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Optimization of a Power Management Process in a Printed Electronics Smart Label System

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***Abstract*—The topic of this research was to investigate and optimize power management of a printed electronics prototype device used for quality assurance of Ready-to-Eat food products. Printed electronics enables the manufacturing of thin, lightweight products and components, which can be part of a functional system. In order to maintain the lightweight and thin nature of the products, a small and thin battery is integrated in these types of autonomous systems. Power consumption of the system should be kept at low level to enable the use of printed batteries.The optimization of power consumption was done at software level. The goal was to reach so low power consumption that the printed prototype device can operate on a food package long enough using a small sized printed battery. Another goal was to study the effects of different operating modes to the power consumption and how much is it possible to affect to them.**

The research started by studying power management in embedded systems and finding out what was the device's power consumption at the start. After that, a plan for optimization procedures was done. The optimization procedures were executed one by one and effects to power consumption was measured. This revealed exactly how much each procedure was affecting to power consumption. Usability also played a key role in finding the optimal solution. As a result, the device's current consumption was optimized to the desired level where it can reach the targeted operating time. All functionalities and usability were maintained in the power optimization process.

Keywords—Printed electronics, smart labels, embedded systems, power optimization, power management

I. INTRODUCTION

PrinLab is a development laboratory for printed intelligence. PrinLab is involved in various projects related to printed intelligence and has also teaching and training activities. PrinLab works very closely with companies and other organizations in printed intelligence. [1] PrinLab is part of the PrintoCent community. [2]

PrinLab has developed a printed smart label for Ready-to-Eat food packaging that monitors the temperature of the product. The measurements collected by the smart label are used to ensure food quality and reduce food waste. The device can be connected to a mobile device using Bluetooth Low Energy technology [3]. The mobile device can read the measurements stored in the device and change the settings of the device. The printed smart label is intended to operate independently using a printed battery [4].

The purpose of the research was to study and optimize the power consumption of the device in question. The task was to optimize the power consumption of the device to be low enough to achieve the required operating time with the printed battery. The purpose of the research was also to find out the power consumption of the different functionalities and operating modes of the device and the extent to which they can be influenced at the software level. The findings made could be utilized in both hardware and software design.
Several prototype versions of the smart label had already been developed. Its software was still in the development phase, where the required functionalities had been implemented, but, for example, power consumption had not yet been taken into account in software development. A working prototype device was used in the work, for which the power consumption optimization and measurements were performed.

This paper has the following structure: Section I introduces to the research. Printed electronics in general, challenges in printed electronics, the smart label hardware and software are presented in Section II. In Section III, the power consumption optimization is presented along with the results. Concluding remarks are given in Section IV.

II. PRINTED SMART LABEL

A. Printed electronics in general

Printed intelligence or as it is more commonly known: printed electronics is a technology in which electronic components are manufactured utilizing traditional printing methods. Printing is an additive method in which a certain amount of functional material is accurately added to the substrate [5], as opposed to removal methods in traditional electronics manufacturing where excess material is etched away.

The method achieves a variety of benefits, such as the speed of the manufacturing process and the reduced need for material. Very thin, flexible, stretchable, and even biodegradable materials can be used as the substrate. This makes it possible to implement more environmentally friendly, sustainable, and completely new types of components and devices, with lower manufacturing costs [6]. These are very important factors in a rapidly digitalizing world where the number of electronic devices will grow tremendously. [7]

One of the challenges of printed electronics devices is often to keep power consumption to a sufficiently low level. For example, the technology enables the production of very thin and flexible devices that integrates a printed battery. However, the capacity of these batteries is relatively limited [4], so low-power systems are crucial to enable applications to achieve the desired functionalities and achieve a sufficiently long operating time.

B. Printed smart label hardware

The prototype device developed by PrinLab is built around a system circuit with very low power consumption (Fig. 1). The device contains two LEDs that can be used to indicate the operation of the system. One of the LEDs is the temperature indicator light, which is used to indicate if the temperature measured by the device is outside the set limits. The second LED is used to indicate the operation of the device to the user. For example, it can be used to illustrate that a device starts operating when it is turned on.

The device has other components, such as the external components required by the DC/DC controller of the system circuit. To measure the temperature, the device uses an internal temperature sensor in the system circuit.

