

OBJECTIVE

To develop and evaluate a low-cost, energy-efficient wireless sensing node capable of continuously monitoring Carbon Dioxide (CO₂), temperature, and humidity for integration into an urban digital twin platform, enabling scalable environmental monitoring that supports healthier, more sustainable cities.

INTRODUCTION

Air pollution is a major public health concern in urban environments. Pollutants such as nitrogen oxides (NO_x), ozone (O₃), and carbon monoxide (CO) have been associated with increased risks of cardiovascular and respiratory diseases (WHO; EPA). However, traditional monitoring systems are costly and spatially limited, making it difficult to capture how emissions vary across cities.

In this study, CO₂ measurements are used as a proxy indicator of human and vehicular activity to support distributed environmental sensing. The system design, calibration accuracy, energy consumption, and communication performance are evaluated to assess its suitability for scalable environmental monitoring.

MATERIALS AND EQUIPMENT

Materials	Additional Information
NDIR CO ₂ Sensor	Gas Concentration Measurement
ARM Cortex-M4 Microcontroller	Embedded System Control
LTE-M Cellular Module	Wireless Data Transmission
MicroSD Data Logging Module	Local Data Storage
NEMA-rated Polycarbonate Enclosure	Environmental Protection
10,000 mAh Lithium-Polymer Battery	System Power Supply
PETG Frame	Structural Mounting Support
MATLAB	Data Processing
Python	Data Analysis/System Integration

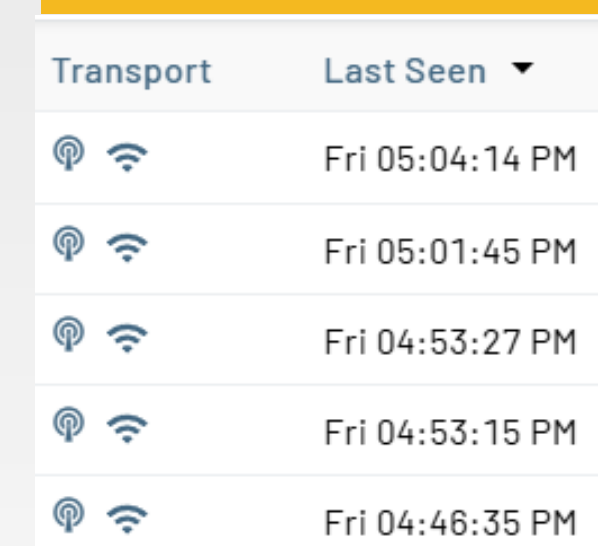
DATA COLLECTION PROCEDURE

Step 1



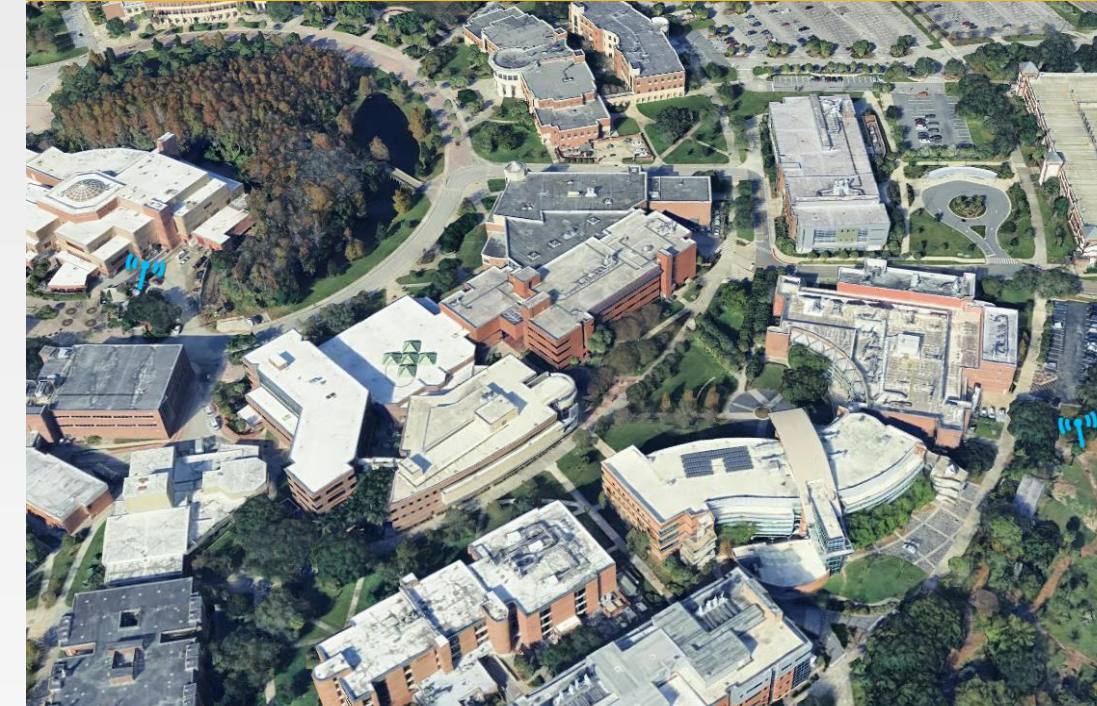
Deploy CO₂ sensor in location of choice.

