AOI2 Wireless High-Temperature Sensor Network for Smart Boiler Systems

Project No.: DE-FE0031895

Dr. Xuejun Lu, Dr. Xingwei Wang,
and Dr. Tricia Chigan (subject to DOE approval)
University of Massachusetts Lowell (UML)

Dr. Dongsheng Li, Advanced Manufacturing LLC (subcontractor)

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

Federal Project Manager: Robie E. Lewis

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Disclaimer

Acknowledgement

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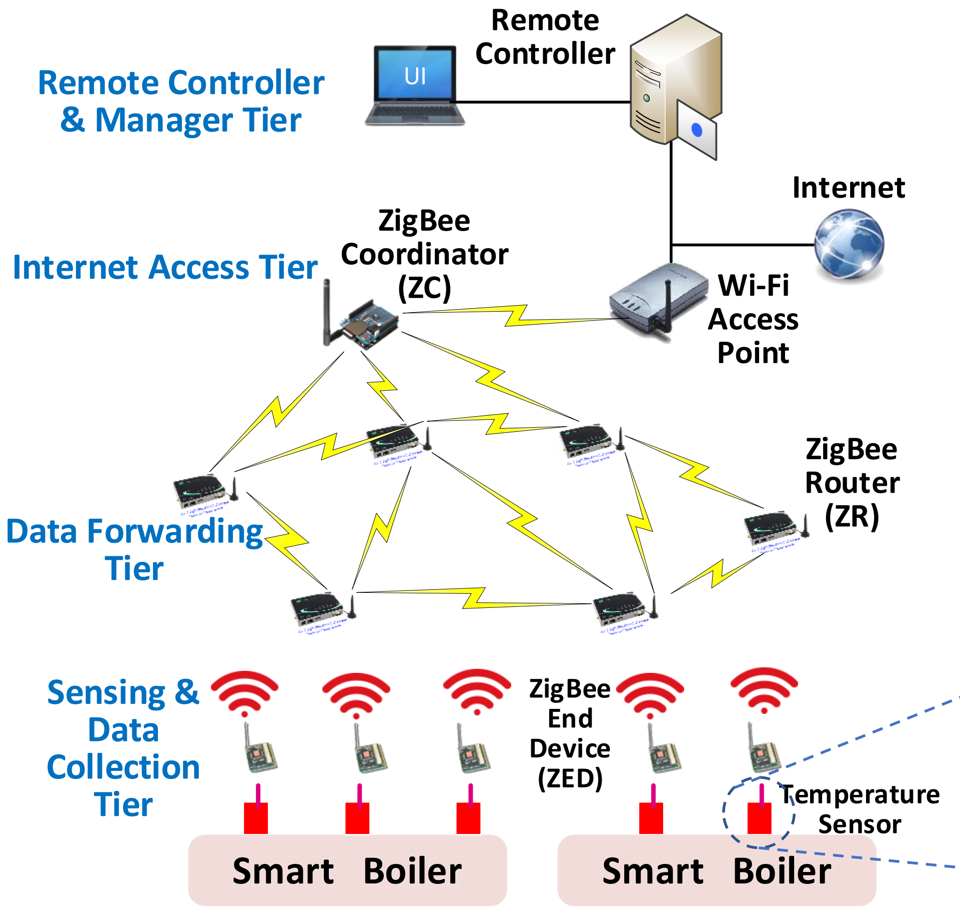
Disclaimer:

Outline

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

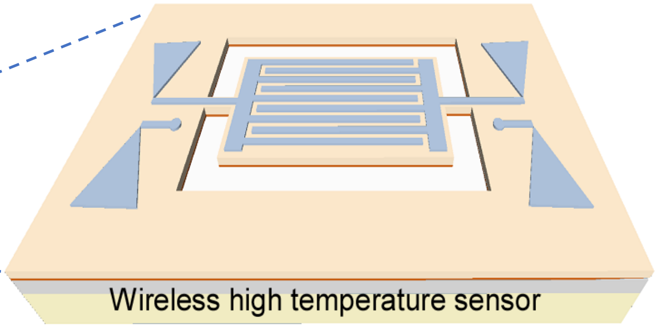
Project objective

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



Schematic architecture of the smart boiler wireless sensor network

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



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.

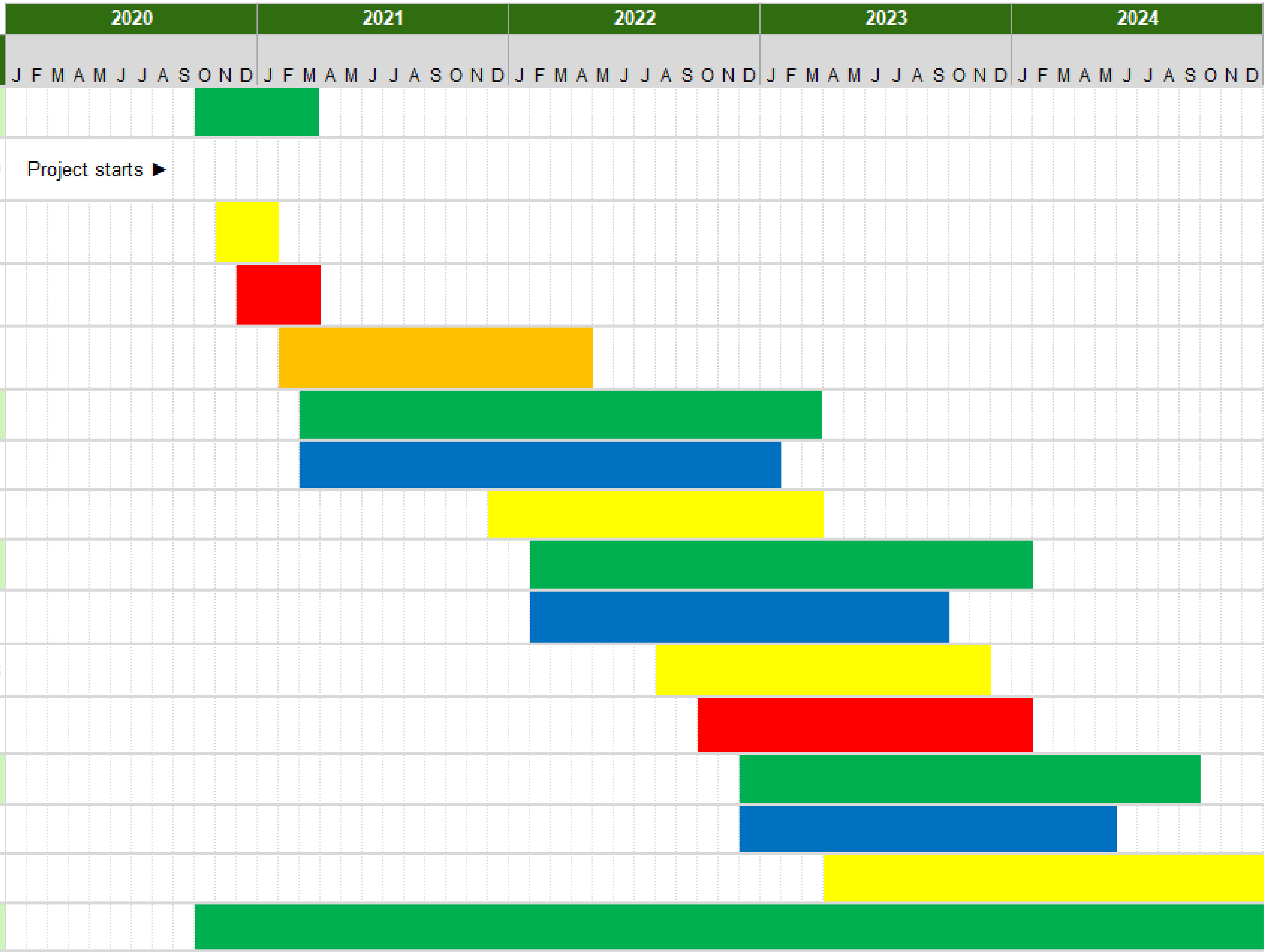
Task 5: Report.

