An Ultra-low Power IoT System for Indoor Air Quality Monitoring

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Abstract. Air pollutions induce most deaths from heart-diseases, lung-cancer, and strokes. Therefore, a mechanism to create cognizance of air pollution amongst the habitats of any locality is indispensable. This work presents an Ultra-low-power IoT System (ULP-IoTS) for Indoor Air-Quality Monitoring. The developed ULP-IoTS provides instantaneous indoor atmospheric air quality readings on Carbon monoxide (CO), Carbon dioxide (CO2), Fine-particle (PM2.5), Temperature, and Humidity. The IoT-node integrates MICS-5524 and MQ-135 DHT-11 multi-sensors with ESP32 (ultra-low-power) microchip. The node architecture exploits ESP32 Deep-sleep, and Modem-sleep configurable modes to complement the Active-mode and aid optimal power-saving. The real-time readings from the ULP-IoT node is dispatched to an IoT-gateway that eventually post the pollutant-reading to an external IoT-server for user-retrieval on android-applications. The test-bed experimental results validate the proposed ULP-IoTS to guarantee long-term minimal power consumption and reliable indoor air-quality tracking.

Index Terms: Air Quality, ESP32, Internet of Things, Power consumption , ULP

1. Introduction

INTERNET of Things(IoT) is a network of linked devices or objects embedded with sensors, internet connectivity, and various hardware-units that enable message exchange and control over the net without hand-operated supports[1]. Over the past years, researchers have made remarkable efforts to develop cost-effective and alternative systems for air quality monitoring using IoT technology [2-6]. Most of these IoT solutions intend to offer low-cost and user-friendly real-time air-quality data acquisition mechanisms. Air pollution conditions are recorded mostly with conventional devices with fixed-monitors [7]. However, typical air-monitors are pricey, weighty, heavy, and have subdued scalability and data availability. Thus, the low-cost sensor-based IoT technology in atmospheric monitoring has drawn notable research attention lately [8], [9], [10], [11].

Wang and Chen in [8] adopted a vehicular sensor network (VSN) to track air quality in major metropolitan cities. The authors suggested an efficient-data
gathering and estimation (EDGE) policy that facilitate the acquisition of the VSN data. Kim et al. in [9], presented a WSN-based real-time air quality monitoring solution which is designed to track degrees of volatile organic compounds, sulphur dioxide (SO₂), fine particle (PM₂.⁵), ozone (O₃), carbon monoxide (CO), nitrogen oxides carbon dioxide (CO₂) and (NO₂). In [10], Firdhous et al. introduce an IoT-enabled IAQM mechanism. The nodes wirelessly communicate with their gateway employing Bluetooth technology, whilst the gateway communication with external-server with Wi-Fi. The authors restrict the suggested mechanism to measurements of ozone produced by photocopiers in indoor office-spaces. In [11], Swati et al. propose a three-phase IoT based AQI monitoring system for air pollution tracking. The suggested system is developed with Arduino and multi-gas sensors. The nodes are duty-bound to observe various atmospheric gases and communicate the recorded readings to cloud-server using Wi-Fi protocol. The authors developed an IoT-Mobair Andriod application that easily allows users to obtain the pollutant readings on hand-held devices.

One of the highest barriers to the successful implementation of IoT is enacting functional and sustained deployment [12]. The IoT multi-functionality comes with an additional cost of power consumption. Although conventional batteries are the most apparent resolution for remote IoT applications, it is not permanently cost-effective. Most alternative IoT-based solutions for air-quality monitoring in the literature do not ensure long-term operation as they focus on user-friendliness and real-time data availability. Therefore, both power-saving, reliability and cost-effectiveness must be well-considered whilst designing IoT solutions for air quality monitoring applications.

In this work, we present an Ultra-low-power IoT System (ULP-IoT) for Indoor Air-Quality Monitoring. The developed ULP-IoT is intended to provide instantaneous indoor atmospheric air quality readings on Carbon dioxide (CO₂), Fine-particle (PM₂.⁵), Carbone monoxide (CO), Humidity and Temperature. The IoT-node integrates MICS-5524 and MQ-135 and DHT-11 multi-sensors with ESP32 (ultra-low-power) microchip. The node architecture exploits ESP32 Deep-sleep, and Modem-sleep configurable modes to complement the Active-mode and aid optimal power-saving. The real-time readings from the ULP-IoT node is forwarded to an IoT-gateway that ultimately post the pollutant-reading to an external IoT-server for user-retrival on android-applications. The proposed ULP-IoTS performance is validated to authenticate the overall reliability and power-saving performance. Explicitly, the unique ULP dispositions of the system aid a user to gain long-term and instant cognition on data about pollution concentration in indoor settings at minimal cost.

![ULP-IoTS network set-up](Fig.1)

### 2. Proposed Ultra-low-power IoT System

This section gives describes the proposed ultra-low-power IoT system (ULP-IoTS).