Step 2



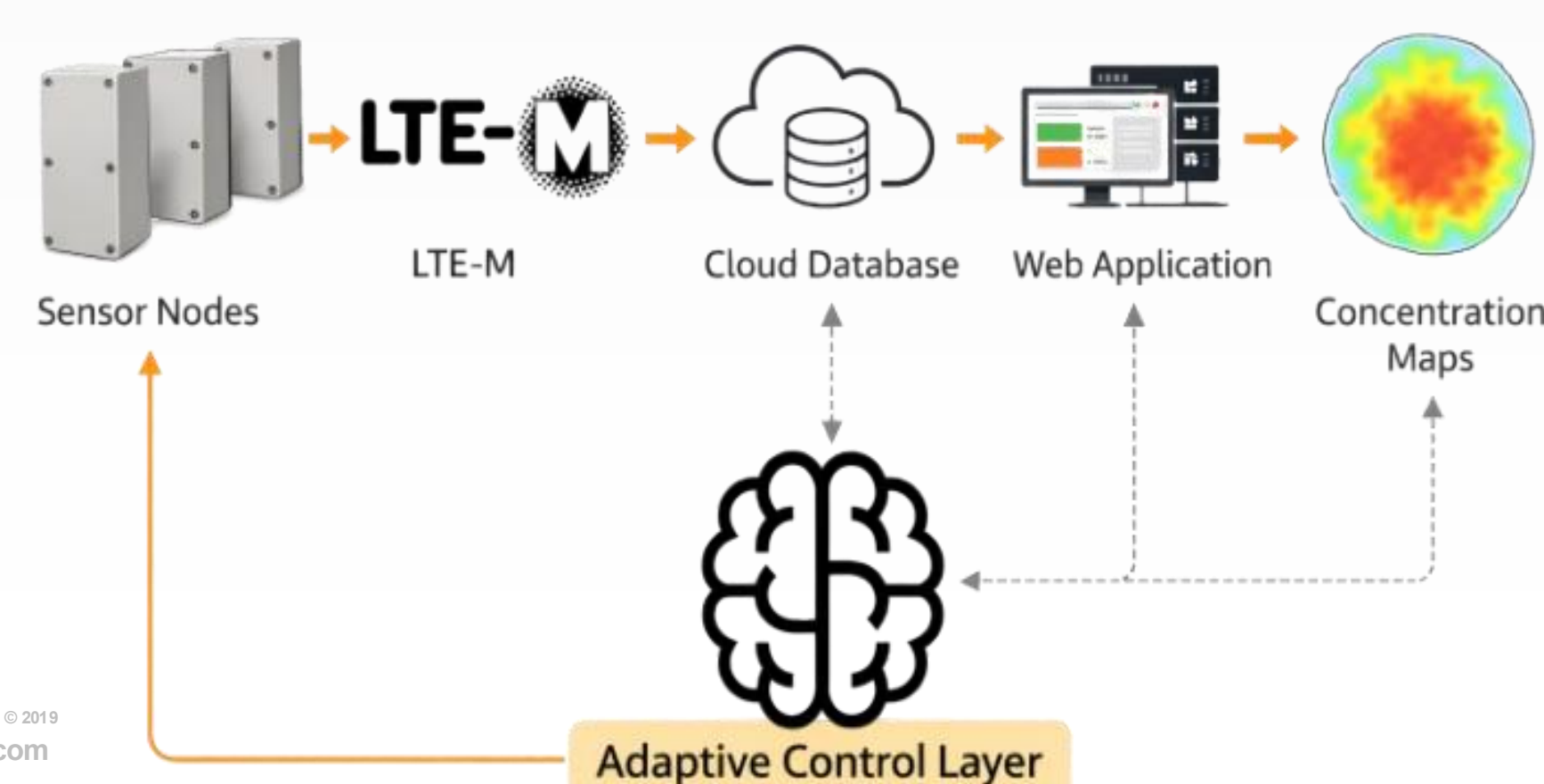
The CO₂ sensor uses LTE-M to transmit its data to a cell tower, which is then retrieved by the cloud.