Milestones

DOE Project Schedule

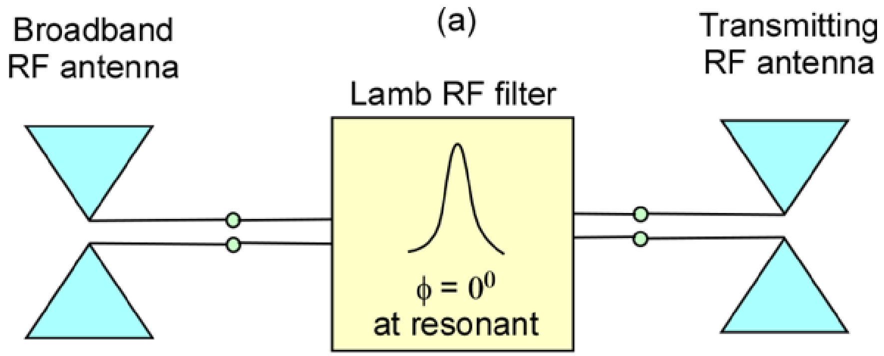
University of Massachusetts Lowell

TASK DESCRIPTION	PLAN START	PLAN END
Task 1 Obtain optimal designs of the wireless sensor network	10/1/2020	3/31/2021
1. Design the high-temperature sensor	10/01/202	12/31/2020
2. Design the broadband antenna	11/1/2020	1/31/2021
3. Antenna coupling through the Lamb filter	12/1/2020	3/30/2021
4. Design the sensor network and perform network simulation	2/2/2021	4/30/2022
Task 2 Fabricate the wireless sensor network	3/1/2021	3/30/2023
1. Fabricate the wireless high-temperature sensor	3/1/2021	1/31/2023
2. Set up the wireless high-temperature sensor network	12/1/2021	3/30/2023
Task 3 Characterize the wireless high-temperature sensor network	2/2/2022	1/31/2024
1. Characterize the high-temperature sensor	2/2/2022	9/30/2023
2. Characterize the RF performance of the antenna	8/1/2022	11/30/2023
3. Characterize the wireless sensor network	10/1/2022	1/31/2024
Task 4 Determine the system stability and reliability	12/1/2022	9/3/2024
1. Characterize the high-temperature sensor reliability	12/1/2022	5/31/2024
2. Characterize the reliability of the senor network	4/1/2023	12/3/2024
Task 5 Report	10/1/2020	12/3/2024

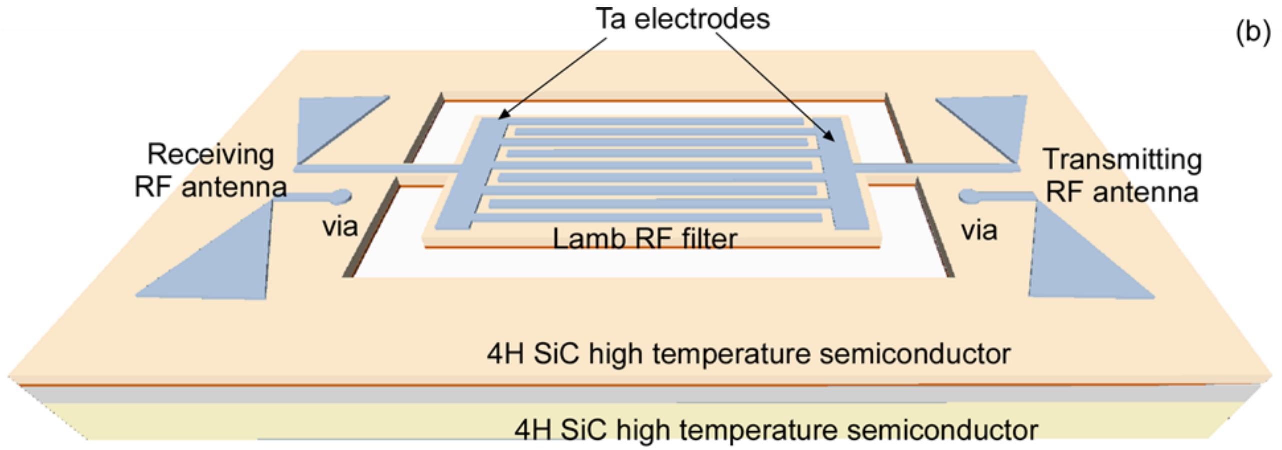


Task 1

Design the High-temperature wireless sensor



(a) Equivalent circuit



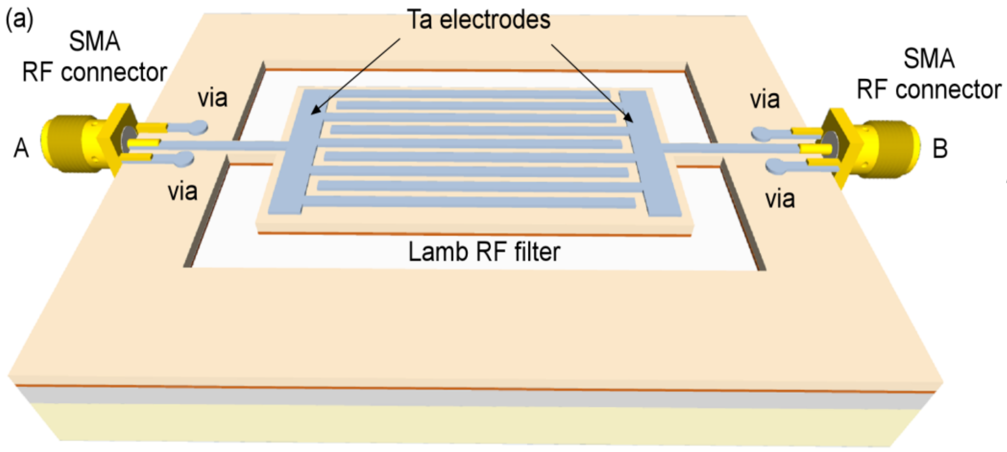
(b) 3D schematic structure

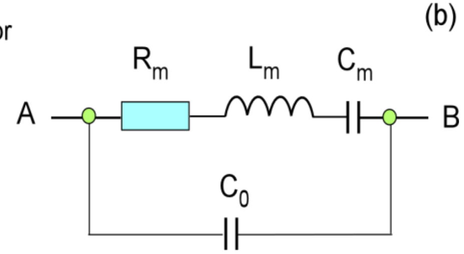
- A Lamb filter[1] sensing structure
- The high-temperature sensor and the bow-tie transmission and receiving antennas are all on the 4H SiC piezoelectric substrate.
- The Lamb filter provides sharp transmission spectrum and a 0^0 degree phase shift at the resonant frequency
- Enables strong coupling 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

