Energy-Efficient Environmental Monitoring System

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***Abstract*—With the rapid evolution of embedded technologies, systems have become increasingly compact and efficient, especially in terms of energy consumption. This enables the development of distributed monitoring solutions where devices are no longer powered by batteries, but by other components capable of storing energy, such as supercapacitors. However, to operate at maximum efficiency, the system must also be optimized from a software perspective, as executing fewer instructions or setting different operating modes for sensors can significantly impact the system's lifespan. This paper aims to present the hardware components, software optimizations, adaptation algorithms for environmental conditions and current system status, as well as the results of the experiments conducted. TinySense is a monitoring system based on an ARM Cortex M4 microcontroller, which uses a supercapacitor as an energy storage element. The supercapacitor is recharged via a solar panel that converts light energy into electrical energy.**

***Index Terms*—monitoring system, energy consumption optimization, ARM microcontroller, solar energy, supercapacitor**

I. Introduction

The accelerated development of embedded technologies has enabled the creation of smart nodes equipped with sensors, capable of collecting and transmitting data wirelessly to a processing center. These compact devices require efficient hardware solutions with low energy consumption and sufficient computing power for local information processing. The use of ARM processors excellently meets these requirements, due to their optimized architecture for numerical operations and native support for advanced signal processing functions. This paper presents the implementation of a wireless sensor node system based on an ARM microcontroller, highlighting its advantages in distributed monitoring applications.

The rapid evolution of hardware components must also be accompanied by the design of efficient software solutions that enable the optimal use of available resources. In this regard, the development of an application that adapts to environmental conditions and the current state of the system, especially the available energy, is necessary.

Thus, the aim of the project is to present, from a hardware and software perspective, a monitoring system based on an ARM processor that uses a supercapacitor as an energy source, as well as the necessary optimizations to ensure the efficient, reliable, and continuous operation of the system. Furthermore, an analysis of its power consumption will be conducted using specialized tools and experiments.

II. State of the Art

A. Examples of Commercial All-in-One Systems

Several manufacturers provide ready-to-deploy environmental monitoring solutions. The **Libelium Plug & Sense!** offers scalable sensor platforms with LoRaWAN and 4G connectivity, supporting solar power modules for autonomous deployments [2]. **Milesight** provides specialized sensors including the AM300 Series for indoor air quality and IP67-rated EM500 Series for outdoor applications [3]. **Dragino** offers open-source LoRaWAN nodes like the LHT65 and versatile LSN50v2 for distributed monitoring networks [4]. The **Davis Instruments AirLink** focuses on professional air quality monitoring with real-time particulate matter measurement and Wi-Fi connectivity [5]. The **Onset HOBO RX3000** provides a modular platform with ten sensor ports, 4G cellular communication, and integrated solar charging for remote research applications [6]. What sets TinySense apart from these commercial solutions is its focus on merging with the environment at the point it is unnoticeable, while still offering a highly efficient and reliable solution for environmental monitoring. One other key difference besides size, is that TinySense uses supercapacitors as energy storage elements, which allows it to operate continuously without the need for battery replacements, thus reducing maintenance costs and environmental impact.

B. Similar Research Projects

In recent years, research in the field of embedded systems has evolved rapidly, particularly in the direction of autonomous wireless devices, which are becoming efficient and sustainable. Many of these systems are powered by conventional batteries. However, limitations such as difficult-to-access spaces, component degradation and environmental impact have led to the search for alternative solutions.

Such progress was achieved by Iyer et al. [1], who developed a microsystem capable of being transported by wind, operating without a battery and collecting environmental data. The device is equipped with a set of solar panels, a light sensor and a temperature and humidity sensor. The entire system is powered by a capacitor and is mounted on a polymer membrane inspired by dandelion seeds as can be clearly seen in figure .

