Implementation and Evaluation of the Proposed IoCT System:

The Internet of Carbon Things (IoCT) system integrates low-power wireless networks, edge computing, and cloud analytics to enable end-to-end carbon emission monitoring in agricultural environments. At the core of the device-level implementation is the Newracom NRF7292 chipset running a custom-built `sample_ioct_client` application. This application collects real-time data from sensors measuring Tier 1, Tier 2, and Tier 3 greenhouse gas (GHG) emissions, such as CO_2, CH_4, and N_2O, and transmits them over a Wi-Fi HaLow (IEEE 802.11ah) link to an edge gateway. On the edge side, the system processes incoming data and calculates CO_2-equivalent (CO_2e) values using Tier 1 (direct emissions), Tier 2 (indirect emissions), and Tier 3 (supply chain emissions) values. The edge device performs filtering, anomaly detection, visualization, and historical trend comparison using a lightweight Flask server and MQTT-based communication. While current data is simulated, the system is fully capable of working with real sensor inputs when available, as the ingestion logic is designed to switch seamlessly to live data collection. At the cloud level, the Flask-based application receives processed emissions data, stores it in a time-series database, and generates dynamic visualizations and daily recommendations. Cloud analytics include hourly and daily CO_2e trends and tier-specific gas trends, which are fed back to edge devices via MQTT. The system simulates a real-time feedback loop for emission monitoring, offering suggestions such as reducing tractor use, optimizing nitrogen application, or improving livestock practices. The cloud dashboard also supports geospatial tagging and personalized messages for users, making the IoCT platform a robust tool for precision environmental monitoring and climate-smart decision-making. Overall, this implementation demonstrates the complete IoCT pipeline from real-time sensing at the field level to actionable insights at the cloud, validating its readiness for deployment in agriculture or other emission-critical domains. GitHub Repository: https://github.com/IoCT-Organization/ioct

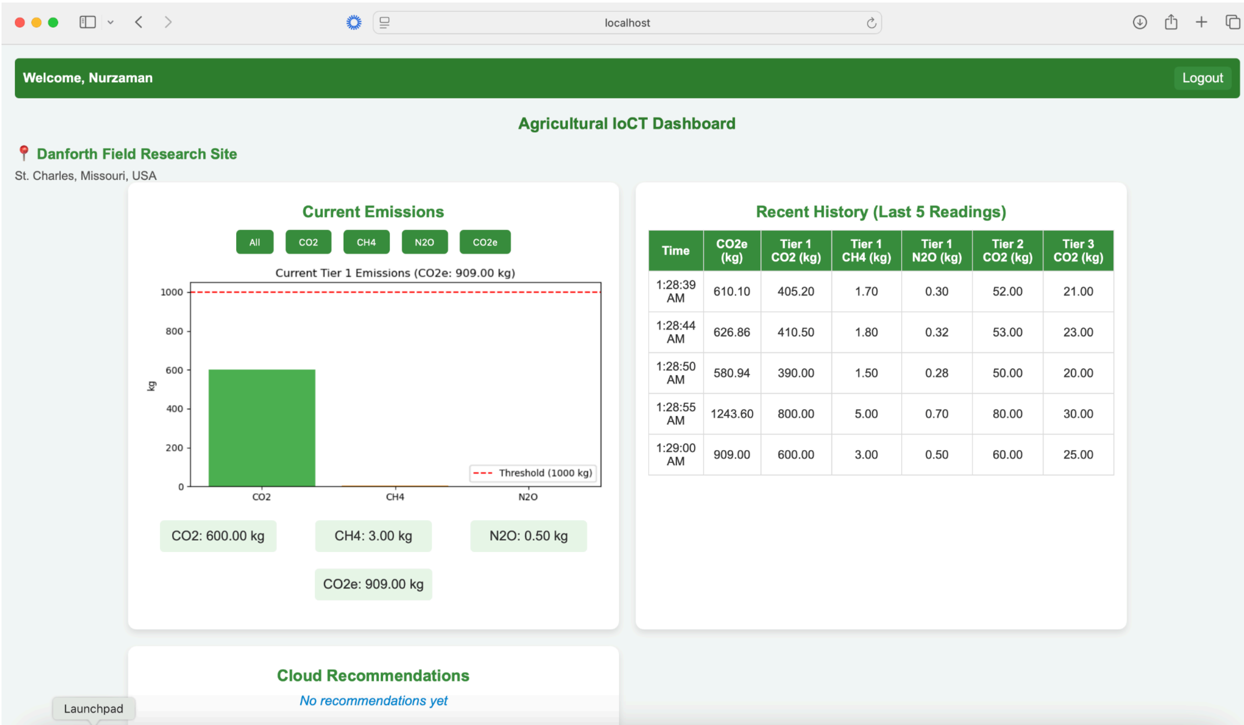

Figure Ex1. Screenshot of Edge GUI for the farmers or the admin at the local field network

