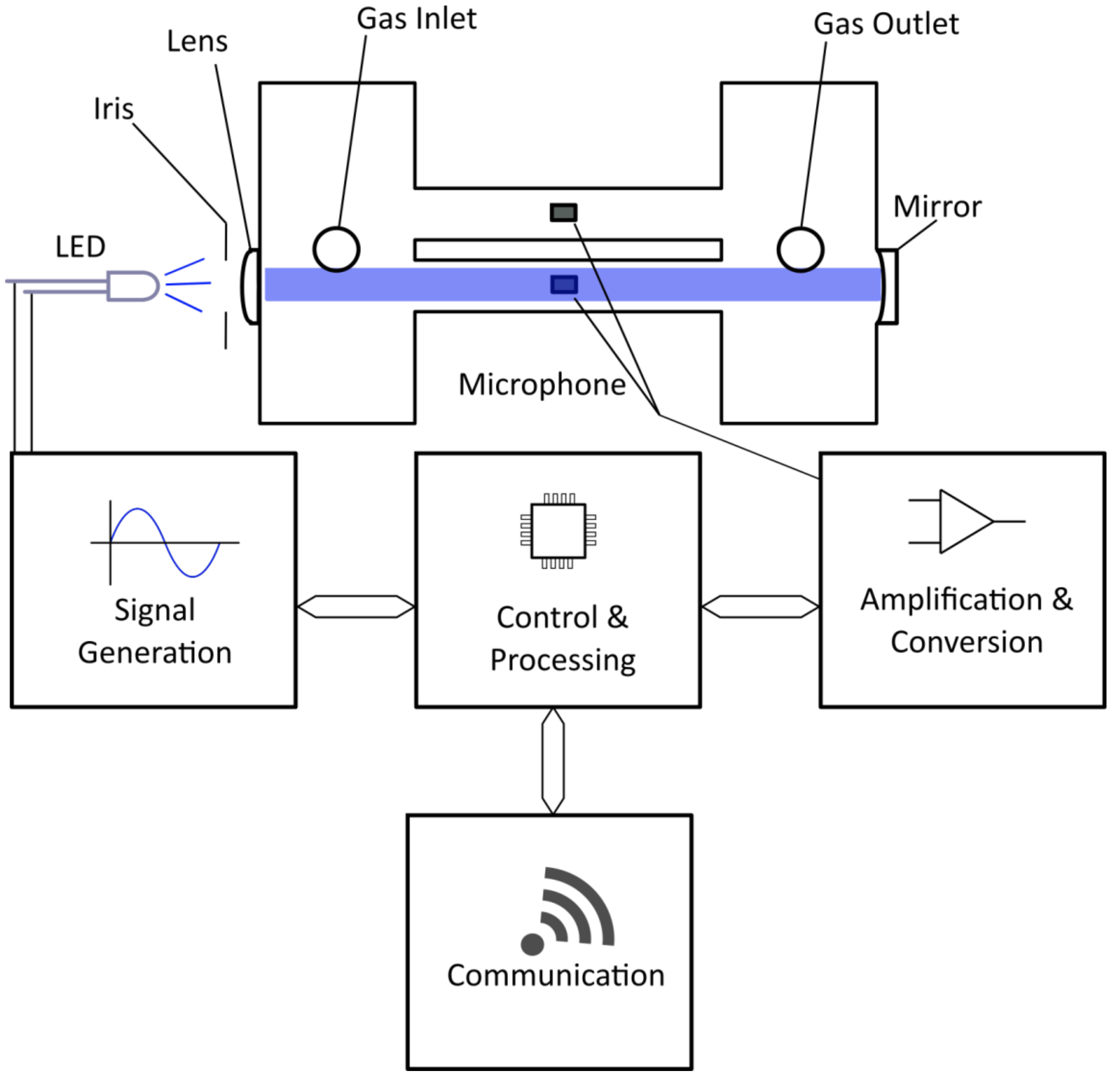
- Wavelength (light source) defines what should be detected



- Standard spectroscopy: Single resonator excited by modulated light source
- Differential spectroscopy: Subtracting background signal from wanted signal
- Multi-gas spectroscopy: Detection of different gases within one sensor

