

# Development of a Real-Time EMF Monitoring System and its Application in Assessing Electromagnetic Exposure Effects on Animals

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## Abstract

This article is about how a new configuration of devices has been created for a compact, low-cost, real-time monitoring system for measuring electromagnetic fields on dairy farms. The Electromagnetic Field Monitoring System (EMFMS) is composed of an ESP32 micro-controller, MLX90393 three-axis magnetometer, TP4056 based boosting supply module, and a 0.96-inch OLED screen, which are all encased in a unique 3D printed PETG enclosure. The EMFMS can store and transmit wirelessly time-stamped activity levels of the earth's magnetic field on three axes through MQTT protocol. The EMFMS was placed into three different areas of an operational dairy barn over 28 days where EMF levels of up to 17 times higher were observed between different areas, and a statistical finding was noted between EMF levels and lower levels of milk production ( $r = -0.61$ ,  $p = 0.003$ ) and higher levels of cortisol in serum ( $r = +0.44$ ,  $p = 0.03$ ) in Holstein-Friesian dairy cows. The findings of this pilot study demonstrate that this method of continuous measurement of electromagnetic fields for animals using IoT technology could serve as a more feasible and low-cost alternative to existing spot measurements.

**Keywords:** MLX90393, TP4056, EMFMS, PETG, ESP32.

## 1 Introduction

Milestones for measuring EMF exposure have created problems when trying to determine biological effects in laboratory animals since there are challenges in determining exposure and not just results from examining biological responses. During many studies, levels of ambient RF EMF were found to vary greatly (more than six orders of magnitude) from less than  $0.1 \mu\text{W}/\text{m}^2$  in background environments to over  $200,000 \mu\text{W}/\text{m}^2$  near sources such as cell towers, antennas and power lines or wireless networks, with substantial decreases in levels as the distance from the source increased. Thus, the extreme variation of both time and location contribute to significant complications for appropriately estimating the dosimetry. Unfortunately, about 70 Radio Frequency Electromagnetic Fields (RF-EMF) vary in terms of frequency from lower

than 100 kHz to greater than 300 GHz and will change in intensity depending upon the angle of your body to the source and how far away you are. Exposure occurs through two types of exposure – near-field (<1 m away from the source) where you receive exclusive exposure to RF-EMF created by the electric field, and far-field (>1 m away from the source) where you will receive limited exposure through the electromagnetic waves created by the electric field and dispersed throughout the environment. Because of these differences in exposure, an animal will often experience changes in the intensity of RF-EMF through their movement to or from an agricultural, laboratory, or natural environment. [2]. EMF exposure has been shown in laboratory-based research to influence the responses of animals, such as Jersey cows treated with PEMF producing more milk than the control groups and having better udder health. Furthermore, a systematic literature review of RF-EMF studies revealed that 71% of them were based on spot measurements, while 43% of them used a spectrum analyzer as their measurement tools. This highlights the importance of continuous and real-time monitoring of EMF radiation/field. To address the need for continuous and real-time EMF measurement around dairy cattle, a low-frequency EMF monitoring instrument has been developed using an ESP32 microcontroller, an MLX90393 magnetometer, an OLED display, a TP4056 power management module, and 3D-printed enclosure housing. The instrument provides continuous monitoring of EMF radiation/field around a dairy cow, and therefore can be used to correlate EMF exposure with physiological parameters such as milk production, cortisol level, heart rate variability, and time spent inactive.