[1]*Lin, C.-M. et al. Thermally compensated aluminum nitride Lamb wave resonators for high temperature applications. Applied Physics Letters 97, 083501, doi:10.1063/1.3481361 (2010)*

Task 1

Lamb-filter temperature shift





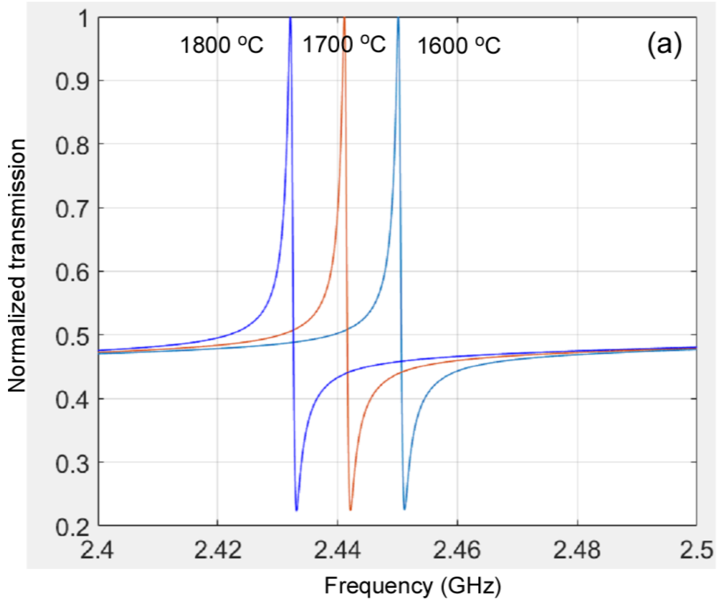
$$Y = \frac{1}{R_m + j\omega L_m + \frac{1}{j\omega C_m}} + j\omega C_0$$

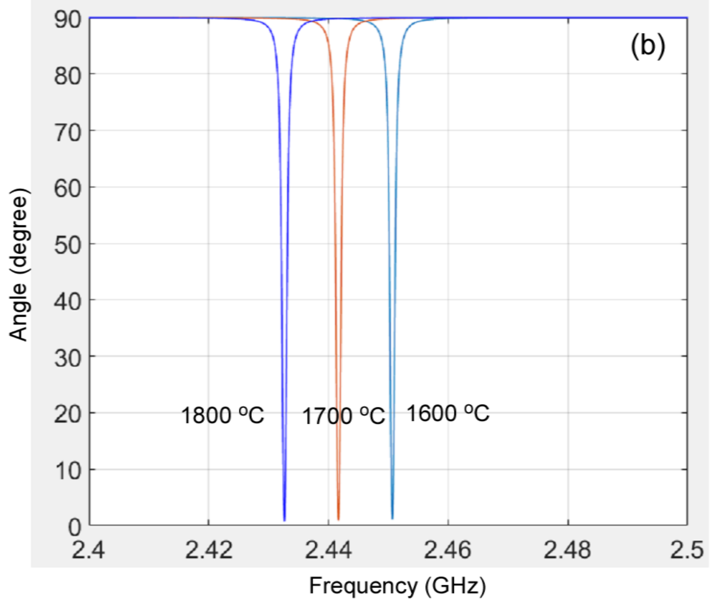
$$= \frac{1 + \frac{C_0}{C_m} - \omega^2 C_m L_m + j\omega C_0 R_m}{R_m + j\omega L_m + \frac{1}{j\omega C_m}}$$

$$\Gamma = \frac{F}{V} = e_{31} \cdot l \qquad C_m = \frac{\Gamma^2}{k_{eq}},$$

$$L_m = \frac{m_{eq}}{\Gamma^2} \qquad C_0 = \frac{\varepsilon_r \varepsilon_0}{t} wl$$

