Battery-Free LoRaWAN Sensor Nodes based on STM32WL5

The Internet of Things (IoT) continues to expand across smart cities, industrial monitoring, smart agriculture, logistics, infrastructure supervision, and environmental sensing. In most current deployments, wireless sensor nodes are powered by batteries because they provide flexibility and allow untethered installation. However, the rapid growth of IoT is also increasing battery usage, replacement effort, environmental impact, and maintenance cost. In large-scale or hard-to-access deployments, battery replacement can become expensive and impractical. These limitations have motivated strong interest in battery-free sensor nodes that can operate autonomously by harvesting energy from the environment.

This work presents a maintenance-free, battery-free LoRaWAN sensor node powered entirely by harvested solar energy. The platform is built around the STM32WL55 microcontroller, which combines an ultra-low-power Arm Cortex-M core with integrated sub-GHz radio support for LoRaWAN communication. Its objective is to demonstrate how a wireless sensor node can function without batteries while still supporting reliable sensing and long-range communication, without using dedicated PMIC.

The hardware platform is based on the STEVAL-HARVEST1 energy harvesting board combined with the NUCLEO-WL55 development board through the Morpho connector. Energy harvested from the solar panel charges a storage made up of ceramic capacitor and supercapacitor elements. The system is suitable for both indoor and outdoor environments and can operate at light levels as low as 400 lux. This dual-storage approach allows the node to accumulate energy during periods of illumination and continue functioning when light is reduced or absent. The same photovoltaic device can also be used as an ambient light sensor, reducing component count and simplifying the hardware design.

A major challenge in solar-powered wireless sensor nodes is the intermittent and variable nature of harvested energy. To address this issue, the STM32WL55's Programmable Voltage Detector (PVD) is used to supervise the storage voltage and determine when enough energy is available for sensing and transmission. This eliminates the need for a dedicated power management IC while providing precise voltage-based wake-up control. The MCU remains in a low-power STOP mode while continuously monitoring the supply voltage. Once the voltage exceeds a predefined threshold, the device wakes up, activates a set of low-power sensors, and transmits a LoRaWAN packet.

The sensor suite includes the **STTS22H** for temperature and humidity, **LIS2DU12** for acceleration sensing and **SHT40** for humidity and temperature measurement. The collected data is then transmitted as a LoRaWAN packet by the **NUCLEO-WL55JC1**, enabling long-range communication with a LoRa gateway and network platform such as **The Things**

Network. This confirms end-to-end connectivity in the LoRaWAN ecosystem and demonstrates that useful sensing can be achieved under strict energy constraints.

The operational behavior of the node is organized by a finite-state machine, which manages transitions between harvesting, low-power standby, sensing, and communication states. State transitions are triggered by timer events, voltage-threshold detection through the PVD, and task scheduling signals. This control strategy ensures that the node performs energy-intensive tasks only when the energy budget allows it, thereby preventing brownout conditions and improving the reliability of autonomous operation. After transmission, the MCU returns to low-power mode, allowing the storage capacitor and supercapacitor to recharge from the photovoltaic source.

Experimental validation shows that the platform can achieve very low average power consumption, below 50μW, while supporting periodic LoRaWAN transmissions every 15 minutes. Communication tests demonstrate a range of approximately 1 km in urban environments, which is consistent with the long-range advantages of LoRaWAN. The system can also remain operational for up to 12 hours in complete darkness, thanks to the energy stored in the supercapacitor stage. These results confirm that battery-free operation is feasible when low-power electronics, efficient energy harvesting, and adaptive control are combined in a carefully designed architecture.

The main advantages of the proposed solution are its battery-free operation, maintenance-free deployment, low component complexity, and compatibility with commercial off-the-shelf hardware. By combining the STM32WL55's integrated radio and PVD functionality with a photovoltaic harvester and capacitor-based storage, the system avoids the need for batteries and dedicated power management ICs while maintaining dependable performance. This makes the platform attractive for remote and off-grid applications such as precision agriculture, structural health monitoring, cold-chain logistics, environmental observation, and smart infrastructure.

Future improvements may focus on increasing harvesting efficiency through improved photovoltaic modules, larger storage elements, or hybrid energy sources such as thermal, vibration, or radio-frequency harvesting. Adaptive power management algorithms, including machine learning-based techniques, could optimize sensing and transmission schedules according to available energy and application requirements. Additional sensors and local edge-processing capabilities could also enhance system intelligence and reduce communication overhead. Overall, this work demonstrates a practical and scalable approach to sustainable IoT design using ambient solar energy and ultra-low-power wireless communication.