Step 3



Data analysts then retrieve the data from the cloud for data interpolation.

SYSTEM-LEVEL DATA PIPELINE



CO₂ INTERPOLATION

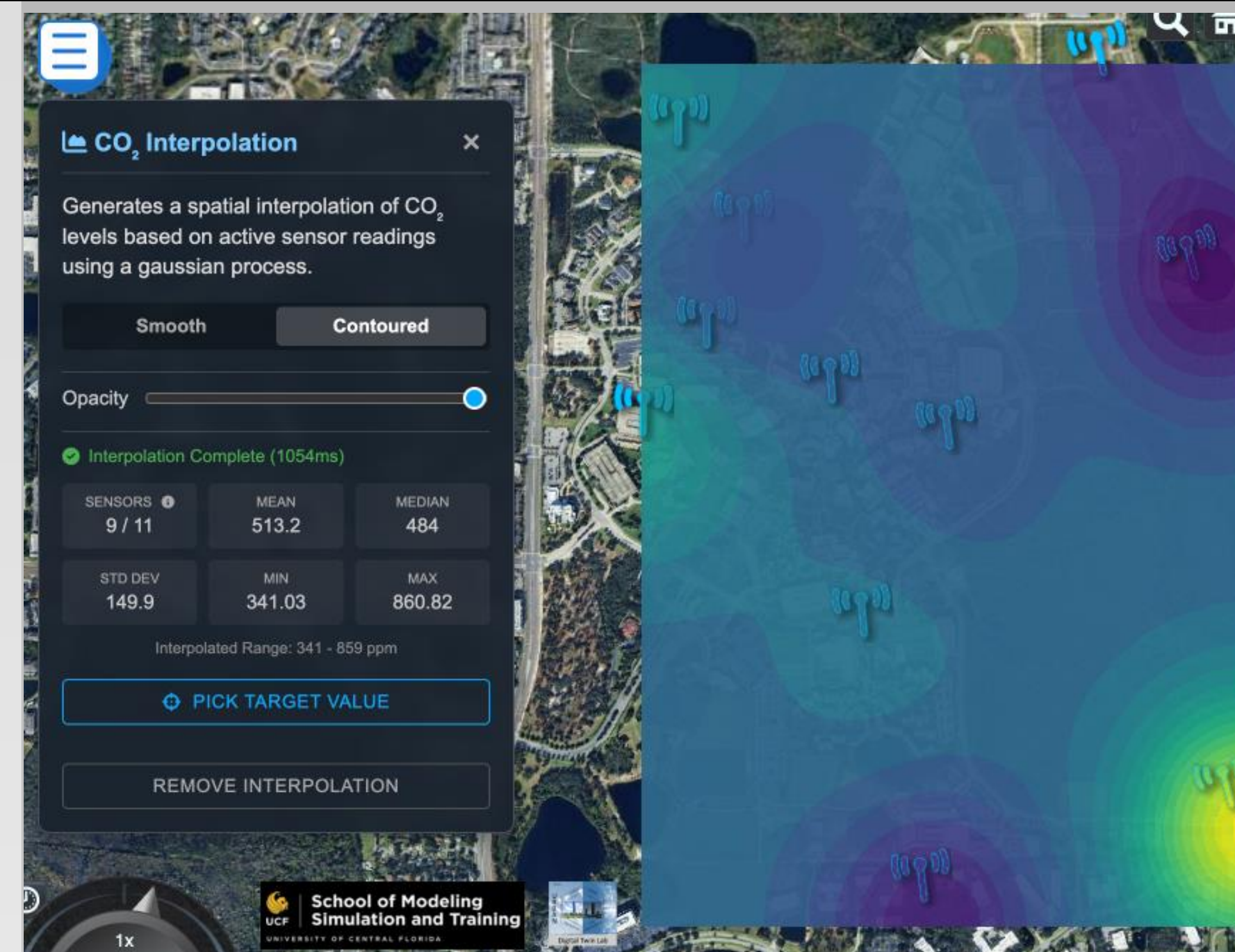


Figure 1. shows the discrete sensor measurements are interpolated using a Gaussian Process model to reconstruct a continuous CO₂ concentration field across the monitored area.