Sensor System Design

- Design facts:
  - Two sensing modes
    - Standard Spectroscopy
    - Differential Spectroscopy
  - 450 nm LED
    - ~10 mW optical power
  - ~2.26 kHz modulation
  - Electret microphones
  - Digital Lock In Amplifier
  - Special purpose ADC
  - Ultra low power ARM
  - LoRa transceiver



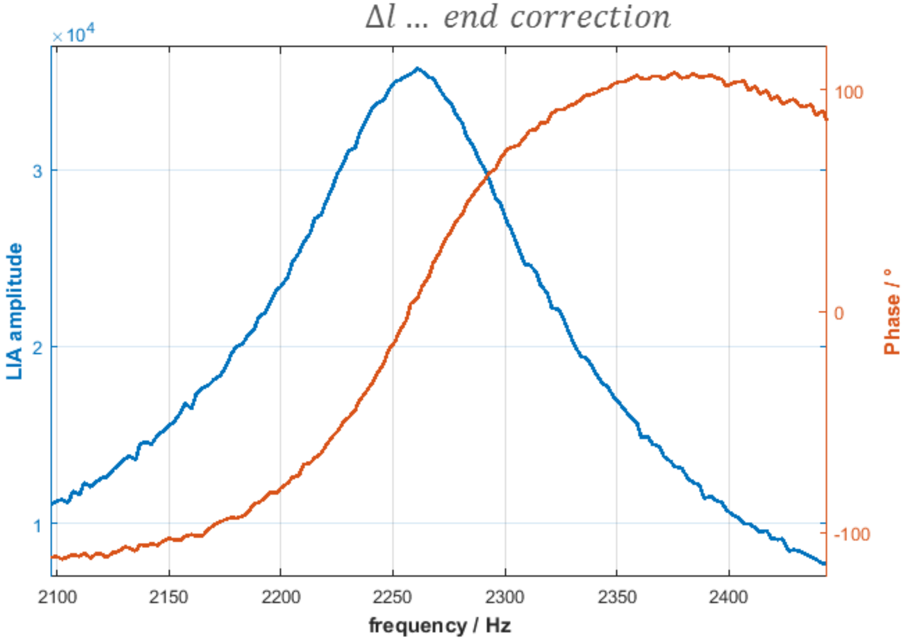
Photoacoustic Cell Design

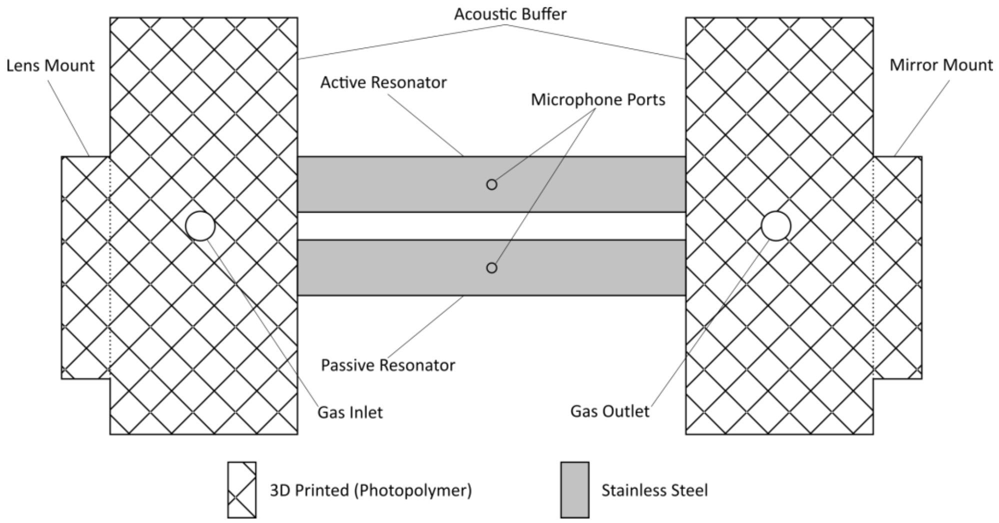
- Resonator + acoustic buffer
- Resonance frequency:

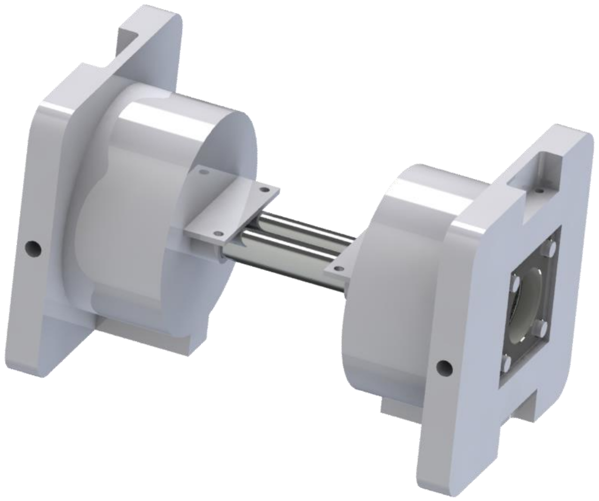
$$f_n = \frac{n\,c}{2(l + \Delta l)} \text{ [2]}$$

f_n … *resonance frequency*
n … *resonance frequency number*
c … *speed of sound*
l … *length of the resonator*
Δl … *end correction*

- Q-Factor: ~23



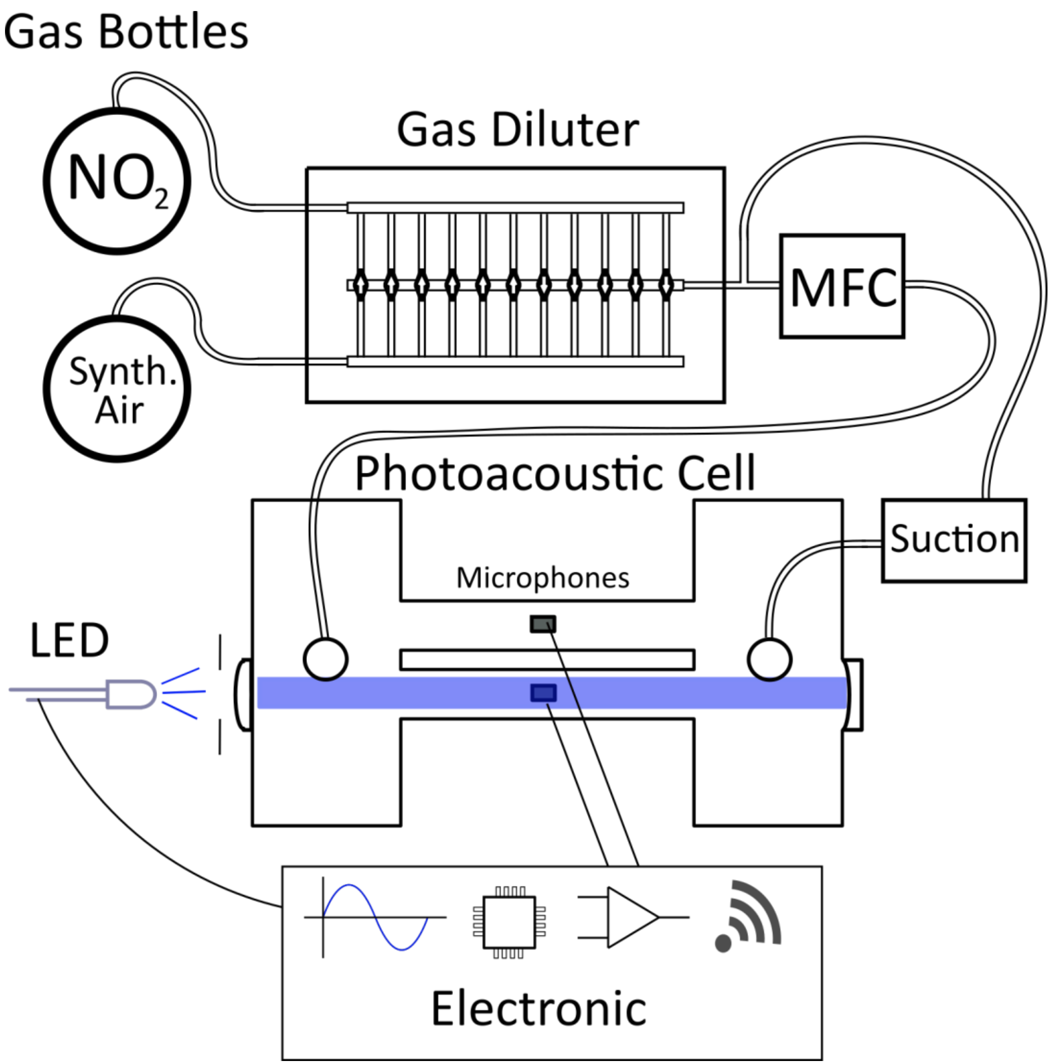




[2] A. Miklós, P. Hess and Z. Bozóki. “Application of acoustic resonators