The main difference between this system and the one presented in this paper is the microcontroller architecture. In the work by Iyer et al., an ATtiny20 microcontroller is used,

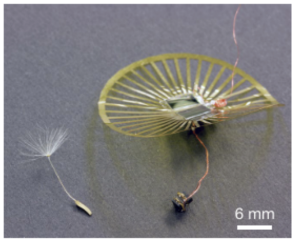

Fig. 1. Wind-dispered microsystem [1].

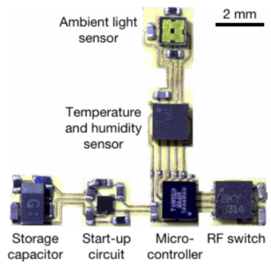

Fig. 2. Wind-dispered microsystem circuit [1].

which is less performant and less efficient than the one used in this project, an ARM Cortex M4.

III. Hardware and Software Design

A. Working Principle

The entire working principle can be separated into two main independent parts: the energy harvesting and the data acquisition. The entire process follows the flow chart shown in figure 3.

- **Energy Harvesting**
  The energy harvesting starts with the conversion of solar energy into electrical energy using a 22 mm x 7 mm solar panel. The generated energy is converted to a higher voltage using the BQ25570 boost converter, which is capable of operating with input voltages as low as 100 mV. The output of the boost converter is regulated to 3.3 V, which is the operating voltage of the system. This energy is also stored in the CPH3225A supercapacitors, which are connected in series to increase the storage capacity. When there is not enough light to generate sufficient energy, the system can continue to operate using the stored energy in the supercapacitors.
- **Data Acquisition**
  The data acquisition process starts with the microcontroller being programmed through the JTAG/SWD interface. In order to connect to the computer, the Segger J-Link is used, which is a powerful programming and debugging tool the supports the nRF52832 microcontroller. One of the most helpful features of the J-Link is the Real-Time Transfer (RTT) [11], which allows the microcontroller to write data into a specific region of the memory that is read by the J-Link software on the computer. It is extremely helpful for debugging purposes, as it allows the user to see the point in the code where the microcontroller is currently executing instructions, as well as the values of the variables at that point in time.
  The microcontroller is programmed to periodically wake up from sleep mode, perform measurements from the sensors, store the data in its internal memory, return to sleep mode, wake up again after a certain period of time to send the measurements via Bluetooth Low Energy to a smartphone or a computer and return to sleep again. After that, the cycle repeats. The communication with the sensors is done using the I^2C protocol. As previously stated in the Hardware Components section, the sensors use the same I^2C interface, so the microcontroller can communicate with them base on their I^2C address. The BME280 has the address 0x76, while the IIS2MDC has the address 0x27.

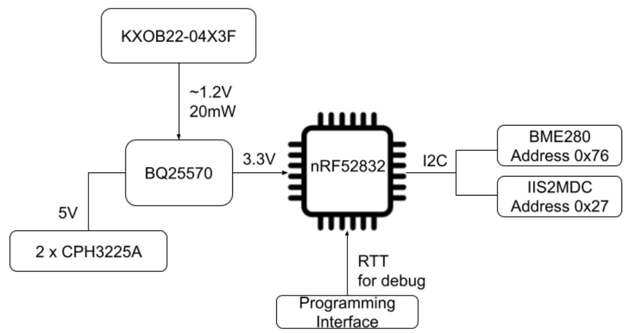

Fig. 3. TinySense's working principle.

B. Hardware Design

The most complex component of the system, besides the microcontroller is the boost converter, which is responsible for converting the low voltage generated by the solar panel into a higher voltage that can be used to charge the supercapacitors and power the microcontroller.

The BQ25570 is a highly efficient boost converter designed for energy harvesting applications. And the best part is that it can operate with input voltages as low as 100 mV, which is perfect for our usecase.

The best way to understand how the BQ25570 functions is to look at the graphic representation of the voltage threshold shown in the datasheet [8] as well as in figure 4.