$$y(x) \sim GP(m(x), k(x, x'))$$

NUMERICAL RESULTS

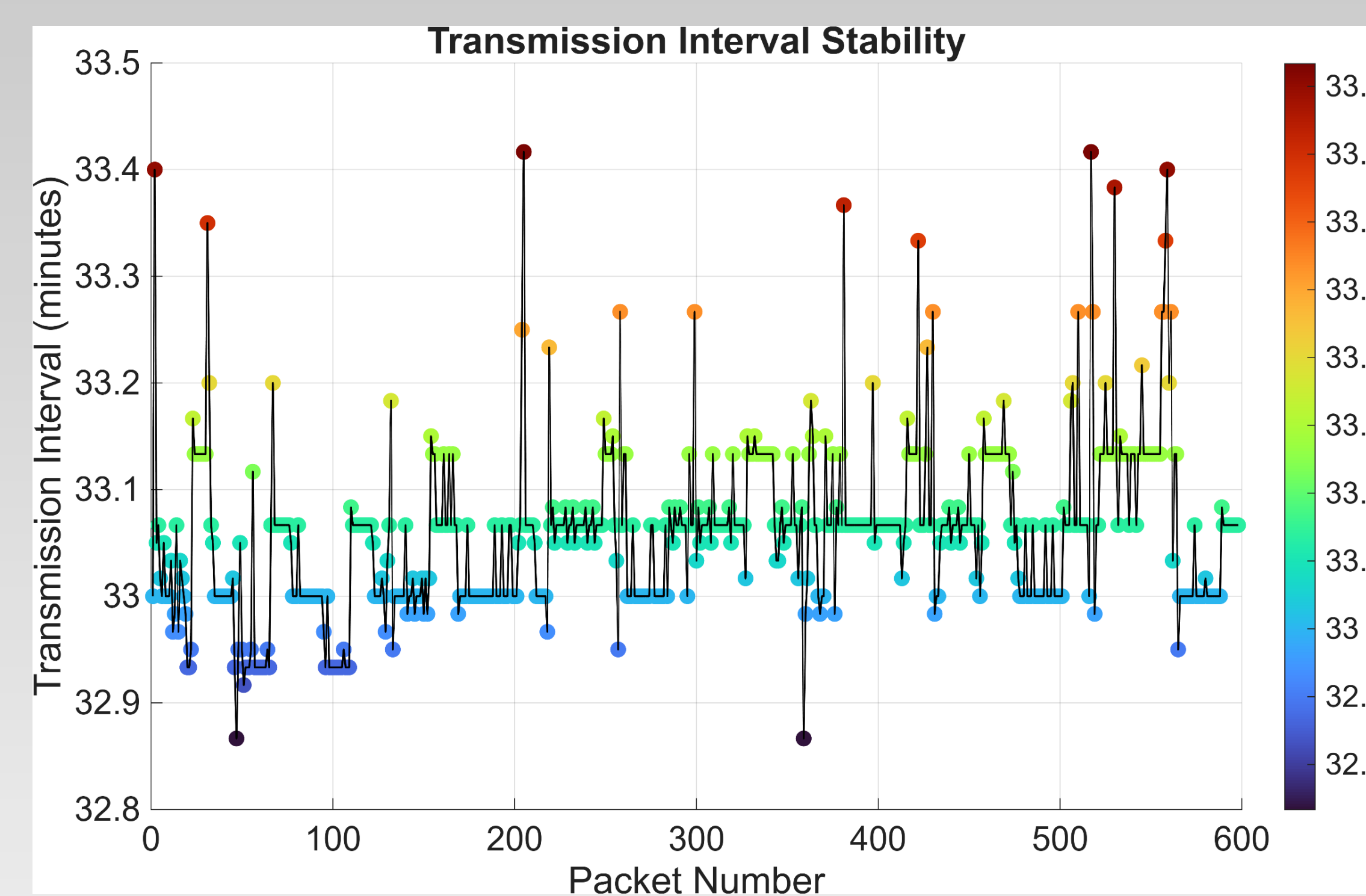


Figure 2. shows the transmission interval between consecutive sensor data packets during deployment.