in photoacoustic trace gas analysis and metrology.” In: Review of Scientific Instruments 72 (4 2001). doi:10.1063/1.1353198.

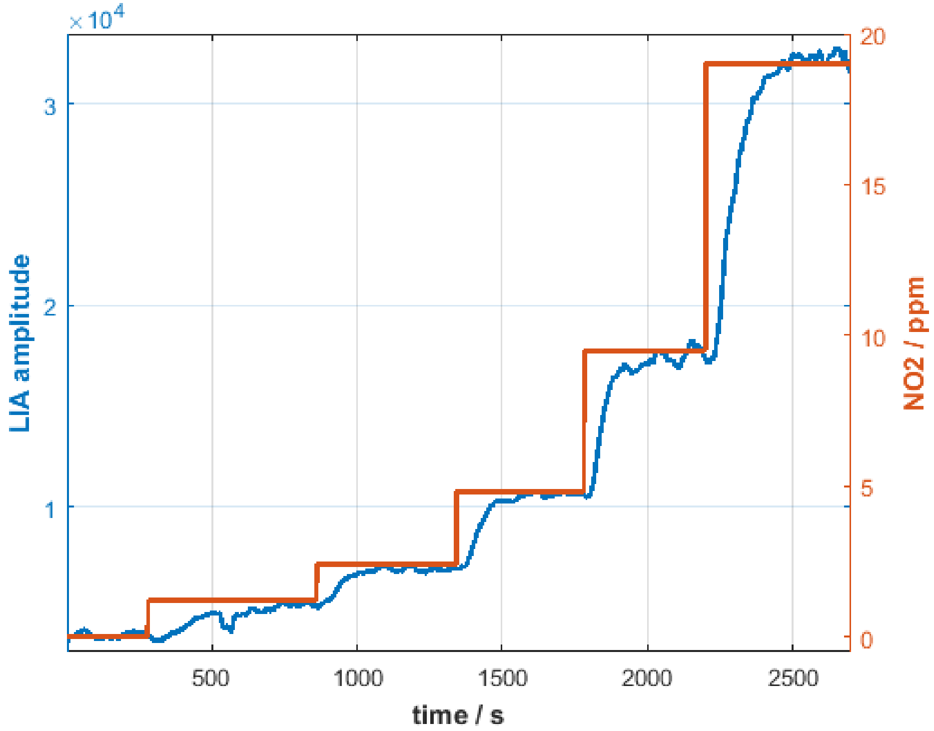
Laboratory Validation Setup

- Results are using the „Standard Spectroscopy“ mode
- „Differential Spectroscopy“ mode is still under investigation
- Gas mixture variable
- Gas flow control