$$k_{eq} = \frac{Elt}{2w} \qquad R_m = \frac{\sqrt{L_m/C_m}}{Q}$$

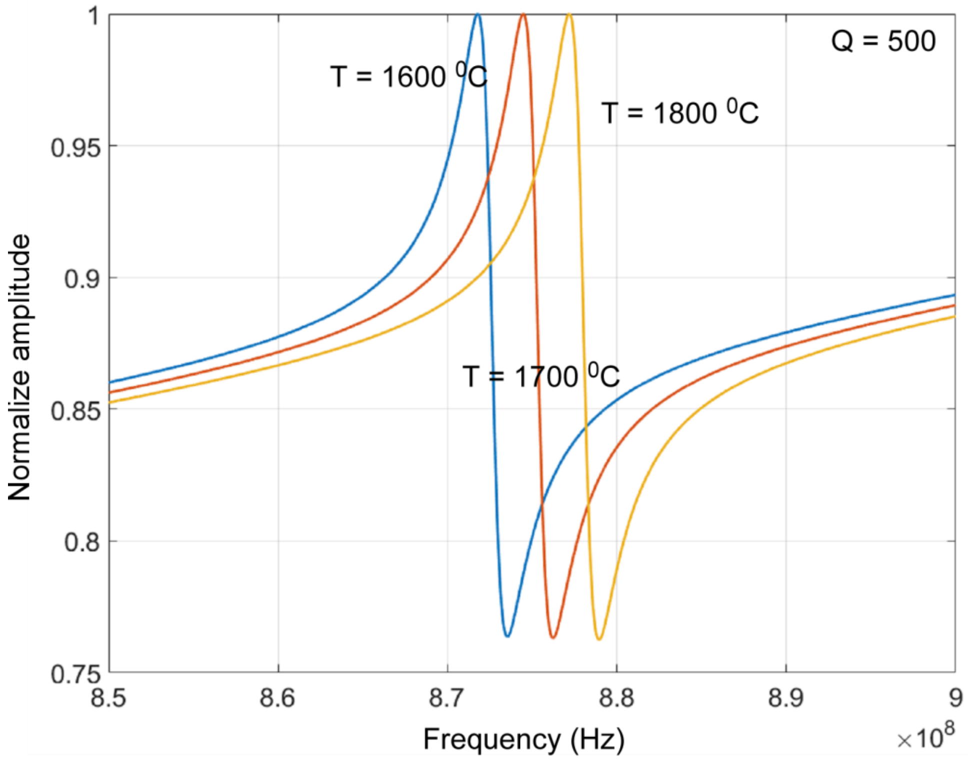


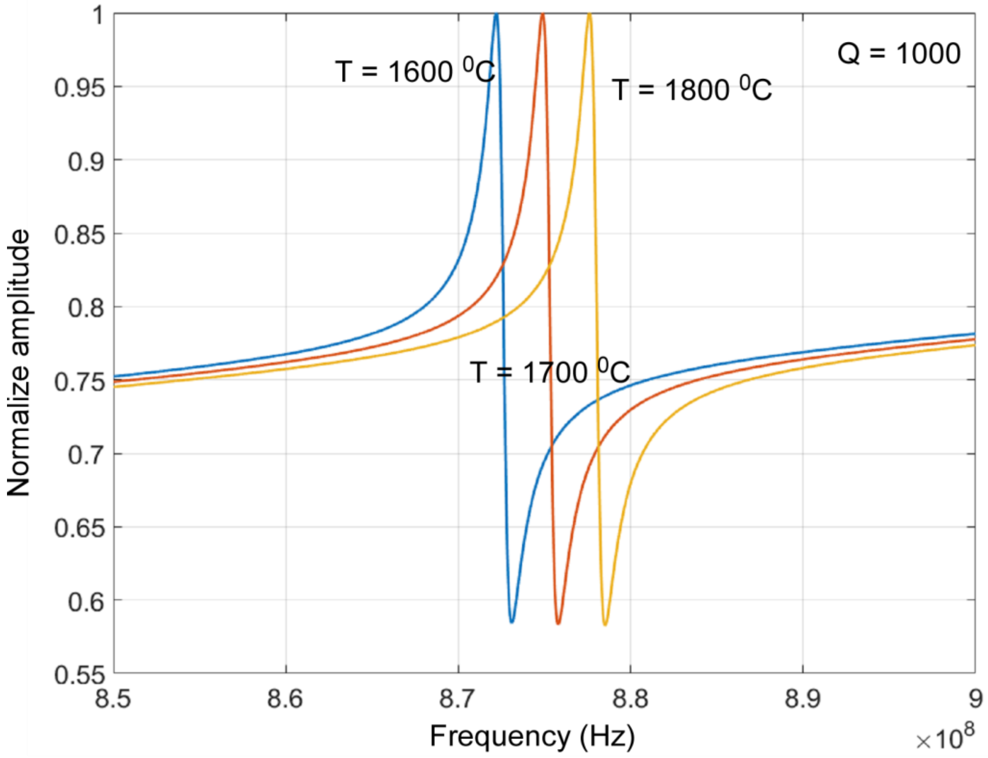


Lin, C.-M. et al. Thermally compensated aluminum nitride Lamb wave resonators for high temperature applications. Applied Physics Letters 97, 083501, doi:10.1063/1.3481361 (2010)

Task 1

Lamb-filter temperature shift (900 MHz)





Task 1

Summary of design parameters

Design parameters for 2.4 GHz filter

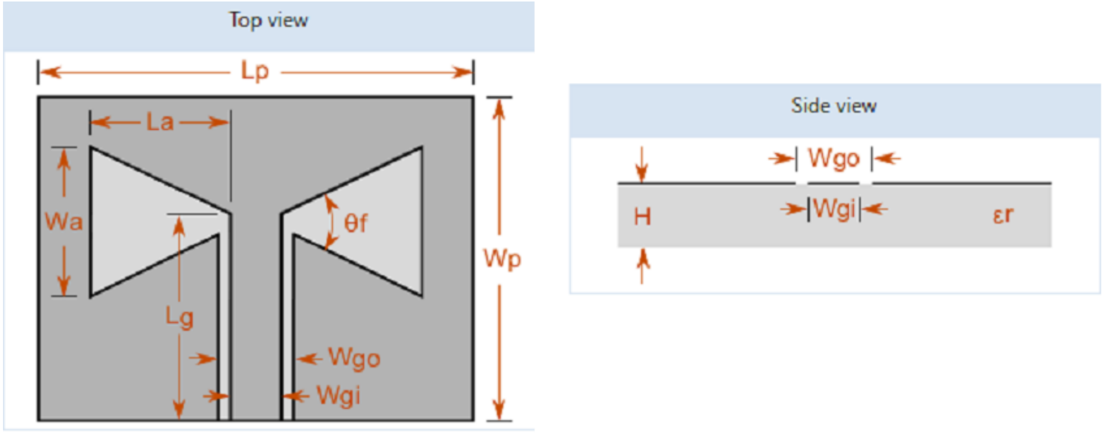
Length (mm)	Thickness (mm)	Width (mm)	CTE (/K)	Meq (kg)	e31 (C/m^2)	E (Pa)
6.0	0.2	0.0104	-42e-6	1.25×10^{-6}	0.2	7.0×10^{11}

Design parameters for 900 MHz filter

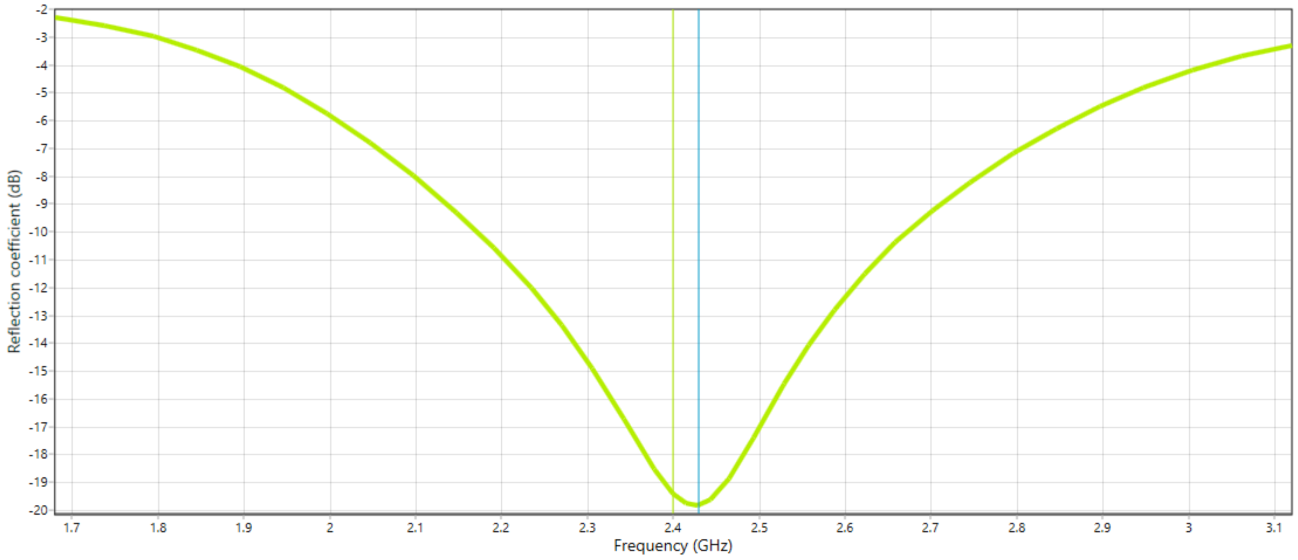
Length (mm)	Thickness (mm)	Width (mm)	CTE (/K)	Meq (kg)	e31 (C/m^2)	E (Pa)
6.0	0.2	0.0285	-42e-6	1.25×10^{-6}	0.2	7.0×10^{11}