Battery Discharge Profile & Linear Trend

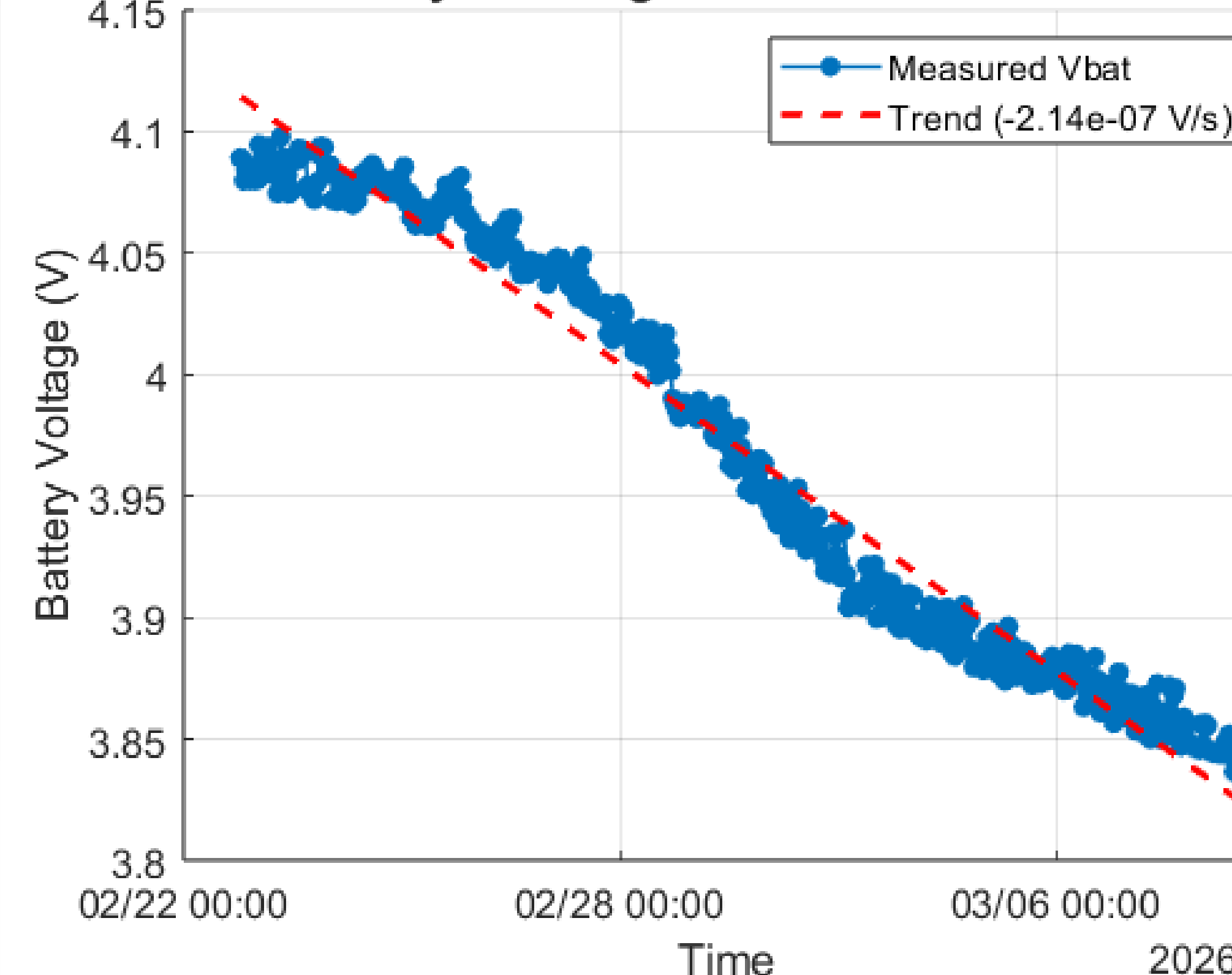


Figure 3. shows the measured battery voltage over time during the deployment period.

METHODS

Collect Environmental Measurements Obtain Sensor Sampling Frequency (f_s)

$$f_s = \frac{1}{\Delta t}$$

Each sensing node records CO₂ concentration, temperature, and relative humidity using an NDIR Sensor at fixed sampling intervals

For each node: $\Delta t =$ Sampling interval between measurements

Transmit Sensor Data via LTE-M

Sensor readings are buffered locally and transmitted in batches through the LTE-M cellular network to a cloud database.

$$\Delta t_i = t_{i+1} - t_i$$

Calibrate CO₂ Measurements

$$CO_{2cal} = \beta_0 + \beta_1 CO_{2ref} + \beta_2 T + \beta_3 RH$$

Reference CO₂ measurements are aligned with sensor timestamps. A multivariate regression model via python corrects sensor readings using temperature and humidity.

Analyze Telemetry Data (MATLAB)

$$I_{avg} = \frac{Q_{used}}{t_{deploy}}$$

Exported JSON telemetry data are processed to compute:

- transmission frequency
- sampling statistics
- battery performance

CONCLUSION

The performance of the wireless CO₂ sensing node was successfully evaluated through calibration and system-level telemetry analysis. Environmental compensation using temperature and humidity improved agreement between the low-cost sensor and the reference analyzer.

Sensor calibration was performed using multivariate regression, reducing measurement bias and improving statistical correlation between the two instruments.

System performance was validated through the following observations:

- Calibration improved agreement between the low-cost sensor and the reference analyzer, increasing correlation from $R^2 \approx 0.38$ to $R^2 \approx 0.89$.
- Raw sensor measurements exhibited systematic bias relative to the reference instrument prior to calibration.
- Wireless telemetry analysis showed stable communication behavior with transmission intervals near the programmed ~33-minute schedule.
- The sensing platform demonstrated reliable operation during field deployment with low power consumption.

The calibration results indicate that low-cost environmental sensors can provide reliable measurements when combined with appropriate environmental correction and wireless sensing infrastructure.

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