The prototype device uses Nordic Semiconductor's nRF52832 system circuit. This system circuit is built around a 64 MHz ARM Cortex-M4 (FPU) processor. This ultra-low power system circuitry includes a wide range of supported protocols and features and is well suited for implementing a variety of applications utilizing Bluetooth Low Energy technology. [3] A version of this system circuit with 512 kB of flash memory and 64 kB of RAM was used in this research.

In Fig. 2 the latest prototype of printed smart label is shown.

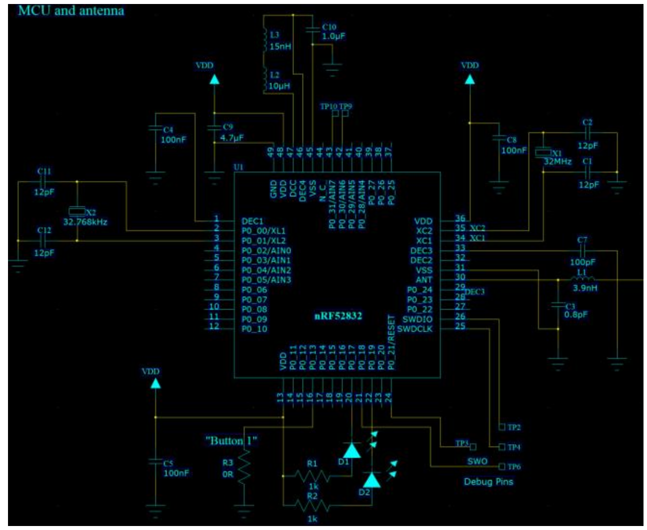


Fig. 1. Schematic of printed smart label

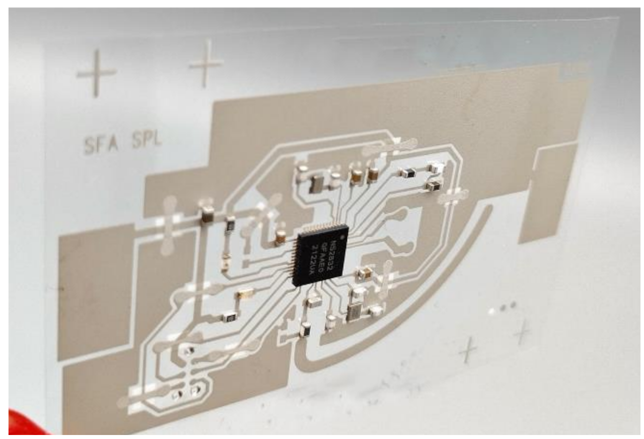


Fig. 2. Prototype of printed smart label

C. Printed smart label software

When started, the program reads the configuration file stored in the Flash memory, which contains, among other things, the temperature limit values and the setting for saving the measurements in the device memory. Thus, the values and settings stored in the file are retained even if the device is restarted or turned off. This allows the device to be pre-configured with the desired values and settings, and then only needs to be switched on when the device is to be used. After that, the device starts operating independently according to the predefined settings and can be connected to via Bluetooth at any time.

The required functionalities had been implemented in the software, with which the functionality of the device could be verified and tested, but for example, the optimization of power usage had not been taken into account in the software development.

The prototype device software was developed using Nordic Semiconductor's nRF Connect SDK (NCS) software development package. The software development package is suitable for software development of devices based on the nRF52, nRF53 and nRF91 series products in IoT systems [8]. It includes the Zephyr real-time operating system and also includes a comprehensive range of application protocols, protocol patches, libraries, device drivers, and sample programs to facilitate development. The version of the software development package in use was 1.7.1. [9]
In addition to the prototype device, Nordic Semiconductor's nRF52 DK development platform was used in the software development. The development platform includes the same system circuit as the prototype device and has, for example, four user-programmable LEDs and a push button. The development platform includes a SEGGER J-Link error tracker, which can be used to program and debug both on-board and external system circuits. The development platform was also utilized in this work, for example, for programming a prototype device. [10]

III. POWER CONSUMPTION OPTIMIZATION

A. Measurement of power consumption

Nordic Semiconductor's Power Profiler Kit II measuring device was used in conjunction with the Power Profiler application to measure power consumption. The tools used in the measurement and the system circuit were therefore all products of Nordic Semiconductor. With the help of the tools, it was easy to measure power consumption and review and analyze the results.
In this research, all measurements were performed with the same settings, where the device functioned both as a current meter and as a power source for the device being measured. The supply voltage was 3 volts and the measurement speed was 10,000 measurements per second.