Methods

Broadband antenna



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



Simulated 3dB bandwidth. A broadband operation of 800 MHz can be achieved

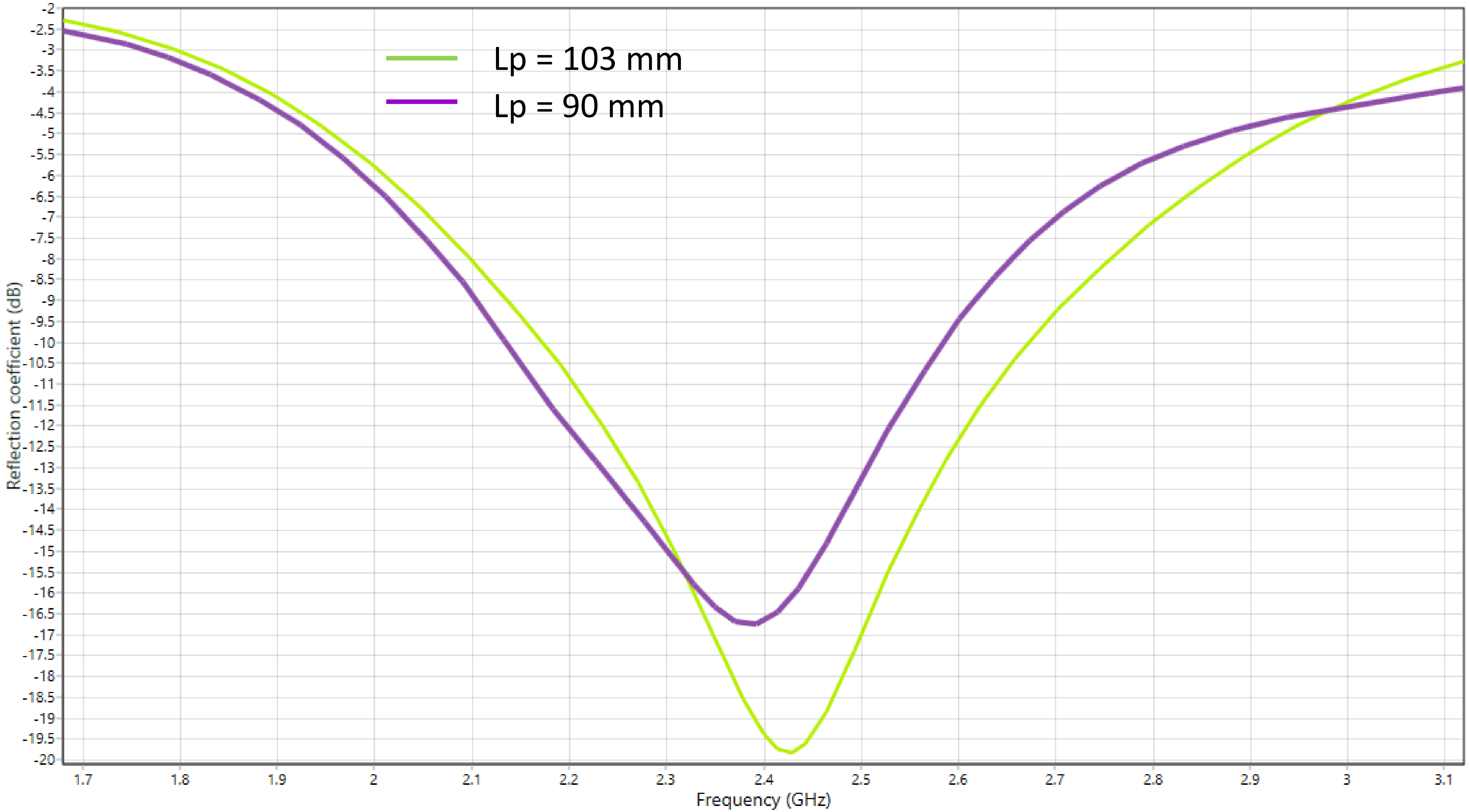
- Antenna coupling

$$S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad Z_L = Z_0 \frac{1 + \Gamma e^{-j\beta L}}{1 - \Gamma e^{-j\beta L}} \qquad \Gamma = \left(\frac{Z_{filter} Z_{antenna}}{Z_{filter} + Z_{antenna}} - Z_0\right) \Big/ \left(\frac{Z_{filter} Z_{antenna}}{Z_{filter} + Z_{antenna}} + Z_0\right)$$

2.4 GHz Antenna design

2.4 GHz antenna S11

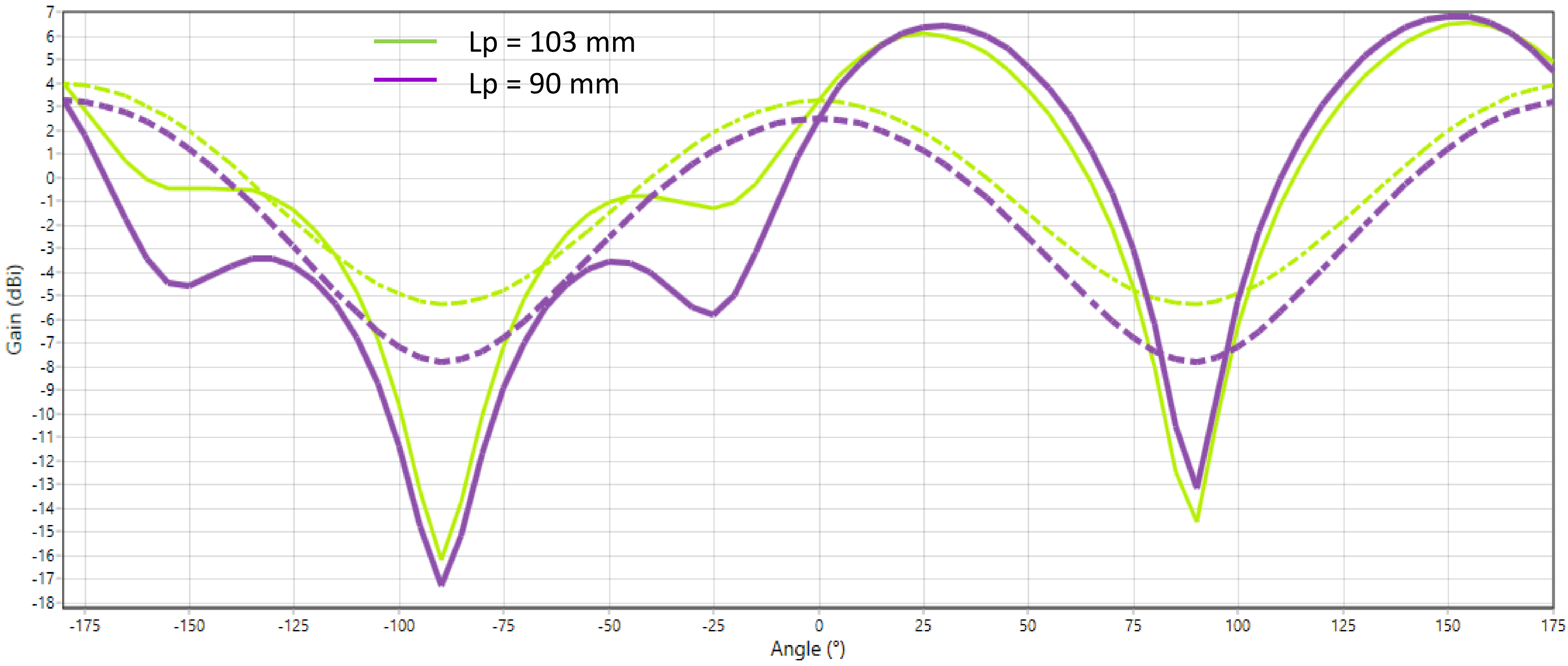
Substrate thickness	Relative permittivity	La	Wa	Lp	Wp	Lg	Wgi	Wgo
2.8	9.66	33.3	40.5	90	90	66.6	3.2	5.2