#### A. Overview of proposed ULP-IoTS architecture

Figure 1 illustrates the proposed ULP-IoTS network set-up. The proposed ULP-IoTS is expected to reveal the human-triggered activities capable of causing bad-air and affecting indoor atmospheric air quality negatively. The IoT-node architecture is also expected to satisfy both needs for cost-effectiveness, user-friendliness, accuracy, and real-time data availability. The ULP-IoTS comprises multi-sensor node devices that are duty-bound to monitor Fine-particle (PM₂.⁵), and Carbon Dioxide...
(CO₂), Carbon Monoxide (CO), Humidity, and Temperature, and transfers the tracked measurements to the IoT-gateway in a single-hop. The gateway is expected to post the real-time information secured from the nodes to a cloud-server for user retrieval on an android application. Hence, a user can access the air pollutant readings via a mobile application or website.

The feature of low cost sensor varies broadly. Thus, applicable calibration and smoothing schemes are applied at the IoT-node to resolve pre-calibration issues, detect, and remove outliers. The IoT-node architecture is shown in Figure 2. It comprises Sensing-Unit, Processing-Unit, Transceiver-Unit, and Power-Supply. The sensing-unit integrates MiCS-5524 and MQ-135 sensors for CO and CO₂/PM₂.₅ measurements [13], [14].

The sensing unit also incorporates a DHT-11 sensor for Humidity and Temperature reading. Sensory readings from the node’s ADC unit are passed to an ESP 32-Ultra low power microchip module. The gateway is based on Raspberry pi 3B module, as shown in Figure 3(a) and (b). The IoT-node and IoT-gateway communication follow Wi-Fi 802.11 b/g/n protocol while that of the IoT-gateway and IoT-server follows HTTP (Hypertext Transfer Protocol (HTTP)).

B. Ultralow power-saving mode at IoT-node

The developed ULP-IoT architecture exploits the benefits of ESP32 chip deep sleep, and modem sleeps configurable modes to complement the active-mode and aid optimal power-saving at the IoT node. The timing diagram for node operation is illustrated in Figure 4. The active mode is the normal operation mode of ESP32 [15]. In Active-mode, each feature of the node’s ESP chip is active. This mode retains the entirety by keeping ON the processing cores and Wi-Fi module. While exploiting the Wi-Fi functionality, the chip necessitates a current of more than 240mA to function. This mode is the most current demanding and incompetent mode. Thus, to aid optimum power saving, the active mode is periodically disabled based on the indoor air pollution application needs whilst leveraging one other power-saving modes.
During modem sleep, all modules of the node’s chip are active whilst the Wi-Fi radio is turned off. The clock is reconfigurable while the CPU is operational. In modem sleep, the ESP chip consumes about 20mA at a high-speed and 3mA at slow-speed. Additionally, to retain Wi-Fi connectivity, the Wi-Fi radio and CPU are woken-up on predefined interludes. This pattern is referred to as Association Sleep. In this sleep pattern, the power-mode of the chip changes between active and modem sleep modes. This mode is exploited when the chip associate with a router (in station mode) and retains connectivity via DTIM beacons.

During deep sleep, most RAM, digital peripherals, and CPU of nodes are turned off. Only the RTC controller, RTC peripherals such as RTC memories and ULP co-processor are turned on. The ESP chip expends about 0.15 mA-to-10µA (if ULP co-processor is turned on). During this sleep-state, the main CPU is turned on, while the ULP co-processor realizes sensor measurements. The ULP co-processor activates the main system according to the recorded sensor data. This pattern of sleep is referred to as ULP Sensor Monitored-Pattern.

C. ULP-IoTS energy consumption analysis

The ULP-IoTS energy consumption per operational-cycle is estimated with:

$$ E_T = E_{\text{Sense}} + E_{\text{Process}} + E_{\text{Comm}} $$

where $E_{\text{Sense}}$ denotes the energy utilized in sensing the indoor atmospheric humidity, temperature and diverse gases such as PM2.5, CO, and CO2, which can expressed as

$$ E_{\text{Sense}} = \sum_{i=1}^{N} E_{\text{Sense}_i} \cdot (2) $$

Here $i = 1,2,...,N, E_{\text{Sense}_i}$ is the energy expend by an IoT-node in recording/sensing the indoor atmospheric reading, $N$ represents the over-all devices (IoT-nodes). As well, $E_{\text{Process}}$ is the energy expended in processing the various recorded indoor atmospheric data, which is defined as

$$ E_{\text{Process}} = \sum_{i=1}^{N} E_{\text{Idle}_i} \cdot t_{\text{est}} \cdot (3) $$

where $E_{\text{Idle}_i}$ denotes the energy spent by an IoT-node device at the course of transiting from idle to active state, $t_{\text{est}}$ is the time between the transition. Furthermore, $E_{\text{Comm}}$ is the communication energy diffusion of the IoT-node devices, which can be expressed as

$$ E_{\text{Comm}} = \sum_{i=1}^{N} E_{\text{RX}_i} + E_{\text{TX}_i} \cdot (4) $$

where $E_{\text{TX}_i}$ denotes energy for transmission and $E_{\text{RX}_i}$ denotes energy for reception.