The BQ25570 has several voltage thresholds that determine how it operates. And let's explain them from the bottom to the top:

- VSTOR_CHGEN:
  - Rising: When VSTOR is below this threshold and the input voltage from the solar panel is above 100mV, the BQ25570 starts charging the storage element.
  - Falling: If VSTOR is very low and VIN_DC is greater than 600mV, the Cold Start Circuit will begin charging the storage element.
- VBAT_UV:

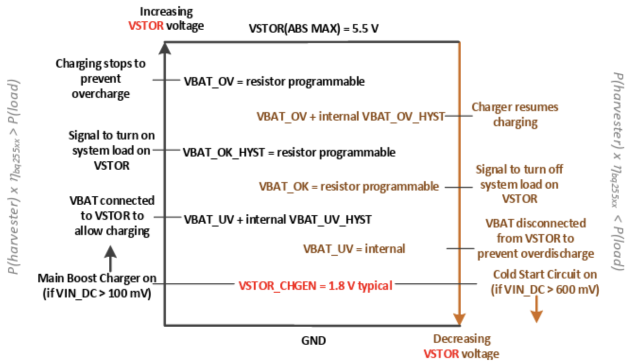

Fig. 4. Voltage thresholds for the BQ25570

  - Rising: When VSTOR is above this threshold on which we add the internal VBAT_UV_HYST, the BQ25570 will connect VBAT to VSTOR in order to charge.
  - Falling: When the voltage on the storage element is below this threshold, the BQ25570 will disconnect VBAT from VSTOR in order to prevent overdischarge.
- VBAT_OK_HYST:
  - Rising: When the voltage on the storage element is above this threshold, the BQ25570 will enable system load.
- VBAT_OK:
  - Falling: When the voltage on the storage element is below this threshold, the BQ25570 will disable system load.
- VBAT_OV:
  - Rising: When the voltage on the storage element is above this threshold, the BQ25570 will stop the charging of the storage element.
  - Falling: When the voltage on the storage element is below this threshold on top of which we add the internal VBAT_OV_HYST, the BQ25570 will enable charging of the storage element.

What is most important is that a part of these thresholds can be set using voltage dividers. This allows the user to set the voltage levels at which the BQ25570 will enable the system load, stop charging the storage element and the output of the boost converter.

C. PCB Design

The PCB design is most importantly compact and two main areas are clearly visible, separated by a virtual line in the middle of the board through the programming interface. The two areas are:

- The left side is dedicated to the energy harvesting circuit, which includes the solar panel, the BQ25570 boost converter, the supercapacitors and the power inductors.
- The right side is dedicated to the microcontroller and the sensors, which includes the nRF52832 microcontroller, the BME280 sensor, the IIS2MDC sensor and antenna.

Using the Autodesk Fusion 360, the PCB design was associated with 3D models of the components, which allows us to visualize the board in 3D. This is shown in figure 5.

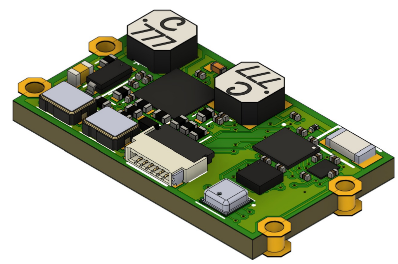

Fig. 5. 3D model of the board

The 3D model of the PCB is very useful for visualizing the board and understanding how the components are placed on the board. However, it is not enough to fully understand the size of the board. That is where photos of the actual board come in handy. The photos are dones using a digital microscope. The photos are shown in figure 6.

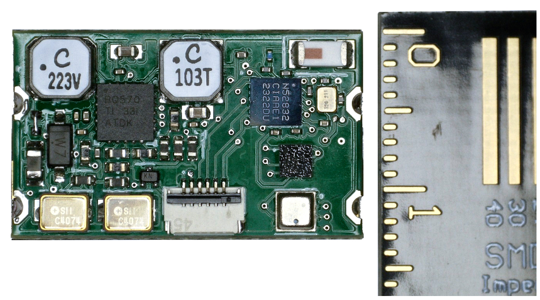

Fig. 6. Photos of the PCB

The board is 22 mm by 13 mm as clearly seen in the photo. It is very small, but still big enough to accommodate two solar panels on the bottom side of the board. The side profile and the bottom side with the solar panels can be seen in figure 7.