2.4 GHz Antenna design

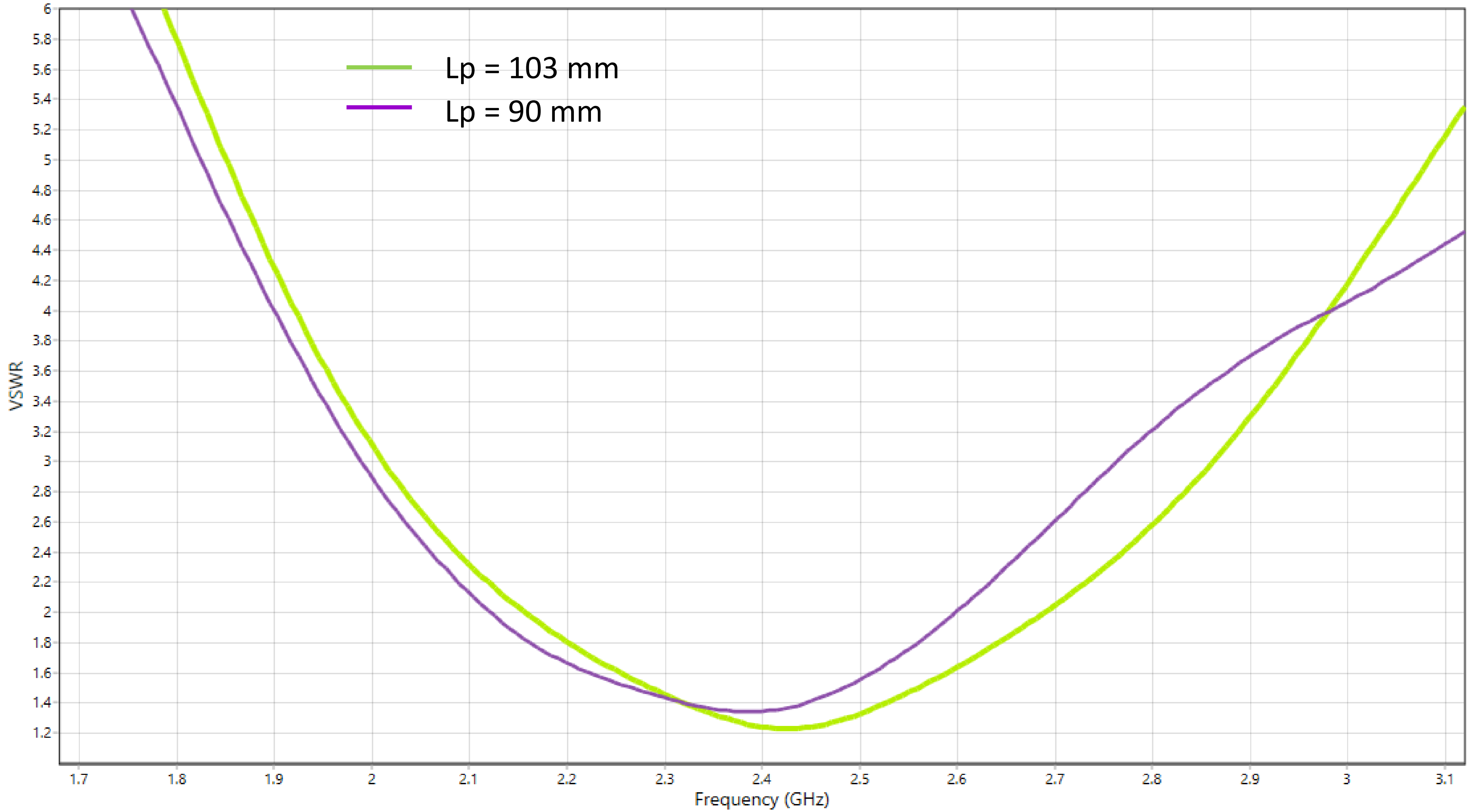
2.4 GHz antenna gain

Substrate thickness	Relative permittivity	La	Wa	Lp	Wp	Lg	Wgi	Wgo
2.8	9.66	33.3	40.5	90	90	66.6	3.2	5.2