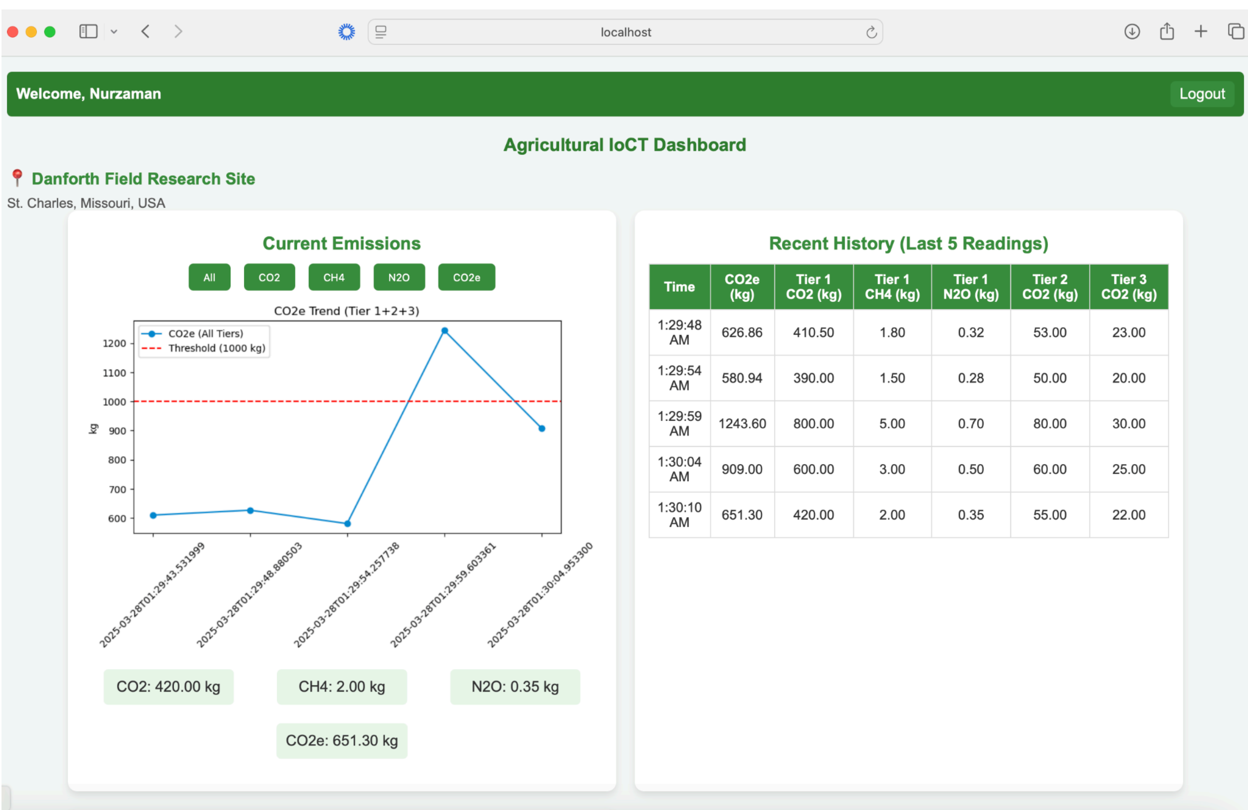

Figure Ex2. Screenshot of Edge GUI2

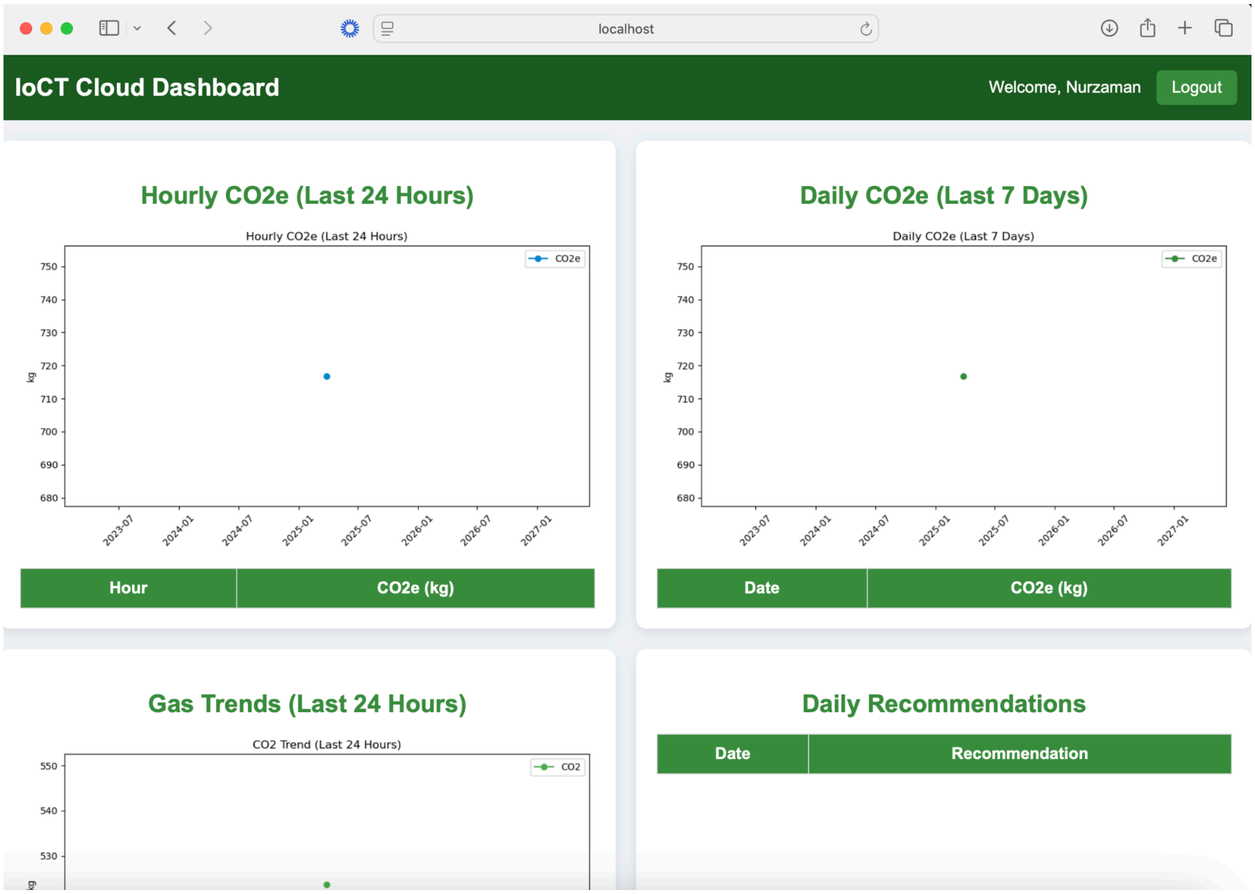

Figure Ex3: Screenshot of Cloud GUI

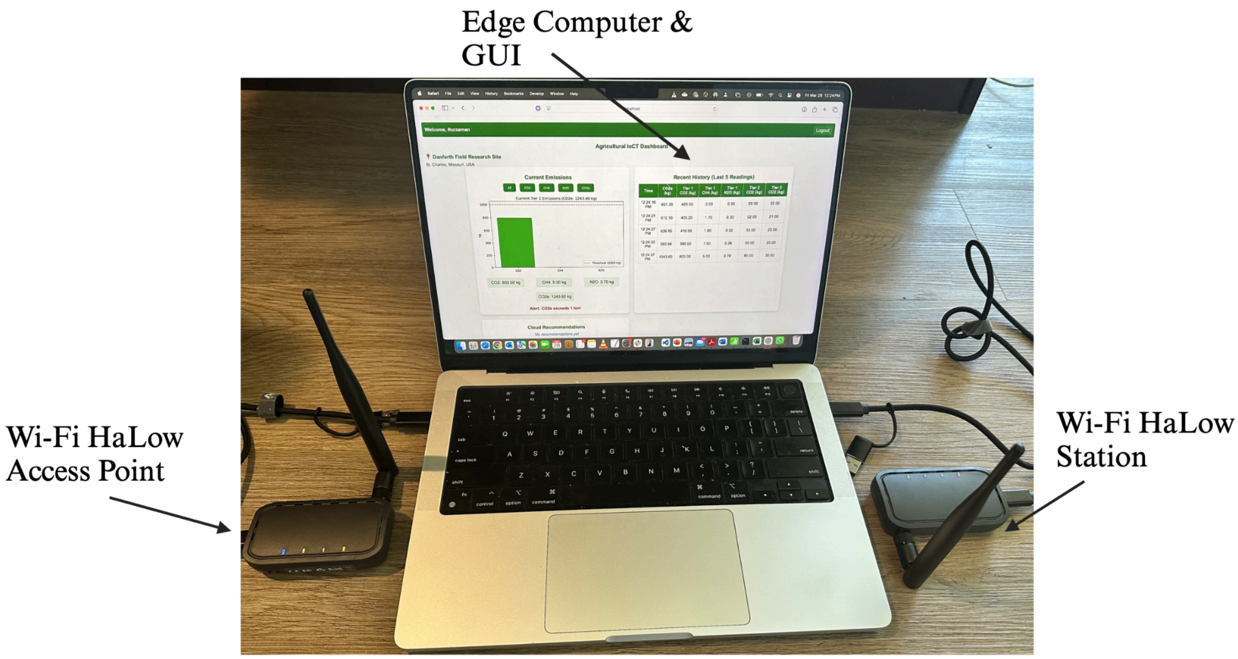

Figure Ex4: Prototype testbed setup of 1-hop Wi-Fi Halow network setup and edge GUI

Practical Evaluation of 1-hop Wi-Fi Halow (Station to AP) Network:

Our pilot Wi-Fi HaLow (IEEE 802.11ah) performance evaluation using two Alfa Network AHPI-7292S devices upgraded to OpenWrt: one serving as a gateway (AP + edge computing on a Raspberry Pi) and the other as a station (STA). Both units communicate on sub-1 GHz channels (1 MHz or 2 MHz), typically at or below 14 dBm for regulatory compliance, with **throughput and latency** measured via TCP iPerf and ping, respectively. We placed the AP in a central lab area and moved the ST to various points indoors, capturing the average round-trip times (RTT) in milliseconds and transport-layer throughput in megabits per second (Mbps). Configuration details—like channel, MCS (modulation/coding level), and bandwidth—were managed through OpenWrt's wireless interface.