Fig. 7. Side profile of the PCB with solar panels

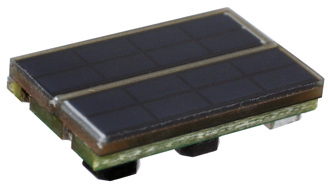

Fig. 8. Bottom side of the PCB with the solar panels

D. Software Design

The software development for the system is done in C using the Nordic Semiconductor SDK, which provides a set of libraries and APIs for the nRF52832 microcontroller. The SDK also includes the SoftDevice, which is a pre-compiled binary file that provides full support for radio communication drivers and scheduler, timing and event management and most importantly, Bluetooth Low Energy protocol stack.

Since there is little energy available in the system, the software has a reduced complexity and is designed to perform only the necessary operations. The program starts with the initialization of the sensors and the Bluetooth Low Energy stack. After that, the device enters the working cycle. The working cycle consists of constantly entering deep sleep mode and waking up periodically to perform measurements from the sensors, store the data in a buffer and broadcast the data via Bluetooth Low Energy.

The main optimization that were applied to the software are mainly focused on reducing the time spent in active mode and putting the senors in the lowest power mode possible (forced mode for BME280, low power mode for IIS2MDC).

IV. Power Consumption Modeling

In this section the results of the calculations and experiments conducted will be presented. The goal is to determine the power consumption of the system in different functional modes.

A. Theoretical Model

Firstly, the theoretical model of the power consumption will be presented. The boost converter is configured to output a voltage of 3.3 V, which is the operating voltage of the microcontroller and the sensors. Based on the datasheet of the microcontroller [7], the microcontroller can operate normally until the voltage drops below 2.2V. This is the exact threshold at which the BQ25570 will interrupt the system load.

By using a weighted average of the current consumption of each mode and the time spent in each mode, the average current consumption can be calculated. Also, by taking into account the power consumption of the sensors in their respective modes, the average current consumption of the system comes to 24.91 μA.

$$I = \frac{dQ}{dt} \tag{1}$$

$$Q = C \cdot V \tag{2}$$

$$\begin{aligned} I &= \frac{d(C \cdot V)}{dt} \qquad \text{(Assuming } C \text{ is constant)} \\ &= C \cdot \frac{dV}{dt} \end{aligned}$$

$$\Delta t = \int C \cdot \frac{dV}{I} = \frac{C}{I} \cdot \int dV = \frac{C \cdot \Delta V}{I} \tag{3}$$

The two supercapacitors are in series, so it is equivalent to a single capacitor with a total capacitance of:

$$C_{total} = \frac{C_1 \cdot C_2}{C_1 + C_2} = \frac{11 \cdot 11}{11 + 11} = 5.5mF \tag{4}$$

$$\Delta V = V_{max} - V_{min} = 5V - 2.2V = 2.8V \tag{5}$$

$$\Delta t = \frac{C_{total} \cdot \Delta V}{I_{avg}} = \frac{5.5 \cdot 10^{-3} \cdot 2.8}{24.91 \cdot 10^{-6}} = 618.2s \tag{6}$$

$$\Delta t = 10.3min \tag{7}$$

B. Longevity Test

In order to validate the theoretical model, a longevity test was conducted. The longevity tests are performed by checking if the Bluetooth Low Energy messages are received and by measuring the signal pin of the BQ25570 boost converter called `V_BAT_OK`.

The boost converter will provide power to the microcontroller and the sensors until the `V_BAT_OK` reaches 2.2V, which is the minimum voltage required for the components to operate.

