AOI2 Wireless High-Temperature Sensor Network for Smart Boiler Systems

Project No.: DE-FE0031895

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Dr. Xinsheng Lou, General Electric (GE), vendor

Federal Project Manager: Robie E. Lewis

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Acknowledgement

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Outline

• Project objective
• Background
• Methods
• Tasks
• Progress
• Future work
• Team members
Project objective

Develop a new wireless high-temperature sensor network for real-time continuous boiler condition monitoring in harsh environments

- High-temperature sensors with integrated antennas
- Coupled with a ZigBee end device (ZED)
- Collect and route boiler temperature data in real-time

Schematic architecture of the smart boiler wireless sensor network
Background

The needs

- Boilers and furnaces are extensively used virtually everywhere
- These systems consume the most significant amount of energy
- Optimizing the operation of the systems can lead not only to huge energy savings and bring tremendous benefits to our environment

Estimated impacts

- 1% efficiency improvement provides energy savings of around 30 billion kilowatt-hours (kW·h)
- ~ 300 billion cubic feet of natural gas
- ~ 17 million tons of carbon emission reduction
Tasks

**Task 1:** Obtain optimal designs of the wireless high temperature sensor network.

**Task 2:** Fabricate the wireless high-temperature sensor and build the wireless sensor network.

**Task 3:** Characterize the wireless high-temperature sensor and evaluate the performance of the wireless high-temperature sensor.

**Task 4:** Determine the system stability and reliability.

**Task 5:** Report.
## Milestones

### DOE Project Schedule
University of Massachusetts Lowell

<table>
<thead>
<tr>
<th>Task Description</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1 Obtain optimal designs of the wireless sensor network</td>
<td>10/1/2020</td>
<td>3/31/2021</td>
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<tr>
<td>1. Design the high-temperature sensor</td>
<td>10/01/2022</td>
<td>12/31/2020</td>
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<tr>
<td>2. Design the broadband antenna</td>
<td>11/1/2020</td>
<td>1/31/2021</td>
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<tr>
<td>3. Antenna coupling through the Lamb filter</td>
<td>12/1/2020</td>
<td>3/30/2021</td>
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<tr>
<td>4. Design the sensor network and perform network simulation</td>
<td>2/2/2021</td>
<td>4/30/2022</td>
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<tr>
<td>Task 2 Fabricate the wireless sensor network</td>
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<td>3/30/2023</td>
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<td>1. Fabricate the wireless high-temperature sensor</td>
<td>3/1/2021</td>
<td>1/31/2023</td>
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<tr>
<td>2. Set up the wireless high-temperature sensor network</td>
<td>12/1/2021</td>
<td>3/30/2023</td>
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<td>Task 3 Characterize the wireless high-temperature sensor network</td>
<td>2/2/2022</td>
<td>1/31/2024</td>
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<tr>
<td>1. Characterize the high-temperature sensor</td>
<td>2/2/2022</td>
<td>9/30/2023</td>
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<tr>
<td>2. Characterize the RF performance of the antenna</td>
<td>8/1/2022</td>
<td>11/30/2023</td>
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<td>3. Characterize the wireless sensor network</td>
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<td>1/31/2024</td>
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<td>Task 4 Determine the system stability and reliability</td>
<td>12/1/2022</td>
<td>9/3/2024</td>
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<tr>
<td>1. Characterize the high-temperature sensor reliability</td>
<td>12/1/2022</td>
<td>5/31/2024</td>
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<td>2. Characterize the reliability of the sensor network</td>
<td>4/1/2023</td>
<td>12/3/2024</td>
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<td>Task 5 Report</td>
<td>10/1/2020</td>
<td>12/3/2024</td>
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</table>
Design the High-temperature wireless sensor

- A Lamb filter\(^1\) sensing structure
- The high-temperature sensor and the bow-tie transmission and receiving antennas are all on the 4H SiC piezoelectric substrate.
- The Lamb filter provides sharp transmission spectrum and a 0\(^0\) degree phase shift at the resonant frequency.
- Enables strong coupling of the integrated antennas.
- The resonant frequency shifts with the temperature, allowing temperature measurement through the transmission and receiving and the coupling properties of the antennas

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Lamb-filter temperature shift

\[ Y = \frac{1}{R_m + j\omega L_m + \frac{1}{j\omega C_m}} + j\omega C_0 \]

\[ R_m + j\omega L_m + \frac{1}{j\omega C_m} = 1 + \frac{C_0}{C_m} - \omega^2 C_m L_m + j\omega C_0 R_m \]

\[ R_m + j\omega L_m + \frac{1}{j\omega C_m} = \Gamma \frac{F}{V} = e_{31} \cdot l \]

\[ C_m = \frac{\Gamma^2}{k_{eq}} \]

\[ L_m = \frac{m_{eq}}{\Gamma^2} \]

\[ C_0 = \frac{\varepsilon_r \varepsilon_0}{t} \cdot w \cdot l \]

\[ k_{eq} = \frac{Elt}{2w} \]

\[ R_m = \sqrt{\frac{L_m}{C_m}} \]

Task 1

Lamb-filter temperature shift (900 MHz)
### Design parameters for 2.4 GHz filter

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
<th>CTE (/K)</th>
<th>Meq (kg)</th>
<th>e31 (C/m²)</th>
<th>E (Pa)</th>
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<tbody>
<tr>
<td>6.0</td>
<td>0.2</td>
<td>0.0104</td>
<td>-42e-6</td>
<td>1.25×10⁻⁶</td>
<td>0.2</td>
<td>7.0×10¹¹</td>
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### Design parameters for 900 MHz filter

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<th>Length (mm)</th>
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<td>6.0</td>
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</table>
Methods

Broadband antenna

Antenna design parameters using Antenna Magus and CST Microwave Studio®.