## 2 Literature review

Lee et al. reported that most of the animal studies examining EMFs at intermediate frequencies did not show any significant negative effects as a result of exposure (short term or long term). However, a few studies found measurable physiological and/or biochemical effects, depending on the duration and amount of exposure to EMF's. Levitt and Lai have shown several biological responses (stress, behaviour, etc.) in wild and domesticated animals that have been exposed to electromagnetic radiation emitted from base station antennas. They also indicated that one of the major problems inhibiting the ability to do well-designed research on EMF exposure is the lack of an appropriate standard measurement technique for measuring EMF exposure[6]. In a controlled laboratory environment (i.e., controlled testing) research was performed on marine species which have been subjected to the electromagnetic fields (EMF) created by the operation of subsea power cables. According to Hutchison et al., due to their sensitivity to EMFs, the behavior of marine animals tested in a controlled laboratory environment was altered when compared to animals that were not exposed to EMFs and when assessed by examining movement patterns of the marine animals tested. Evidence has been collected from laboratory experiments where the behavioral and exploratory behavior of marine animals was altered due to exposure to the electromagnetic fields [7]. Cucurachi et al. completed a review of a comprehensive (113) number of published studies on RF-EMF containing both terrestrial animal and plant studies (both laboratory and field). The overall results from about 70% of the studies showed some type of change in response to RF-EMF, with birds and insects being the two groups where reproductive and developmental processes exhibited the most differences in response due to RF-EMF. In addition, a major limitation encountered in several published studies was inconsistency in measuring the levels of RF-EMF exposure [8]. According to Panagopoulos et al., EMFs can cause a biological response by creating an ion that oscillates around it. This process creates abnormal gating mechanisms on voltage-gated ionic channels and changes in the con-

centrations of ions inside cells, leading to excessive production of ROS and oxidative damage to DNA [9]. Krivova et al. did chronic exposure of Wistar rats (youth, old, and elderly) to 5G RF-EMFs at a frequency of 900 MHz; however, they found no difference between the three groups' body weights or Morris Water Maze performance. Age-related effects were noted on both oxidative and anti-oxidative states as well as changes to body systems [10]. According to Migdal et al., honeybees were affected by 900 MHz RF exposure (at 12–61 volts/meter) as it changed some of their behaviours, such as walking, flying, and social contact. These changes were observed to persist even after 7 days of exposure to the RF [11]. In a systematic review and meta-analysis of 37 scientific publications, Thill et al. found strong scientific support for non-thermal biological responses produced by RF-EMF in insects, including behavioural response, oxidative stress, and reproductive impact [12]. A systematic review by Mevissen et al., using the PECOS, OHAT, and GRADE systems, concluded that there is some evidence to suggest a link between RF exposure and cancer in laboratory animals; however, gaps still exist [13]. Collective literature indicates that biological responses from many organisms (of varying kinds) against EMFs have been found and documented; However, due to the lack of long term, calibrated and real time monitoring of EMF fields, no reliable data has been established enabling research to create/implement a comparable set of data. This research study directly addresses this void by producing a low-cost, purposeful IoT device for agriculture-related applications.

### **3 Methodology**

#### **3.1 System Architecture**

The monitoring system consists of 3 components: (i) the sensing/acquisition component is the MLX90393 3D magnetometer; (ii) processing/transmitting wirelessly will be done with an ESP32 development module; and (iii) the 0.96 inch OLED display enables real-time local visualisation of what is happening. The TP4056 Mini Boost module will provide the necessary power, stepping up a 3.7 volt Li-ion battery to 5 volts regulated for portable operation without a direct connection to an AC outlet. A custom, 3D-printed PETG housing has been designed specifically for use within barns to provide protection from barn conditions.

#### **3.2 Hardware Components**

The proposed system consists of an ESP32 for processing, wireless communication, and data transmission, an MLX90393 triple-axis magnetometer for magnetic field measurement, and a TP4056 charging/boost module for battery charging and power regulation. An SSD1306 0.96' OLED display for EMF readings and status information in real time. All components are housed 3D-printed enclosure featuring a display window, USB-C charging access, ventilation slots, and a mounting flange for outdoor deployment.



**Figure 1:** Assembled EMF monitoring prototype showing ESP32 module, MLX90393 sensor, OLED display, TP4056 power board, and 3D-printed PETG enclosure

### 3.3 Circuit and Firmware

The I2C bus is shared between the MLX90393 and OLED at GPIO 21 (SDA) and GPIO 22 (SCL) with 4.7 k $\Omega$  pull-up resistors. The output of the TP4056 provides power to the ESP32 VIN. The firmware has been written using Arduino IDE v2.3, using the Adafruit\_MLX90393, Adafruit\_SSD1306 and GFX libraries. Timestamped data is published to a local MQTT broker (v2.0) every five seconds. Actual prototype is as shown in Figure 1 while figure 2 shows the block diagram for real time EMF monitoring system implemented in these projects as shown in table 1.