B. Determining the baseline

The measurement was performed according to a pre-established measurement plan in which the device was used in its various operating modes. The measurement plan defined the measures to be taken and the time at which they would be performed. This made it easy to view the measurement results afterwards by comparing the measurement data with the measurement plan. The plan made it possible to directly determine from the measurement data in which operating mode the device is in or what function it performs. The measurement gave a good overall picture of the power consumption in the initial situation. It immediately showed that the power consumption of the device was indeed high, as expected (Fig. 3). The results also showed the effect of different operating modes on power consumption.

The information obtained in the baseline study could be utilized in the planning phase of power consumption optimization. The results of the measurement also made it possible to verify the effects of the optimization measures during the implementation phase.

Fig. 3. Measurement of prototype device power consumption at baseline

C. Power consumption optimization design

The required operating time of the smart label was 7 days, with a temperature measurement interval of 5 minutes. The battery was defined as Enfucell's SoftBattery 3654. This 3-volt printed battery has a capacity of 24 mAh and is well suited for use in operating conditions where the temperature is above a few degrees Celsius [11]. The reported battery values were used to calculate the operating time of the device.

The operating profile of the device is a crucial factor in the design of power consumption optimization. The device will operate most of the time independently, measuring the temperature and stores it in a flash memory. In addition, the device must also be able to establish a Bluetooth connection at any time. Here, however, it should be noted that the device will very rarely establish a Bluetooth connection in its final operating environment, and even then, the connection will only be active for a short time. Based on this information, the optimization had to focus on keeping the power consumption of the operating mode as low as possible most of the time.

During the design phase, information on the power consumption found in the documentation of the system circuit in use was utilized, as well as Nordic Semiconductor's Online Power Profiler for Bluetooth LE tool. This tool for estimating power consumption could be used to estimate the power consumption of different Bluetooth modes. It is possible to vary different settings and connection parameters and see their effects on power consumption directly. Estimated power consumption data is based on correct measurements.

When carrying out measures, their effects were tested with different parameters and settings, in order to find out to what extent they have the potential to affect power consumption and, in addition, how they affect usability. Therefore, the plan did not specify exactly what values and settings would be used but was intended to serve as a good framework for implementing optimization measures.

D. Power Consumption Optimization Measures

The optimization was done using a plan created at the design stage. The implementation phase included many measurements of the effects of optimization. Measurements were made in several cases with different parameters and their effects on operation and usability in different operating modes of the device were compared. This chapter reviews the main points of the optimization measures and examines the results obtained in power consumption.

The first step in optimization was to disable the serial connection and logging of the program. As can be seen from Fig. 4, this resulted in a reduction in current consumption of about 1.2 mA.

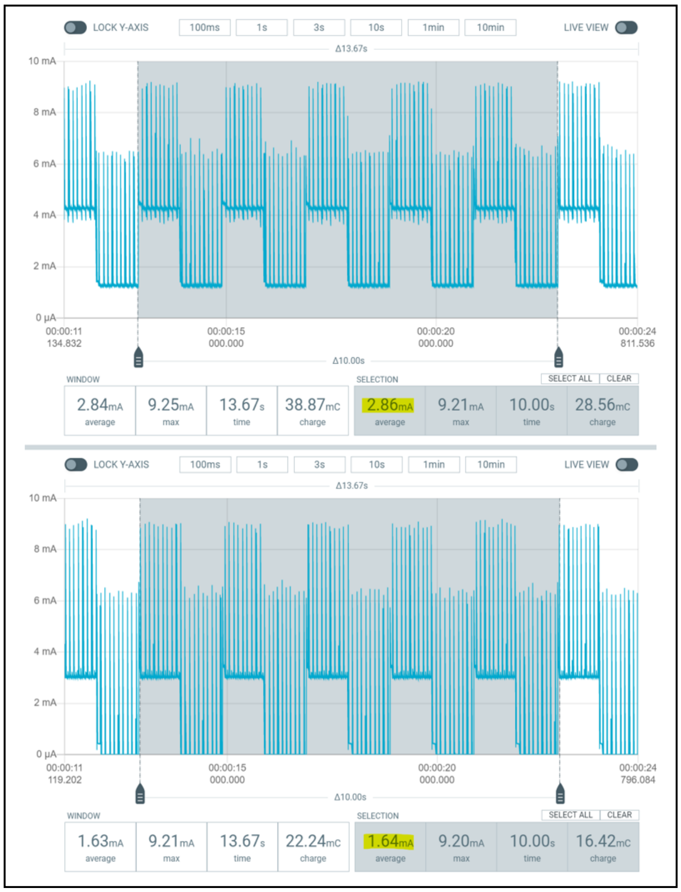


Fig. 4. Prototype device in Bluetooth advertisement mode before and after disabling serial and logging