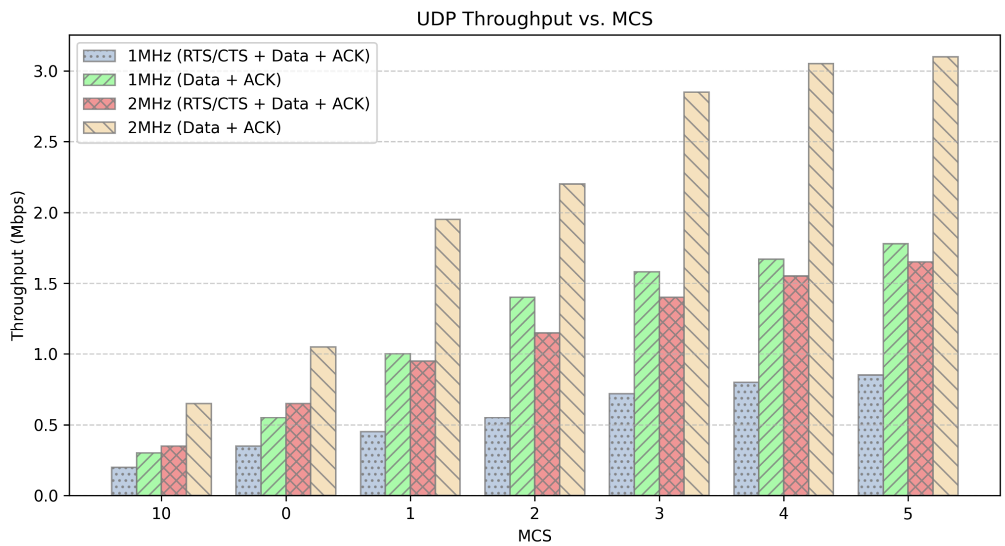

Figure Ex5. Throughput measured with increasing MCSs

Figure Ex5 presents the resulting throughput measurements across Modulation and Coding Scheme (MCS) indices, beginning with MCS 10 (lowest data rate) and extending through MCS 5 (higher data rate). The two bandwidth options—1 MHz and 2 MHz—are compared under two overhead conditions (“RTS/CTS + Data + ACK” versus “Data + ACK” alone), demonstrating how reducing control overhead or increasing channel width yields higher net throughput. These results align well with the patented “Internet of Carbon Things” system, which emphasizes robust low-power connectivity in agricultural environments for real-time, location-specific emission monitoring. By adopting either 1 MHz or 2 MHz sub-1 GHz channels, the field nodes can reliably report Tier 1, Tier 2, and Tier 3 carbon data (e.g., direct, indirect, and supply-chain emissions) to an edge-computing gateway. The higher throughput of 2 MHz can accelerate data collection in moderate-range deployments, while 1 MHz may suffice for extremely long-range or particularly obstructed scenarios. Overall, this pilot confirms that 802.11ah-based solutions, as disclosed in the patent, can effectively integrate both bandwidth settings to optimize emissions monitoring and sustainable farming practices.

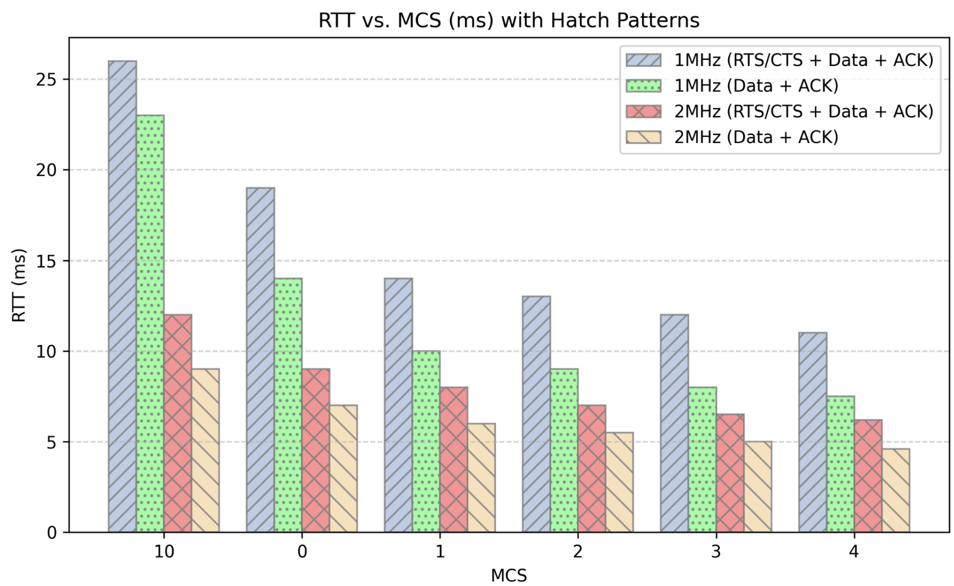

Figure Ex6. Measured RTT with increasing MCCs

As shown in Figure Ex6, channel 1 MHz and the added overhead of RTS/CTS generally increase round-trip times compared to 2 MHz with Data + ACK alone. As MCS improves from left to right (i.e., from MCS 10 to higher rates), the protocol can transmit packets more efficiently, thus reducing average latency overall. The 2 MHz (Data + ACK) remain lowest across MCS levels, indicating that less control overhead and a wider channel yield quicker turnaround. Conversely, 1 MHz (RTS/CTS + Data + ACK) sits highest, reflecting the accumulated overhead of handshaking mechanisms and narrower bandwidth.

This flexibility in adjusting MCS and channel bandwidth suits the varied demands of a heterogeneous "Internet of Carbon Things," wherein remote Tier 1, Tier 2, or Tier 3 emissions data must be captured under different connectivity constraints. Through the proposed Wi-Fi HaLow solution, edge-based networks can dynamically balance extended range, low power, and adequate throughput/latency for precise carbon monitoring tasks.