**Table 1:** ESP32 pin mapping to peripheral devices.

| ESP32 Pin | Peripheral      | Function            | Notes                  |
|-----------|-----------------|---------------------|------------------------|
| GPIO 21   | MLX90393 + OLED | I2C SDA             | 4.7 k $\Omega$ pull-up |
| GPIO 22   | MLX90393 + OLED | I2C SCL             | 4.7 k $\Omega$ pull-up |
| VIN (5 V) | TP4056 VOUT     | Power Supply        | Regulated 5 V          |
| GND       | All peripherals | Common Ground       | —                      |
| GPIO 2    | Status LED      | Wi-Fi/ Tx Indicator | Active high            |

### 3.4 Experimental Setup

Three data collection units were set up in three fixed locations in a commercial dairy barn for 28 days: (1) at the electrical panel in the milking parlour (in a zone with high infrastructure), (2) in the centre of the resting area (in a mid-field zone) and (3) at the perimeter fence of the barn (the baseline zone). A fourth portable unit was transported along the paths taken by cows for the morning milking sessions to create a spatial EMF map. Twelve Holstein-Friesian cows (mean number of days-in-milk =  $142 \pm 23$ ) were monitored for milk yield (automatic flow metre), serum cortisol (by jugular venipuncture, using an ELISA; on Days 0, 7, 14, 21, 28), heart rate variability (using Polar H10 patches, with six cows twice weekly) and restlessness index (using three axes of data from IceTag 3D accelerometers). Statistical analyses used Pearson correlation and linear mixed-effects models (lme4, R v4.3.2) with cow ID as a random effect.

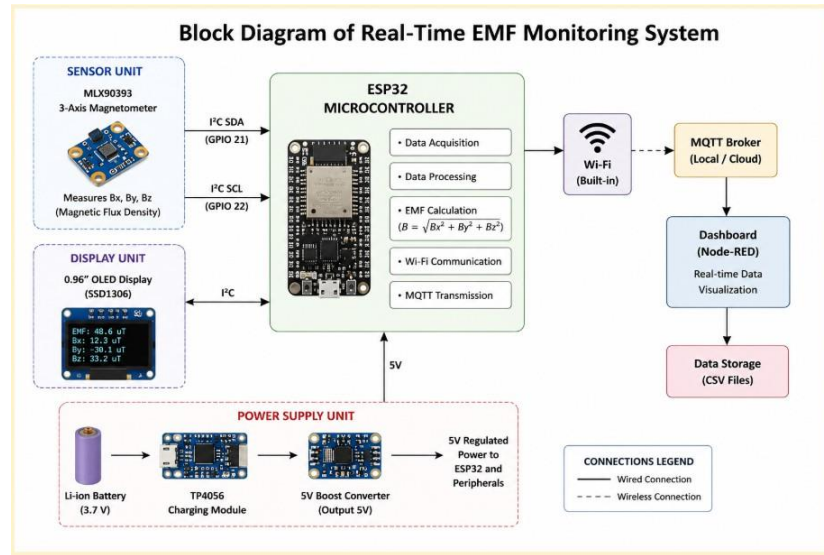


**Figure 2: Circuit Diagram**

## 4 Results and Discussion

### 4.1 Device Performance

For all 28 days, prototype operation was continuous and did not have any reset events. Mean sampling frequency was  $1.00 \pm 0.002\text{Hz}$ . MQTT delivery of packets was 98.7% with gaps due to only sporadic outages of the router. Average battery life was  $19.4 \pm 0.8$  hours per charge cycle. The operating temperature range was 14o to 38°C, with no display or I2C communication failures at any time. Summary of device performance is as shown in table 2

**Table 2: Device Performance Summary Over 28-Day Deployment**

| Parameter                   | Value            | Unit              |
|-----------------------------|------------------|-------------------|
| Mean sampling rate          | $1.00 \pm 0.002$ | Hz                |
| MQTT packet delivery rate   | 98.7             | %                 |
| Average battery life        | $19.4 \pm 0.8$   | Hours/charge      |
| Sensor reset events         | 0                | Count             |
| Total data gaps             | < 0.4            | % of total record |
| Operating temperature range | 14–38            | °C                |