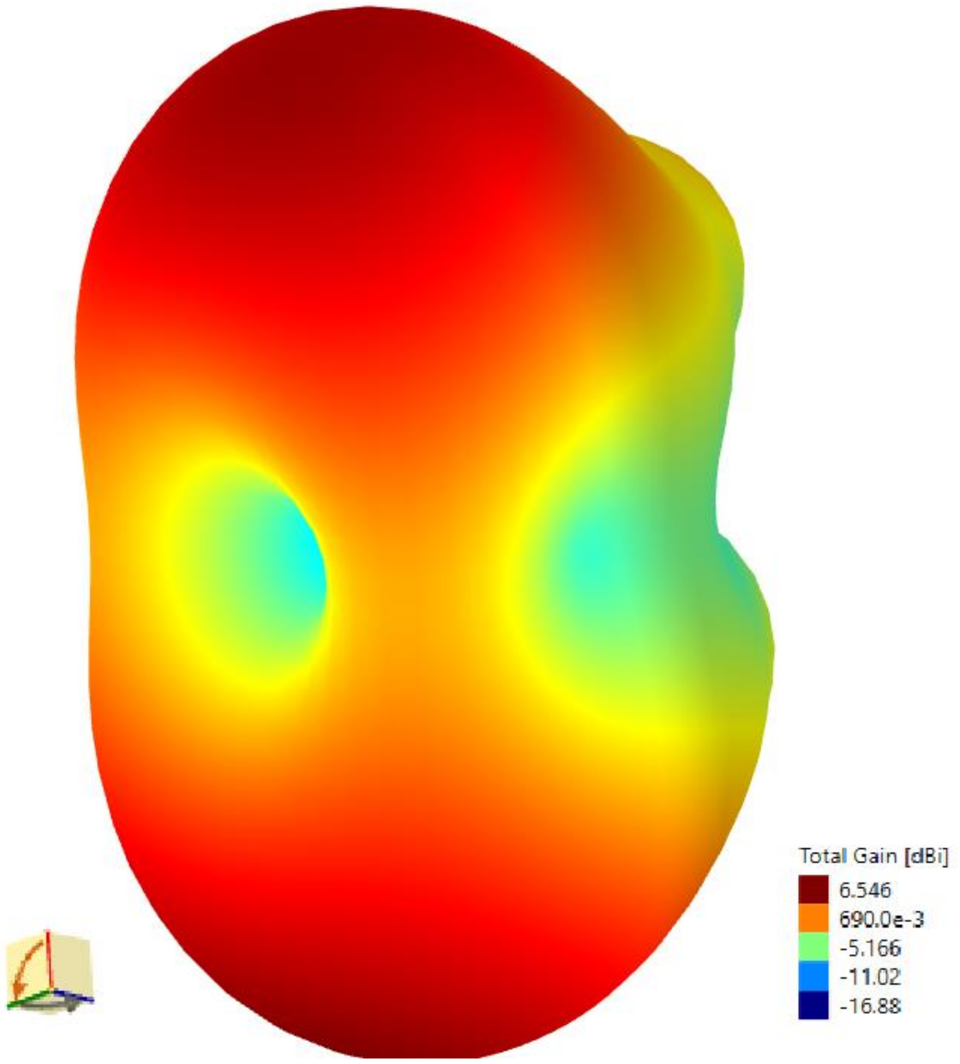
2.4 GHz Antenna design

VSWR

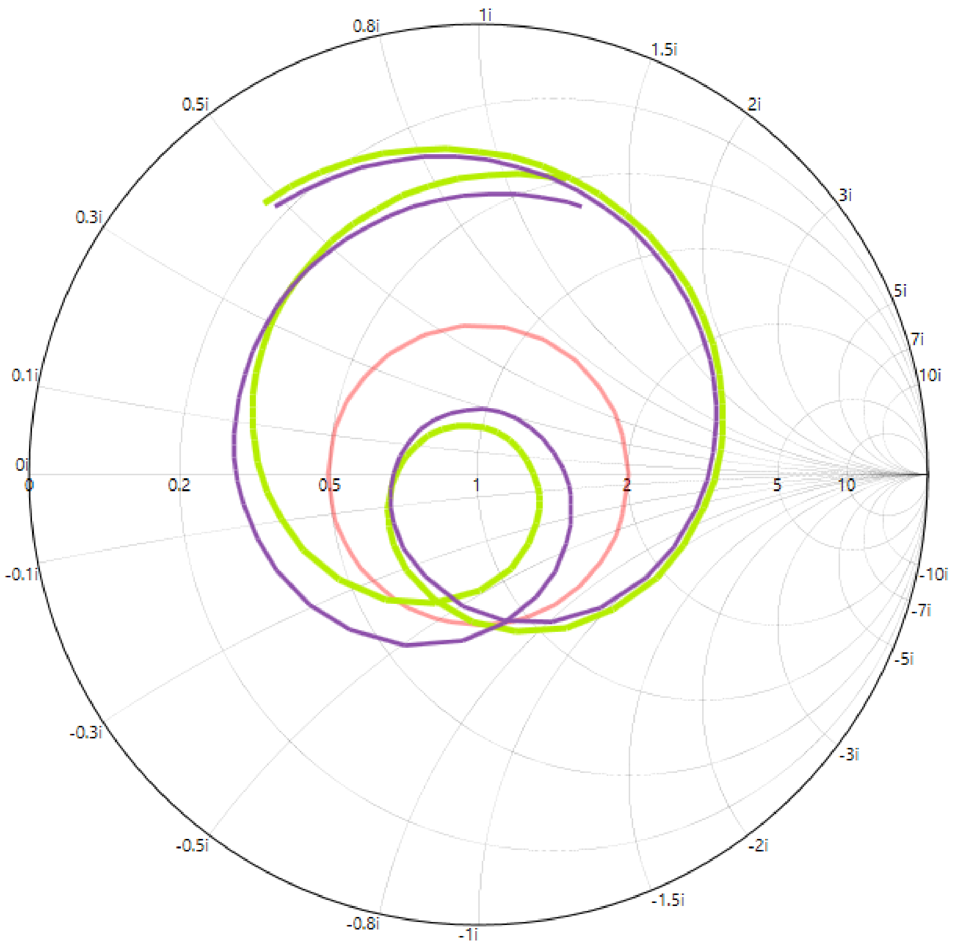


2.4 GHz Antenna design

3D antenna pattern (dBi)

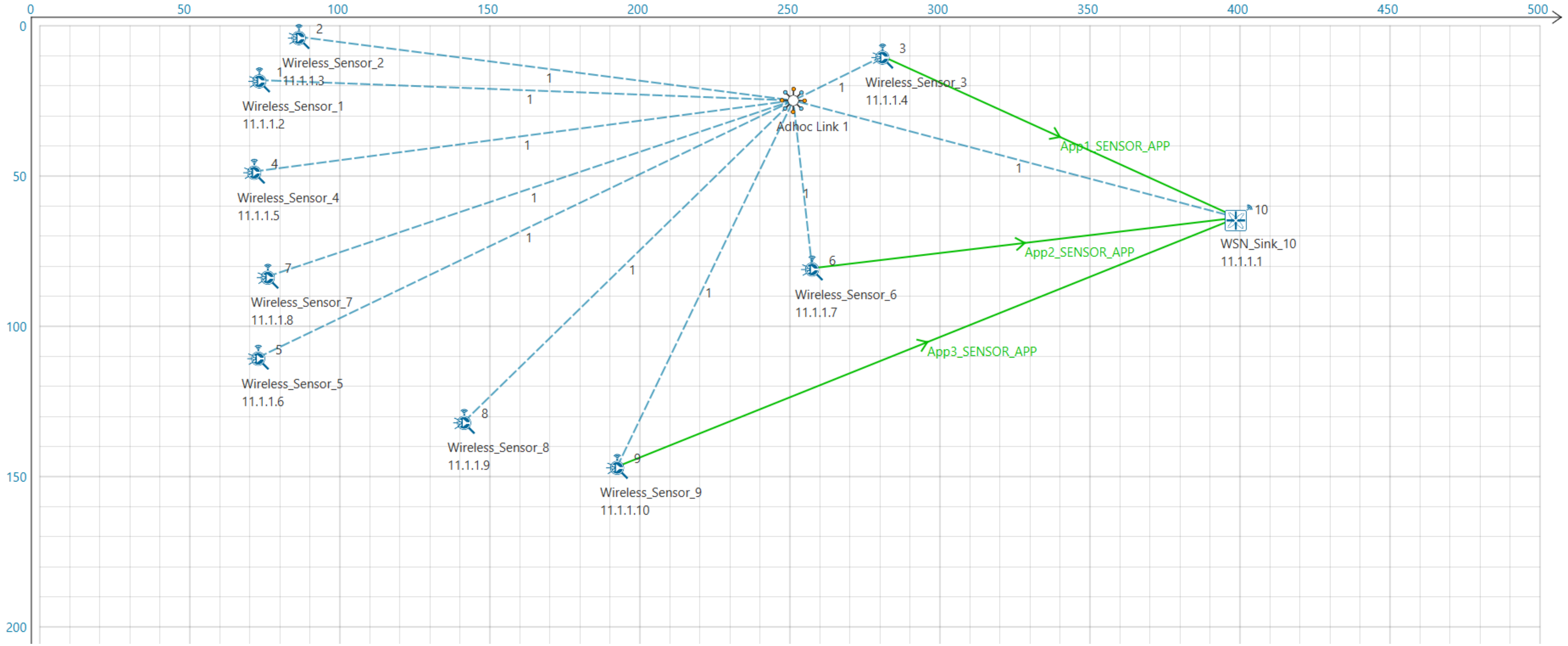


Smith chart



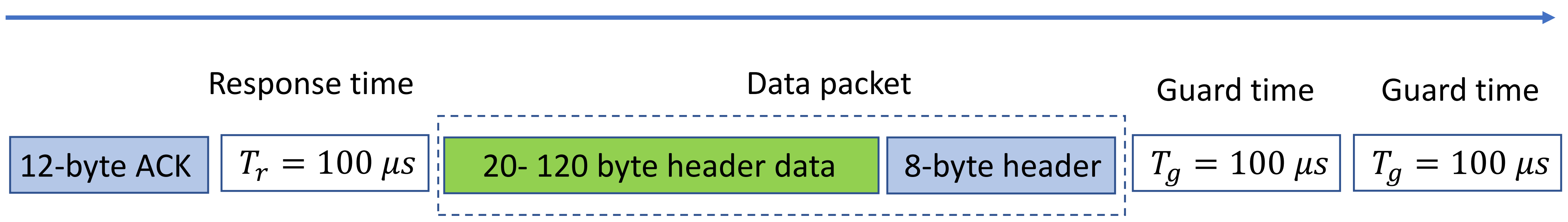
Task 2.2 WSN optimization

Simulate and optimize the wireless high-temperature sensor



Task 2.2 WSN optimization

- Data packets IEEE 802.15.4 Data transmission rate 250 kbps



$T_{ACK} = 384\ \mu s$

$T_{Data} = 32 M_D\ \mu s$

$$T_{Slot} = (684 + 32 M_D)\ \mu s$$

- 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

$$L_{ij}(dB) = -20log_{10}(D_{ij}/D_0) \qquad P_N(dBm) = -93$$

- SNR

$$SNR_r(l) \; = P_{tr}(l) - L_{ij} - P_N$$

- Bit error rate

$$p_e(l) = Q\left(\sqrt{2SNR_r}\right) \qquad p_{ij}(k) = 1 - Q\left(\sqrt{2SNR_r}\right)$$