- Antenna coupling

\[
S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad \quad Z_L = Z_0 \frac{1 + \Gamma e^{-j\beta L}}{1 - \Gamma e^{-j\beta L}}
\]

\[
\Gamma = \frac{(Z_{\text{filter}}Z_{\text{antenna}} - Z_0)}{(Z_{\text{filter}} + Z_{\text{antenna}} - Z_0)}/\left(\frac{Z_{\text{filter}}Z_{\text{antenna}}}{Z_{\text{filter}} + Z_{\text{antenna}} + Z_0}\right)
\]

Simulated 3dB bandwidth. A broadband operation of 800 MHz can be achieved.
2.4 GHz Antenna design

2.4 GHz antenna S11

<table>
<thead>
<tr>
<th>Substrate thickness</th>
<th>Relative permittivity</th>
<th>La</th>
<th>Wa</th>
<th>Lp</th>
<th>Wp</th>
<th>Lg</th>
<th>Wgi</th>
<th>Wgo</th>
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</thead>
<tbody>
<tr>
<td>2.8</td>
<td>9.66</td>
<td>33.3</td>
<td>40.5</td>
<td>90</td>
<td>90</td>
<td>66.6</td>
<td>3.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Lp = 103 mm
Lp = 90 mm
**2.4 GHz Antenna design**

### 2.4 GHz antenna gain

<table>
<thead>
<tr>
<th>Substrate thickness</th>
<th>Relative permittivity</th>
<th>La</th>
<th>Wa</th>
<th>Lp</th>
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</table>

![Graph showing antenna gain for two different lengths of Lp: 103 mm and 90 mm.](image)
2.4 GHz Antenna design

VSWR

- \(L_p = 103\) mm
- \(L_p = 90\) mm
2.4 GHz Antenna design

3D antenna pattern (dBi)  

Smith chart
Task 2.2 WSN optimization

Simulate and optimize the wireless high-temperature sensor network
Task 2.2 WSN optimization

- Data packets: IEEE 802.15.4 Data transmission rate 250 kbps

<table>
<thead>
<tr>
<th>Response time</th>
<th>Data packet</th>
<th>Guard time</th>
<th>Guard time</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-byte ACK</td>
<td>20-120 byte header data</td>
<td>8-byte header</td>
<td>T_r = 100 μs</td>
</tr>
</tbody>
</table>

\[ T_{ACK} = 384 \, \mu s \]

\[ T_{Data} = 32 M_D \, \mu s \]

\[ T_{Slot} = (684 + 32 M_D) \, \mu s \]

- Power consumption for each sensor node

\[ P_{Proc.} = 5.4 \, mW, \quad P_{PCB} = 6.0 \, mW \]

\[ P_{Total} = 11.4 \, mW \]
Task 2.2 WSN optimization

- Loss
  \[ L_{ij} (dB) = -20 \log_{10}(D_{ij}/D_0) \quad P_N (dBm) = -93 \]

- SNR
  \[ SNR_r (l) = P_{tr} (l) - L_{ij} - P_N \]

- Bit error rate
  \[ p_e (l) = Q(\sqrt{2SNR_r}) \quad p_{ij} (k) = 1 - Q(\sqrt{2SNR_r}) \]

- Successful probability for a n-byte packet
  \[ p_{ij} (l, n) = [1 - Q(\sqrt{2SNR_r})]^{8n} \]

- Successful probability for an AKC packet
  \[ p_{j,i} (k, 12) = [1 - Q(\sqrt{2SNR_r})]^{96} \]
Task 2.2 WSN optimization

• Repeat times for a n-byte packet

\[ M = \frac{1}{p_{ij}(l,n)p_{j,i}(k,12)} \]

• Energy consumption for one n-byte packet

\[ E_{tr} = 11.4 \text{ mW} \times (32 \times 120) \mu s + M[P_{tx}(l)T_{data} + P_{rx}(l)(T_{Slot} - T_{data})] \]

\[ = 43.8 \ \mu J + M[P_{tx}(l)T_{data} + P_{rx}(l)(T_{Slot} - T_{data})] \]
Task 2.2 WSN optimization with Tx power and packet sizes
Future work

• Continue set up the WSN using the optimized parameters
• Evaluate the sensor material
• Start the fabrication of the high-temperature sensor
Team members

- **Dr. Xingwei Wang, US Citizen**
  - Ph.D. in Electrical Engineering, Virginia Tech 2006
  - Research experience in optical fiber sensors and high temperature sensors

**Selected Publications of Dr. Wang**


Team members

• Dr. Tricia Chigan, US Permanent Resident (subject to DOE’s approval)
  ❑ Ph.D. in Electrical Engineering, State University of New York at Stony Brook 2002
  ❑ 18 years research experience in wireless networking

Selected Publications of Dr. Chigan
Team members (pending for approval)

- Students pending for DOE approval
  - Lidan Cao
  - Boyang Xiang
  - Andres Biondi
  - Rui Wu
Thank you!