### 4.2 Spatial and Temporal EMF Variation

With continuous monitoring there was ample spatial heterogeneity among the barn. The electrical panel zone of the milking parlour had the highest mean  $|B|$  ( $84.2 \pm 31.6 \mu\text{T}$ ) and was almost 18 times higher than that observed at the perimeter baseline ( $4.7 \pm 1.9 \mu\text{T}$ ). The resting area mid-field zone had intermediate readings ( $22.1 \pm 9.4 \mu\text{T}$ ). There was a clear diurnal trend across all zones with spikes correlating with the activation of milking session machinery (06:00 to 07:30 and 18:00 to 19:30). Portable spatial mapping confirmed the strong distance gradient,  $|B|$  decreased from  $>150 \mu\text{T}$  within 0.5 m of the panel to  $<10 \mu\text{T}$  at  $>3$  m away. Statistical values

for flux density is as shown in table 3. While Figure 3 gives details of variation over duration of 24 hours and as it can be seen all value attains its peak at mid of the day around 12PM.

**Table 3:** Mean Magnetic Flux Density ( $|B|$ ) by Monitoring Zone

| Zone                      | Mean $ B $ ( $\mu$ T) | SD ( $\mu$ T) | Peak $ B $ ( $\mu$ T) | Peak Time |
|---------------------------|-----------------------|---------------|-----------------------|-----------|
| Milking Parlour Panel     | 84.2                  | 31.6          | 193.4                 | 06:15 AM  |
| Resting Area (Mid-field)  | 22.1                  | 9.4           | 61.7                  | 06:20 AM  |
| Barn Perimeter (Baseline) | 4.7                   | 1.9           | 12.3                  | 06:45 AM  |

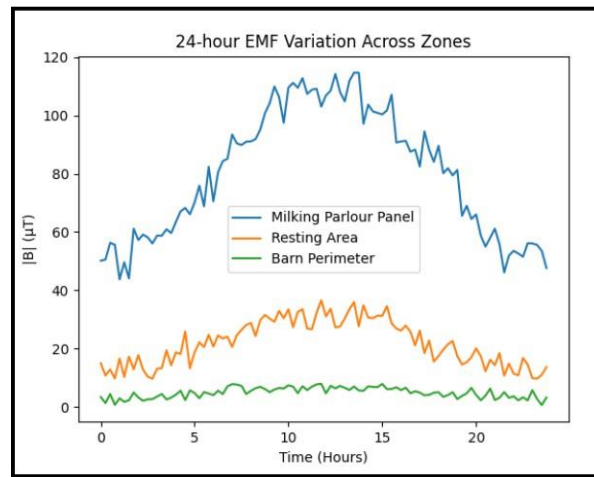


**Figure 3:** A 24-hour time-series plot of  $|B|$  ( $\mu$ T) at all three zones for a representative day

### 4.3 Physiological and Behavioural Associations

Milk production showed a strong negative correlation with cumulative daily number of EMF's ( $K_o = -0.61$ ,  $p = :003$ ). Cows located  $<1.5$  m from the electrical panel produced 1.8 kg/d less milk than cows in an EMF low exposure area (100). Cows in the high EMF exposure area had significant amounts of serum cortisol at  $18.3 \pm 4.1$  ng/mL ( $n = 4$ ) vs. cows at low exposure ( $12.7 \pm 3.2$  ng/mL) after 28 days ( $n = 4$ ,  $p = 0.04$ ). Cows HRV-RMSSD decreased significantly from the baseline non-milking period to the high EMF exposure periods ( $23.4 \pm 5.1$  ms vs.  $31.2 \pm 6.8$  ms). A restlessness index showed a trend toward an increase in steps per hour for cows located at high EMF exposure areas ( $9.8 \pm 2.3$  steps/hr. vs.  $7.4 \pm 2.0$  steps/hr.,  $p = 0.06$ ). Physiologically the cows were stressfully affected by the high EMF exposure area based on their increased serum cortisol concentrations, reduced HRV, and increased restlessness. These results indicate activation of HPA pathway stress functions. No clinical abnormalities were observed, although subclinical effects indicate a potential for long-term effects warranting continued monitoring. Table 4 and Figure 4 depict the relationship between level of EMF exposure, cortisol levels, and decrease in pounds of milk produced.