- Successful probability for a n-byte packet

$$p_{ij}(l,n) = \left[1 - Q\left(\sqrt{2SNR_r}\right)\right]^{8n}$$

- Successful probability for an AKC packet

$$p_{j,i}(k,12) = \left[1 - Q\left(\sqrt{2SNR_r}\right)\right]^{96}$$

Task 2.2 WSN optimization

- Repeat times for a n-byte packet

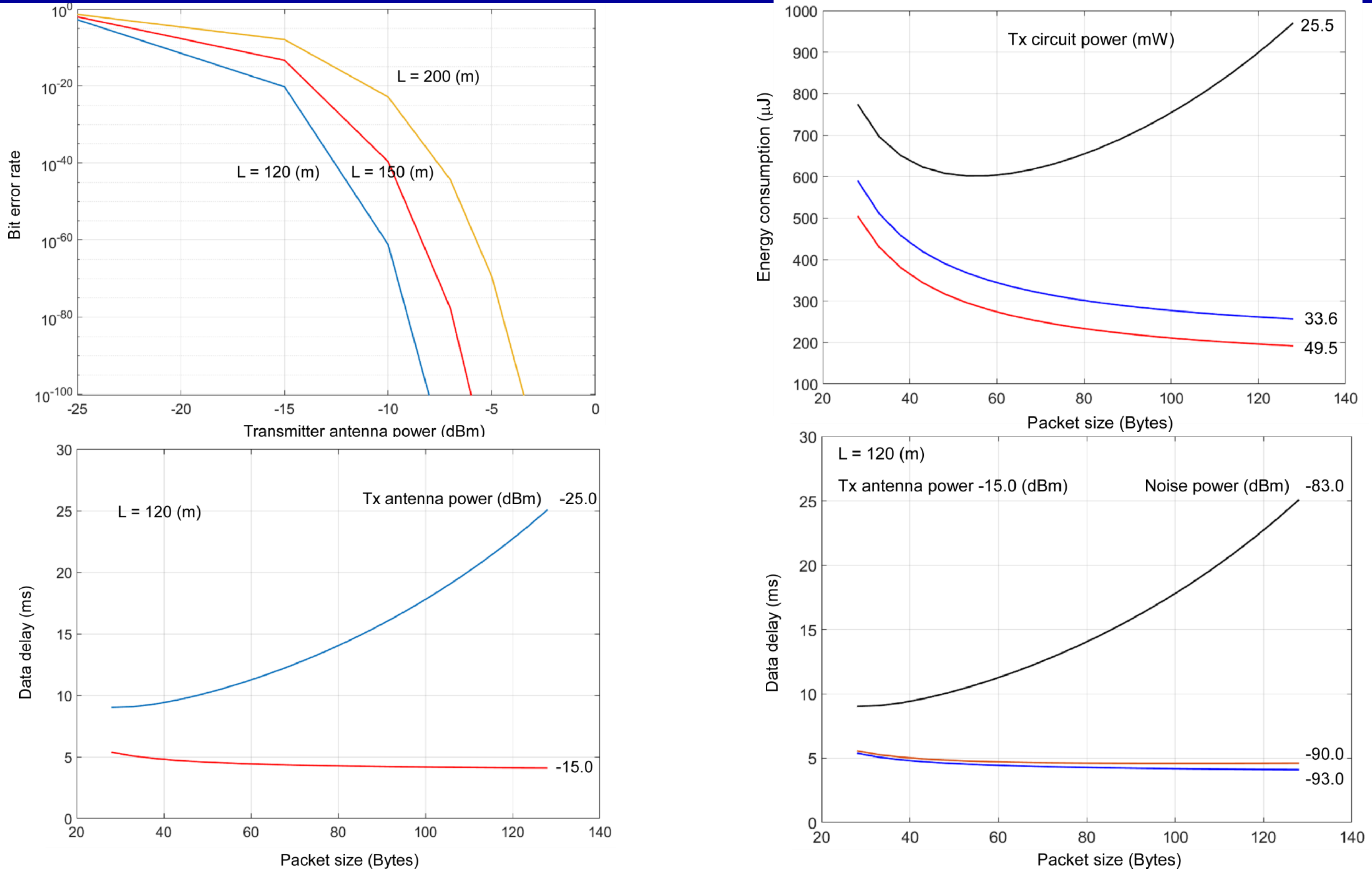
$$M = \frac{1}{p_{ij}(l,n)p_{j,i}(k,12)}$$

- Energy consumption for one n-byte packet

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

$$= 43.8\, \mu J + M[P_{tx}(l)T_{data} + P_{rx}(l)(T_{Slot} - T_{data})]$$

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

1. Jingcheng Zhou, Xu Guo, Cong Du, Xinsheng Lou, Chengyu Cao, Xingwei Wang, "A Fiber Optic Acoustic Pyrometer for Temperature Monitoring in an Exhaust Pipe of a Boiler" IEEE Photonics Technology Letters, 31 (19), 1580-1583 (2019).
2. Jingcheng Zhou, Xu Guo, Cong Du, Chengyu Cao, and Xingwei Wang, "A Fiber Optic Ultrasonic Sensing System for High Temperature Monitoring Using Optically Generated Ultrasonic Waves" Sensors, 19 (2), 404 (2019).
3. Xu Guo, Jingcheng Zhou, Cong Du, and Xingwei Wang, "Highly Sensitive Miniature All-Silica Fiber Tip Fabry-Perot Pressure Sensor", IEEE Photonics Technology Letters, 2019.
4. Jingcheng Zhou, Xu Guo, Cong Du, and Xingwei Wang, "Ultrasound beam steering using a fiber optic ultrasound phased array", Optics Letters, 44(21), 5390-5393 (2019).
5. Xu Guo, Nan Wu, Jingcheng Zhou, Cong Du and Xingwei Wang (2020). Validation of an ultrasound transducer's generation and receiving function on one single-mode fiber. Optics and Lasers in Engineering, 127, 105962.

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

1. L. Li, C. Chigan, "An Energy-Efficient Privacy Preserving Security-oriented DSA with Low Latency," *IEEE Transactions on Vehicular Technology*, Vol. 68 (11), pp. 11283-11294, Nov., 2019.
2. S.Yuan, L. Li, C. Chigan, "On MMD-based Secure Fusion Strategy for Robust Cooperative Spectrum Sensing," *IEEE Transactions on Cognitive Communications and Networking*, Vol. 5 (3), pp. 504-516, Sept., 2019.
3. L. Li, S.Yuan, C. Chigan, "A Relay Selection based Bidirectional Full-Duplex Communication Scheme," *in Proceedings of IEEE ICC 2018 Workshop - 3rd Workshop on Full-Duplex Communications for Future Wireless Networks*, May, 2018.
4. S.Yuan, L. Li, C. Chigan, H. Zhu, "Stochastic Game Approach for Long-term Fairness-aware Radio Resource Allocation," *in Proceedings of IEEE Global Communications Conference (Globecom 2017)*, Dec. 2017.
5. C. Zou, C. Chigan, "Dynamic Spectrum Access based Cryptosystem for Cognitive Radio Networks," *Wiley Journal of Security and Communication Networks*, Oct. 2016.

Team members (pending for approval)

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

Thank you!