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

Markus Knoll, Philipp Breitegger, Alexander Bergmann

Institute of Electronic Sensor Systems, Technical University of Graz

12.09.2018
Motivation
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)  
  $\alpha$ ... absorption coefficient of the gas  
  $P_0$ ... optical power of the light source

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:
  \[ f_n = \frac{n c}{2(l + \Delta l)} \quad [2] \]
  - \( f_n \) ... resonance frequency
  - \( n \) ... resonance frequency number
  - \( c \) ... speed of sound
  - \( l \) ... length of the resonator
  - \( \Delta l \) ... end correction
- Q-Factor: \(~23\)

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\(\sigma\))
- Allan Variance (background signal)

<table>
<thead>
<tr>
<th></th>
<th>2 s</th>
<th>20 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(\sigma)</td>
<td>0.63 ppm</td>
<td>0.23 ppm</td>
</tr>
<tr>
<td>3(\sigma)</td>
<td>1.90 ppm</td>
<td>0.68 ppm</td>
</tr>
</tbody>
</table>
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]

Conclusion

- Power consumption: \( \sim 100 \text{ mA} \rightarrow \sim 330 \text{ mW} \)
- Sensor response time: 4 to 100 s (dependent on integration time)
- Lifetime:
  - 4 AA batteries, 2500 mAh, 10s measurement duration
  - Measurement cycle 15 minutes: \( \sim 94 \text{ days} \)
  - Measurement cycle 60 minutes: \( \sim 376 \text{ days} \)
- Area of 2-8 km\(^2\) (urban region) could be covered by single sink
- Sensor size currently \( \sim 250 \text{ mm} \times 100 \text{ mm} \)
- 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