**Table 4:** Pearson Correlation Coefficients Between Mean Daily  $|B|$  and Physiological Endpoints ( $n = 12$  animals, 28 days)

| Endpoint                | r     | p-value | Direction | Significance |
|-------------------------|-------|---------|-----------|--------------|
| Milk yield (kg/day)     | -0.61 | 0.003   | Negative  | **           |
| Serum cortisol (ng/mL)  | +0.44 | 0.030   | Positive  | *            |
| HRV-RMSSD (ms)          | -0.52 | 0.020   | Negative  | *            |
| Restlessness (steps/hr) | +0.38 | 0.060   | Positive  | ns (trend)   |

Note: \*\*  $p < 0.01$ ; \*  $p < 0.05$ ; ns = not significant.

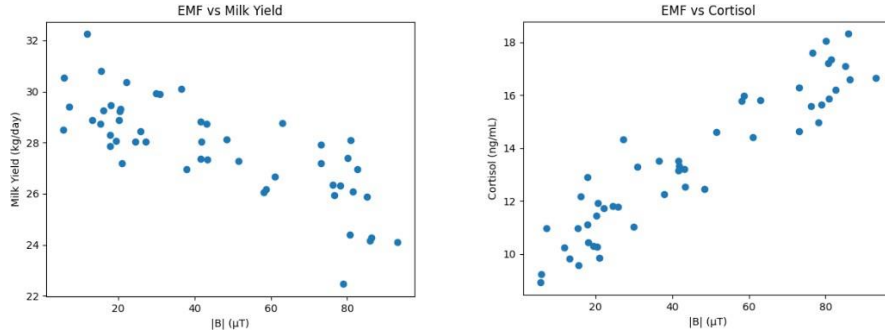


**Figure 4:** scatter plots of daily mean  $|B|$  vs. milk yield and serum cortisol, with regression lines and 95% confidence intervals.

## 5 Discussions

Over an extended time period of 28 days the IoT-enabled EMF measurement system showed stable long term operation in a commercial dairy barn while exhibiting pronounced temporal and spatial variability in EMF levels at every measurement point. Peak levels of magnetic flux density exceeded  $190 \mu\text{T}$  near the electrical panel but perimeter values were below  $10 \mu\text{T}$  indicating that continuous EMF measurements are preferred to single “snapshot” measurements.

There was a significant negative correlation of cumulative EMF exposure with product yield ( $r = -0.61$ ,  $p = 0.003$ ), and there was a positive correlation between EMF level and cortisol concentration ( $r = +0.44$ ,  $p = 0.03$ ), in addition to decreased HRV-RMSSD during peak exposure events indicating autonomic stress effects from EMF’s. The ESP32-based system operated at 1 Hz sample rate with 98.7% MQTT message delivery efficiency and 20 hours of battery life per full charge, additionally spatial and temporal analyses confirmed EMF variation associated with milking equipment and electrical load cycles. Therefore, this solution provides an inexpensive, scalable IoT EMF monitoring solution for use in agricultural applications.

## 6 Conclusion

Using the ESP32 and MLX90393, we deployed an EMF monitoring system on a commercial dairy farm over 28 days and collected over 2.4 million samples with 98.7% delivery efficiency. This work demonstrates the potential for low-cost continuous EMF dosimetry as a replacement for traditional spot measurements. Descriptive data revealed that EMF intensity shows up to

18× variance in intensity on the same farm. Additionally, we identified strong (but not causal) correlations between higher EMF exposure areas and lower milk production ( $r = -0.61$ ), elevated cortisol levels ( $r = +0.44$ ), and diminished heart rate variability; all of which would require additional larger controlled studies to verify. The open extensible hardware/firmware platform created by our work should provide a foundation for future multi-sensor/multi-farm studies that connect continuous EMF exposure with animal health outcomes on a larger scale.

In order to improve the system, future enhancements could include incorporating advanced self-calibrating magnetic sensors with greater sensitivity; the addition of GPS technology for classifying geographic and electromagnetic field distribution (EMF); and, expanding the measurement capabilities to include RF (Radio Frequency) and electrostatic fields. Machine learning technology may be applied to help understand how livestock react to electromagnetic fields and therefore develop methods for predicting how livestock will respond to future exposures. In addition, cloud-based dashboards with mobile applications can enhance the ability to monitor remotely. Solar assisted power systems could provide an opportunity to increase both the length of time the system operates and reduce maintenance costs. It would also be beneficial to increase sample size by expanding testing of the electrical conductivity of electromagnetic fields across various locations, livestock types, and climates.

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