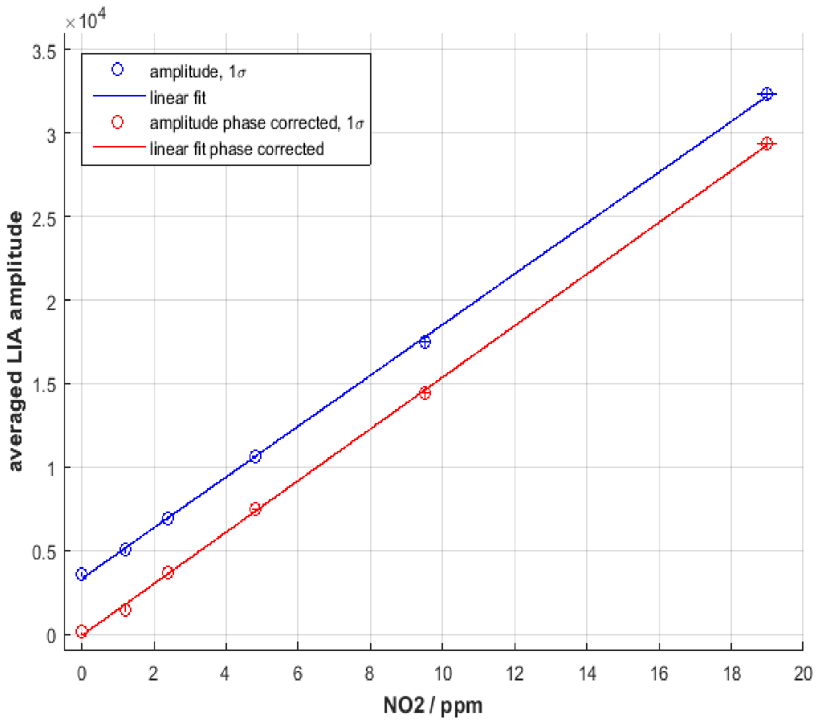


Sensor Response

- 20s integration
- Different concentrations measured over a period time



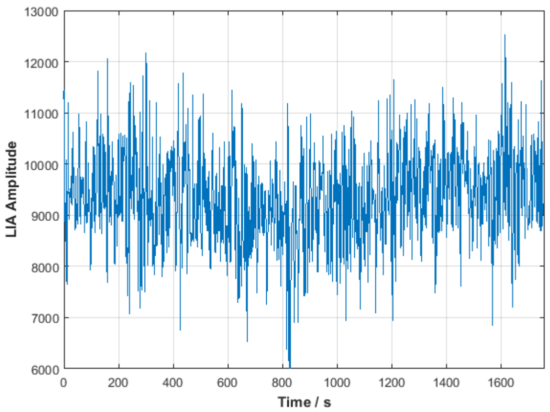
- Integration over several minutes
- Sensor response function

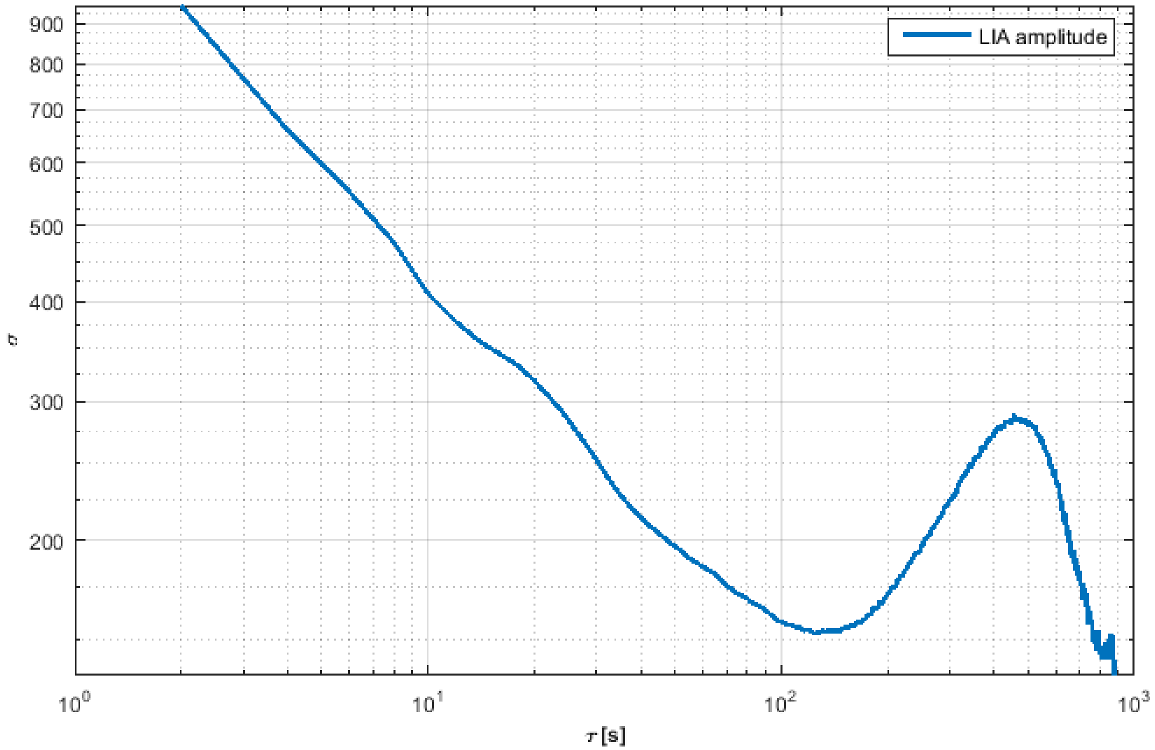


Limit of Detection

- Dependent on the integration time
- Limit of detection: 90 ppb (100 s integration, 1**σ**)
- Allan Variance (background signal)