There are three different software versions that were tested. Each adds another feature to the system, which increases the power consumption. In all versions where BLE messages are sent at a fixed interval, once every minute.

The results are presented in table I.

TABLE I
Longevity Tests Results

Code Version	Operation Time	With Solar Panel (Artificial Lighting)
Deep Sleep	2 hours 20 minutes	∞
BLE Messages	15 minutes	26 minutes
BLE Messages + Sensor Readings	8 minutes	12 minutes

The artificial lighting used in testing isn't sufficient to keep the system alive continuously. However, it is worth mentioning that after the system shut down, the solar panels were still exposed to light and the system was able to recharge and operate again. This is due to the fact that the BQ25570 boost converter is able to start charging the supercapacitors even when the voltage is very low.

The situation is totally different when the solar panels are directly exposed to sunlight. In this case, the system can operate continuously without any interruptions, as the solar panels are able to provide enough energy to keep the system alive.

The difference between the theoretical and the measured operation time can be attributed to other factors, such as the power consumption of the other components on the board, but most importantly, the inconsistency of the power consumption. Since the microcontroller changes state all the time, power consumption can vary significantly. For example, if the microcontroller is sending a BLE message, the power consumption will be much higher than when it is in deep sleep mode. Additionally, non-ideal effects such as leakage currents in the supercapacitors, inefficiencies in voltage regulation and parasitic losses in passive components reduce the usable stored energy. Variations in capacitor equivalent series resistance (ESR) introduce extra power losses during discharge. Taken together, these factors explain why the experimental operation time is shorter than the theoretical estimate.

C. Transmission Distance Test

Another important aspect of the system besides current consumption and longevity is the transmission distance. This metric directly impacts the system's ability to communicate with other devices and to transmit data over long distances. In order to test the distance, it must first be determined the external factors that can influence the transmission distance. The most important factors are the environment, the obstacles and the interference. The possible environments are indoor and outdoor, while the obstacles can be walls, trees, buildings and so on. The interference can be caused by other devices that operate on the same frequency, such as Wi-Fi routers, microwaves and other Bluetooth devices.

In order to test the transmission distance, the system was placed in a fixed position and the nRF52840 Dongle or a smartphone was moved away from the system until the signal was lost. The distance was measured approximately using a measuring tape or by counting the steps that were between the two devices. This process was repeated eight times for each situation and the average maximum transmission distance was calculated.

The test were performed both in outdoor and indoor spaces with little to no interference. The results of the tests are shown in table II.

TABLE II
TRANSMISSION DISTANCE TEST RESULTS

Environment	Maximum Tranmission Distance (m)	Obstacles
Indoor	22.3	—
Indoor	6.8	1 floor
Indoor	11.7	2 walls
Outdoor	33.2	—

V. CONCLUSIONS

The objective of this thesis is the development of solar-powered, battery-free environmental sensors that can operate continuously using harvested energy, especially for long-term deployments in remote locations.

In this paper, it is also presented the detail selection process of the components used in the system, including the microcontroller, sensors and power management circuit. The harmonious integration of these components along with the software elements ensures that the system operates efficiently, consuming minimal power while maintaining the required functionality.

Furthermore, the work details the theoretical and measured power consumption of each system component to justify their selection during the design process. The comprehensive power analysis demonstrates that the system achieves a low average current consumption, enabling sustainable operation with solar energy input and making it suitable for deployment in challenging environmental conditions.

The research can be extended by exploring the new version of the microcontroller, nRF52840, which offers enhanced features and lower power consumption or by integrating an external timer to allow the system to turn off and wake up only when necessary. From a hardware perspective, additional improvements could be included such as adding an external timer or a real-time clock (RTC) to allow the system to turn on in order to lower the average current consumption in deep sleep mode. From a software perspective, the implementation of a mesh network protocol could be considered to enable communication between multiple sensors, allowing for a more comprehensive environmental monitoring system. This would not only increase the data collection capabilities, but also enhance the system's resilience and reliability in remote locations.

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