Next, the effect of a change in the temperature measurement interval of a prototype device on power consumption was examined. At baseline, the temperature measurement interval was 1 second and was changed to 10 seconds. In the measurement of power consumption, it was found that the temperature measurement interval of as little as 10 seconds has a power consumption close to the 1 second period between temperature measurements (Table I). The final measuring interval of the device will be relatively sparse, according to the specification 5 minutes, so the share of temperature measurement in the total power consumption of the device was insignificant at this stage. However, it is good to note that the lower the total power consumption of the device, the higher the proportion of temperature measurement. Thus, the temperature measurement interval was still left for 10 seconds at this stage, but it would be changed to the value according to the requirements specification at the end of the optimization.

TABLE I. EFFECT OF TEMPERATURE MEASUREMENT INTERVAL ON DEVICE POWER CONSUMPTION

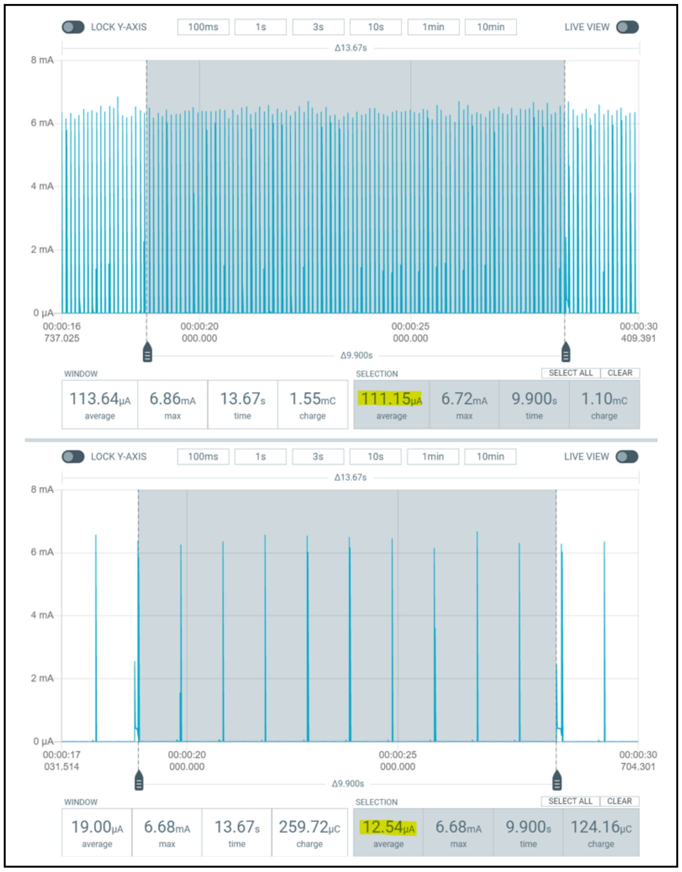
Operating mode	*Average power consumption*
Temperature measurement interval 1 s	132,9 µA
Temperature measurement interval 10 s	112,0 µA

After changing the temperature measurement interval to 10 seconds, the effects of the change in the Bluetooth advertising interval on power consumption were examined. The Bluetooth advertising interval was changed from 100 milliseconds to 1 second (Fig. 5). It was found that when looking at the period of 9.9 seconds between temperature measurements in the advertising mode, the power consumption dropped significantly (Table II). This was a significant improvement in power consumption, especially as the device will spend most of its time in that mode. Sufficiently low power consumption in this mode of operation is therefore critical, as it allows the device to operate in a designed manner so that a Bluetooth connection can be established to it at any time without having to wake up the device separately from deep power control mode. However, fewer advertising intervals reduce the visibility of the device when scanning nearby Bluetooth devices, and it may take longer to connect to it. When testing the device in conditions where ten other devices using Bluetooth Low Energy technology were operating at the same time, no problems occurred during the slower advertising interval. However, this still needs to be tested at a later stage in the development of the prototype, under conditions similar to its natural operating environment.

