Abstract

Energy availability is a major concern for battery-powered Internet of Things (IoT) nodes, particularly for the widespread deployment of wireless sensor networks (WSNs). In order to address this challenge and make IoT nodes self-sustainable by utilizing harvested power, it is imperative to design nodes that consume very low power and the sensors must be redesigned to be more efficient than commercially available sensors. To ensure the long-term sustainability of wireless sensor networks, this dissertation is focused on developing energy-harvested smart IoT platforms that are efficient and versatile enough to be used in various applications. We have developed low-power sensors with similar sensing quality to replace high-cost ones for air quality monitoring. Retrofitting of energy-sustainable smart energy metering has also been explored in this dissertation.

As a first step, we have designed a 5G-capable environmental sensing network (ESN) node prototype called an air pollution monitoring device (APMD). APMD has electrochemical sensors to measure carbon monoxide, sulfur dioxide, nitrogen dioxide, and ozone, besides temperature and humidity sensors, along with particulate matter (PM) sensors to measure $PM_{2.5}$ and PM_{10}. The node has been equipped with a solar energy harvesting unit and a rechargeable battery as a backup to power up the module. By utilizing an on-board GPS subsystem, APMD packs all these gathered air quality data in a frame with physical location, time, and date and sends them to a cloud server. The node can communicate through WiFi and NB-IoT connectivity. We have experimentally demonstrated that compared to the conventional designs with Wi-Fi-based connectivity, the developed system consumes ten times less energy while using 5G NB-IoT communication module, which makes it a very competitive candidate for massive deployment in highly polluted metro cities like Delhi and Kolkata, in India.

The second part of the thesis has extended the design of a low-power PM sensor and experimental validation of deployed APMD. The on-board PM sensor has been designed to measure $PM_{2.5}$ and PM_{10}. The developed APMD was co-located with an accurate reference sensor node to validate the sensing quality, and a series of field data were collected over seven days. In a fully ON state, the on-board PM sensor saves up to 94% energy while maintaining root mean square error (RMSE) of 0.58 for $PM_{2.5}$ and 2.5 for PM_{10}. A power control mechanism has also been applied on the PM sensor to control the speed of the fan by applying a pulse width modulated (PWM) signal at the switch connected to the power supply of the fan. At 100 ms switching period with 30% duty cycle, the on-board

PM sensor is 97% energy efficient compared to the commercial sensor while maintaining sensing error (RMSE) as low as 0.7 for $PM_{2.5}$ and 2.7 for PM_{10}. Our outdoor deployment studies has demonstrated that the designed APMD is 90.8% more power efficient than the reference setup, with a significantly higher coverage range, while maintaining an acceptable range of sensing error.

The third part of the dissertation has discussed the development and evaluation of an analog front end (AFE) for an ultraviolet (UV) based optical gas sensor module designed for air pollution monitoring applications. The proposed system can accurately measure concentrations of NO_2, O_3, and SO_2 by exploiting the principles of light absorption and scattering. Comparative analysis with data from the reference sensor demonstrates a strong correlation, validating the reliability and accuracy of the designed gas sensor module. Unlike traditional electrochemical gas sensors, which necessitate a complex AFE to detect gas concentrations, our designed module offers a more cost-effective solution with enhanced sensitivity and a compact design. This chapter elucidates the working principle, design considerations, and experimental results of the proposed gas sensor module, highlighting its advantages over conventional sensors.

Finally, the dissertation's last part has studied the retrofitting of a smart electricity metering system. A smart electricity meter is an example of an IoT device that is being installed in domestic and industrial premises to monitor power consumption along with various other services such as billing, load forecasting, and dynamic pricing. Usually, these IoT devices sample at a high rate and report the whole data to the cloud. In this process, a large amount of energy is consumed at the IoT node for data transmission, and a large bandwidth is used for transmission over the Internet, though for storage saving, some compression is performed at the destination. To this end, we aim to prune the IoT data at the source node by providing some intelligence, thereby aiding the wireless IoT node's energy sustainability and efficient channel bandwidth usage for scalable deployment. The IoT devices measuring single parameters or multiple parameters are judiciously pruned within an acceptable reconstruction error limit. In this work, we have reported the embedded implementation of data-driven dynamic pruning of multi-parameter smart meter data as an example demonstration of data-smart IoT nodes. Our performance results have shown that the energy and bandwidth savings with multiple univariate data pruning are respectively about 19% and 36%, whereas the savings with multivariate data pruning are respectively about 36% and 98%. The developed embedded data pruning module is 99.09% more energy efficient than the implementation on Raspberry Pi.