3. Experimental analysis

This work's foremost objective is to design and implement an Ultra-low-power IoT system (ULP-IoT) that can meet the needs for power-saving, improved reliability, and cost-effectiveness in Indoor Air Quality Monitoring applications. Therefore, the tracked PM2.5, CO, and CO2 measurements from
the ULP-IoTS is expected to provide a factual-basis for a user to recognize daily indoor pollution-concentrations, the elements involved, and their triggers and implement preventive measures.

Typically, carbon monoxide (CO), when inhaled by humans, can lead to a high amount of poisoning. Carbon-dioxide (CO$_2$) in huge quantities can decrease our concentration levels and be fatal to our physical health. Fine-particle (PM2.5) levels naturally increase when there is little or no wind and can move intensely into respiratory tracts and transverse into the lungs.

Therefore, to test the over-all operation of the proposed ULP-IoTS, a 5-hour indoor AQ measurement experiment was conducted in a (35m x 30m) indoor-space. As metrics to disclose the atmospheric AQ of two target locations (L$_1$, L$_2$)

![AQ web application output](image1)

![Temperature/relative-humidity dependence](image2)

**Fig. 5:** (a) AQ web application output; (b) Temperature/relative-humidity dependence within the indoor-area of interest, CO$_2$, PM$_{2.5}$, and CO concentrations have been studied in addition to temperature and humidity dependence. Figure 5 (a) and (b) illustrate the AQ web application output and the indoor temperature/relative-humidity measurements for the indoor-space under consideration.

**Table 1** presents the hardware parameters.

| Parameter          | Value                  |
|--------------------|------------------------|
| MAC                | Wi-Fi021 M/B/n (point-to-point) |
| Data rate          | 2.4 GHz (20 Mbps)      |
| WiFi Rx packet     | 160*240mA              |
| 1340mA*215mA       | WiFi Rx and listening  |
| 80*50mA            | Battery voltage        |
| Initial-energy capacity | 3.3V/2500 mAh          |
Figures 6 (a), (b), and (c) graphically compares the CO$_2$, CO, and PM$_{2.5}$ for both areas in the indoor-space. Table 2 presents energy consumption analysis for the 5-hours indoor AQ tracking for two IoT-nodes (IoT-N$_1$ and IoT-N$_2$). From the presented energy-consumption result in Table 2, it can be attested that the energy-consumption at both IoT-nodes throughout the 5-hours is reasonably low. These results do not only validate the cost-effective and power-saving features of the proposed ULP-IoTS but authenticate it a first-class solution for indoor AQ tracking applications.

4. Conclusion
In this paper, we proposed an Ultra-low-power IoT System (ULP-IoT) for Indoor Air-Quality Monitoring. The suggested ULP-IoTS offers instant indoor atmospheric AQ data on Carbon monoxide (CO), Fine-particle (PM$_{2.5}$), Carbon dioxide (CO$_2$), Temperature, and Humidity. The IoT-node incorporates ESP32 (ultra-low-power) microchip with MICS-5524, MQ-135 and DHT-11 multisensors. The IoT node architecture applies ESP32 Deep-sleep, and Modem-sleep configurable modes to supplement the Active-mode and expiate optimum power-saving. The tracked CO, CO$_2$, PM$_{2.5}$, Temperature, and Humidity readings from the ULP-IoT node are forward to an IoT-gateway that ultimately posts the data to an external IoT-server for user-retrieval on android-applications.

![Fig. 6](image).

Table II: Energy Consumption Of Iot-Nodes

| Time(hours) | IoT-N$_1$ Energy Consumption (J) | IoT-N$_2$ Energy Consumption (J) |
|------------|---------------------------------|---------------------------------|
| 1-hour     | 1.21                            | 1.44                            |
| 2-hours    | 2.54                            | 2.85                            |
| 3-hours    | 3.10                            | 2.99                            |
| 4-hours    | 3.82                            | 3.84                            |
| 5-hours    | 3.81                            | 3.71                            |
A 5-hours AQ measurement experiment was conducted to validate the proposed ULP-IoT in terms of reliability and power consumption. Various noteworthy evidence has been shown when linking the air quality of the indoor atmosphere with the time-trend. From the tracked CO2, CO and PM2.5 readings, inferences were made to provide cognizance at the user. Ultimately, the energy consumption analysis, confirms the reliability and power-saving efficiency of the proposed ULP-IoT monitoring system.

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