	2 s	20 s
1 σ	0.63 ppm	0.23 ppm
3 σ	1.90 ppm	0.68 ppm

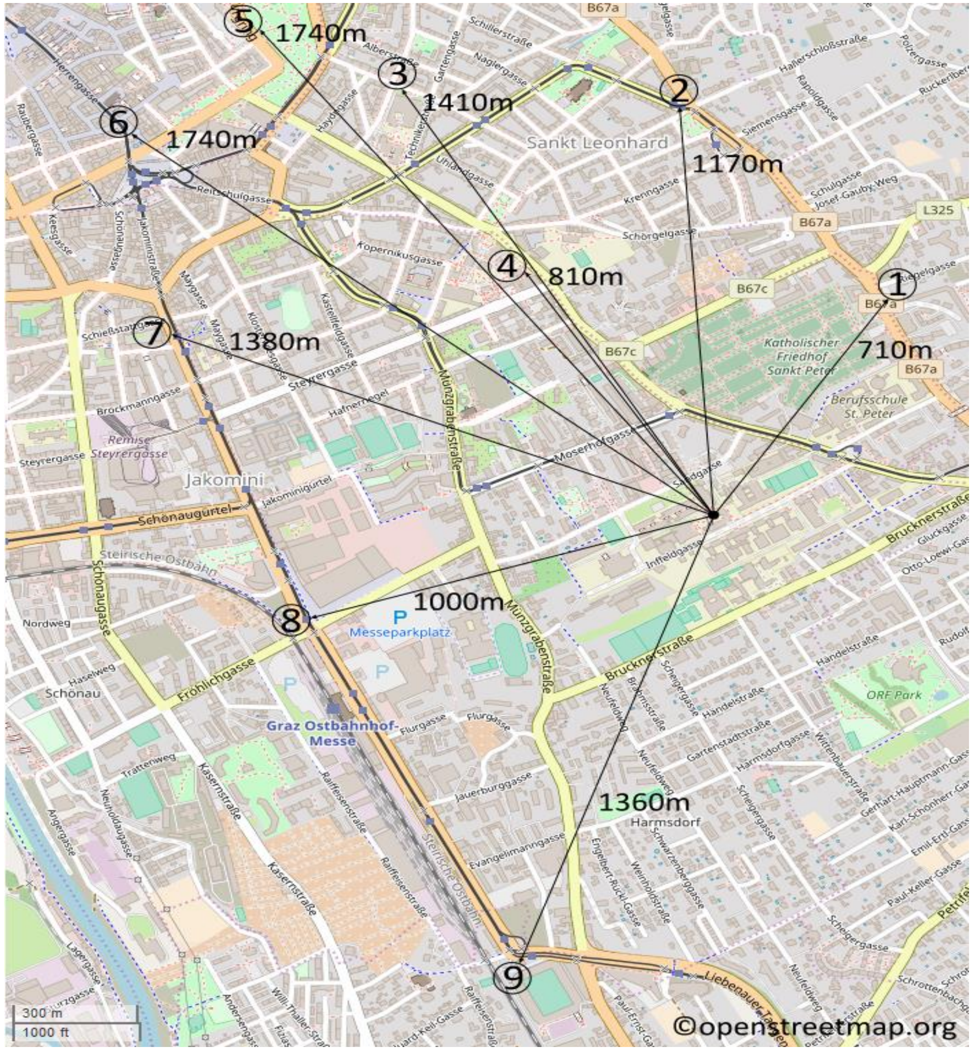


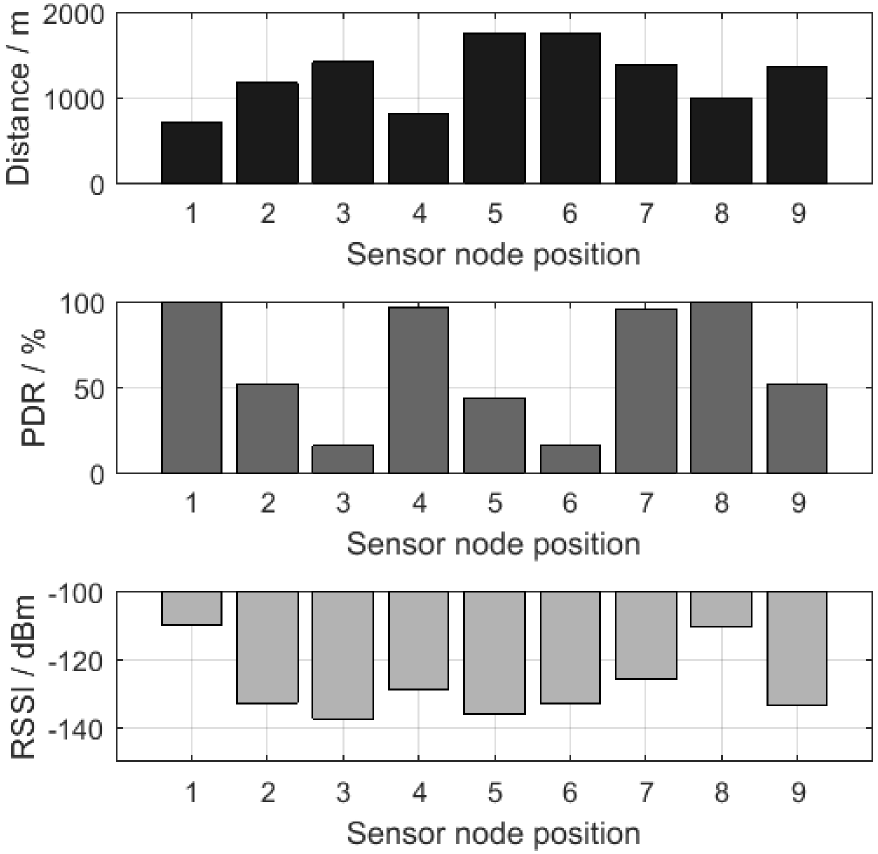


LoRa – Long Range

- LoRa attributes
  - Chirp Spread Spectrum (CSS) technology
  - Operates in the ISM bands
  - Max. RF output power: 20 dBm
  - Max. data rates 37.5 kbps
  - Sensitivity down to -146 dBm
  - Network: Star Topology
  - Data rate, communication distance and robustness depended on parameter setting (SF, CR, BW)
- Distance measurements
  - Urban area (Graz, ~300.000 inhabitants)
  - Sink positioned on the third floor
  - Sensor nodes in ~1 m height beside the street
  - At least 200 packets per node/position sent

LoRa Distance Measurements in Graz [3]





RSSI … received signal strength indicator
PDR … packet delivery rate

[3] M. Knoll, P. Breitegger, A. Bergmann. "Low-Power Wide-Area technologies as building block for smart sensors in air quality measurements." In: e&i Elektrotechnik und Informationstechnik (2018). doi: 10.1007/s00502-018-0639-y

Conclusion

- Power consumption: ~100 mA → ~330 mW
- Sensor response time: 4 to 100 s (dependent on integration time)
- Lifetime:
  - 4 AA batteries, 2500 mAh, 10s measurement duration
  - Measurement cycle 15 minutes: ~94 days
  - Measurement cycle 60 minutes: ~376 days
- Area of 2-8 km² (urban region) could be covered by single sink
- Sensor size currently ~250 mm x 100 mm
- No existing infrastructure required (power supply, data transfer)

Outlook

- Overall a lot of improvements possible
- Power consumption can be lowered by at least 25 %
- Sensor size can be reduced (by a factor of 2 to 4)
- Printing the whole cell
- Differential Spectroscopy validation
- Multi gas sensing: Usage of multiple LEDs (with different wavelength)
- Air quality limits can be reached by using a LED with higher power
- Field measurements necessary to prove the principle