TABLE II. EFFECT OF BLUETOOTH ADVERTISEMENT INTERVAL ON DEVICE POWER CONSUMPTION

Operating mode	*Average power consumption*
BT advertisement 100 ms interval	111,2 µA
BT advertisement 1000 ms interval	12,5 µA

In addition to the advertising interval, it is possible to influence the power consumption of the Bluetooth connection in other ways. The Bluetooth connection has its own adjustable parameters for both the advertising mode of the connection and the mode in which the connection is established. In advertising mode, in addition to the advertising interval mentioned earlier, the size of the advertising package can also affect power



consumption [12]. However, no changes were needed to the advertising package in the program.

Fig. 5. Effects of Bluetooth advertising interval on power consumption. The selected range shown in the figures is between two temperature measurements.

The usability of the device during the connection is smooth. As for the parameters during the connection, it should be noted that while a device in the Bluetooth peripheral role - in this case a prototype device - may require certain connection parameters to be used, a device in the Bluetooth central role - here a mobile application - will decide which parameters to use. Different devices use different connection parameters, so no attempt was made to limit them very precisely to make communication with different devices work as well as possible.

Attention should also be paid to the transmission of information. The less information you need to send, the less power you need. It is also possible to influence power consumption when transmitting larger amounts of data, especially if it can affect how data is received on another device. Whenever possible, the data should be packed and assembled into larger packets, which means fewer packets to send. Sending data is faster and consumes less power.

The system circuit includes an automatic LDO and DC/DC regulator system. The DC/DC controller requires external components that were installed in the prototype device. The DC/DC controller can be enabled programmatically, and if enabled, the system can automatically switch between controllers as needed. The DC / DC regulator can be used to reduce the total power consumption and, in addition, to significantly reduce the peaks in power consumption, which can contribute to a very significant reduction in the operating time of the device. When reviewing power consumption, in addition to the total power consumption, it is also necessary to consider the momentarily high peaks in power consumption and try to reduce them. For devices running on battery power, the values specified by the battery manufacturer for maximum power consumption should also be considered when selecting the type of battery that will be used in the device.

TABLE III. EFFECT OF DC/DC REGULATOR ON DEVICE POWER CONSUMPTION

Operating mode	*Average power consumption*	*Maximum power consumption*
DC/DC regulator in use	13,5 µA	6,58 mA
DC/DC regulator not in use	25,4 µA	12,07 mA

IV. CONCLUSIONS AND DISCUSSION

The purpose of the research was to study and optimize the power consumption of a printed prototype device. The goal of power consumption optimization was to achieve a sufficiently long operating time for the device using relatively small capacity printed battery, while maintaining the existing functionalities and good usability. The aim was also to find out the power consumption of the different operating modes and the extent to which they can be influenced. The results could be used in hardware and software design of similar products in the future.

As a result of the research, the power consumption of the device was optimized to the desired level. This allows the device to operate as planned with a printed battery. In addition, the research collected information on which functionalities in the device consumed any amount of power. The significance of the external components required by the DC / DC regulator placed in the prototype device could also be verified. These findings can also be utilized in the development of new devices. The tools used in the research to measure and analyze power consumption proved to be quite functional and will certainly be used in the future. The research also showed that the measurements of power consumption corresponded well to the values specified by the manufacturer.

The main findings in the research on the optimization of power consumption were the effect of the DC/DC regulator on the power consumption. With it, both the total power consumption of the device and the peaks in power consumption were approximately halved. In addition to these, it turned out that the various parameters of the Bluetooth Low Energy connection can also have a significant effect on power consumption. However, the parameters used are case-specific, and for example, in this research, the focus of the parameters was precisely on the operating mode in which the device will spend most of its time.

The operating times of the device can be calculated based on the measurements, but they do not fully correspond to reality. The values specified by the battery manufacturer can be used to calculate the operating times. It should be noted that the actual operating time of the battery is affected by many factors. For example, excessive power consumption peaks and cold temperature can significantly reduce battery life. The capacity of the battery is also not fully utilized, as at some point the voltage of the battery drops so low that the device that uses it as a power source will no longer be able to operate. Therefore, it is appropriate to perform actual tests on battery life under the operating environment.

In this research, measurements were performed using only one version of the prototype device. In the future, an optimized program with low power consumption will make it easy to test and compare the potential effects of different prototype versions and manufacturing methods on power consumption.

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