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Arhitectură pentru rețele wireless de senzori cu energy harvesting.

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Arhitecture for energy harvesting wireless sensor networks

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Abstract

This thesis proposes a new way of implementing a mobile gateway for Wireless Sensor Networks that simplifies applications running in remote locations, where maintenance is difficult. Wireless Sensor Networks islands need a gateway connection in order to reach the outside world, but this is difficult to provide in all instances. The solution to this problem is to use a gateway mounted on a UAV that can reach those islands and extract data from them. This has been proven to be feasible but adoption is low because of the high cost and the technical background needed to operate it. We propose a simpler, easier to operate and cheaper solution for this problem.

Keywords Wireless Sensor Networks, sparrow, energy harvesting, scheduling

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Chapter 1

Introduction

The main problem faced by Wireless Sensor Networks is autonomy. The location in which some nodes can be installed could be difficult to reach, turning a simple task of changing the batteries of the nodes into an impossible one.

The solution to this problem is powering the devices from alternative sources of energy, process called energy harvesting. In the recent years, energy harvesting has become more and more used in the field of Wireless Sensor Networks. There are plenty of alternative energy sources, such as solar cells, vibration absorption devices, wind mills, thermoelectric generators and others, that can be used to power the nodes or charge their batteries in order to become autonomous.

While the energy source problem has a solution, another problem appears in the form of finding a method to store the generated energy. A battery could be used to store the generate energy, but unfortunately, current technology allows to charge one for a few hundreds of cycles. Considering that a cycle would be used per day, in maximum 2 years, the battery will lose most of its original capacity. An alternative to the battery is using a super capacitor, which has a life of 10 years or 500.000 cycles, but are more expensive and store far less energy than regular rechargeable batteries.

In order to alleviate the amount of stored energy, an scheduling algorithm can be used, algorithm that will dynamically vary the frequency with which the node performs various tasks in order to be able to send data without consuming all the available energy.

In this thesis we will describe the architecture of an energy harvesting wireless sensor network, shortly titled EHWSN. We will present a new node and development platform, the Sparrow R, designed for low power and the problems we encountered when using solar energy and a capacitor as storage. The result of this is an efficient but lightweight algorithm for efficiently using the stored energy.

Chapter 2

Related Work

Energy harvesting has been studied for a long time and many tried to find a solution for their shortcomings. Solar panels are frequently used in EHWSNs because they can generate a lot of power but the power they generate is not consistent and predicting it was on of the challenges to be overcome.

2.1 Prediction generated Energy

Because the solar energy is not constant, in order to predict the generated energy, a history of past-days weather conditions or generated energy must be taken into account. The state-of-the-art algorithm for this is Weather-Conditioned Moving Average (WCMA) [14] which can keep a history of number of days of generated energy in order to predict the generated energy in the next hour. The results of the algorithm are shown to be impressive, with an average error of 9.8% in 45 days of testing.

Because the algorithm requires the generated power to be measured in order to have a precise history of generated solar energy, this algorithm is not feasible in application where the node can be very low power and a small solar panel of just 60mW or less can be used, compared to one used in the paper, which could generate more than 300mW. A simpler solution for hardware as well as software must be found for those applications.

2.2 Using stored Energy

The common approach to optimal packet scheduling is using a water-filling algorithm [17] [?], where the time is divided into slots and given a level of energy to be used in that slot. For better power optimizations, this approach is modified into backward water-filling, directional water-filling, generalized iterative water-filling

[?] for offline (deterministic) scenarios. In order to simulate online (stochastic) scenarios, Gaussian noise is added and the constant water level policy, energy adaptive water-filling[13], time-energy adaptive water-filling[?] can be used. The problem with their approach, in our opinion, and even simpler ones like fuzzy power management [9] is that the complexity of the algorithm is rather high, at least O(N), a constant feedback of consumed energy must be provided. The fact that the results of all the algorithms were simulated and not implemented and tested on a real device, indicated that real conditions, like capacitor leakage or temperature variations are not taken into consideration. Also, every algorithm needs to know how much energy it is using performing different tasks. This is not feasible in real world, in time leading to large errors.

What this mean is that the above algorithms will work best in high power scenarios, where leakage currents are small enough to be considered inexistent. In a low power scenario, the results are very optimal.

Chapter 3

Sparrow R

Most of the nodes are build using AVR processor [3], an 8-bit architecture. Few attempts have been made using newer Arm Cortex-M3 32-bit architecture. The benefits of higher computing power are presented here [11], where a 4.6 throughput can be obtained compared to an 8-bit cpu over the same wireless network. Unfortunately, the downside is higher power consumption that can create difficulties for power supplies. Even though the same average power consumption can be obtained, due to higher power peaks, the power supplies will be depleted more quickly.

The current nodes, Sparrow V3.2 and SparrowV4, use an AVR 8-bit architecture and run at a speed of 16MHz. For our solar powered node, we wanted to use a newer, more powerful and low power microcontroller. Based on the previous requirements, we have chosen an Arm Cortex-M0+ 32-bit Atmel SamR21.

3.1 Performance

We present bellow the main diferences between the two mcus, SAMR21 and ATMEGA128RFA1 [2].

Being a 32-bit architecture and a new architecture, even though SAMR21 consumes 5.5mA compared to 4.1mA of Atmega128RFA1, for simple 32-bit integer addition, SAMR21 consumes only 49nJ per iteration while the 8-bit microcontroller consumes 274nJ, almost 5 times more. Considering performance figures, SAMR21 was 9 times faster with 403950 iterations per second while Atmega128RFA1 managed only 44890 iterations.

Testing the performance of branch predictor, revealed that the M0+ is only 12% better than the older 8-bit counterpart when running at the same speed, but thanks to the frequency difference, it ends up being 3,36 times faster.

Criteria	Atmega128RFA1	SamR21
CPU Speed	16 MHz	48 MHz
CPU architecture	AVR 8bit	Cortex M0+ 32bit
CPU Power	4.1 mA	6.5 mA
Flash	128 kB	256 kB
Ram	16 kB	32 kB
Flash Endurance	50000	150000
Rx Consumption	12.5 mA	11.8 mA
Tx Consumption	14.5 mA @ 3.5mA	13.8 mA @ 4 dBm
Receiver sensitivity	-100 dBm	-101 dBm
Tx Max Power	3.5 dBm	4 dBm
Package	QFN64	QFN48 or QFN32

Table 3.1: Comparison between Atmega128RFA1 and SamR21

Criteria	Atmega128RFA1	SamR21	Total Advantage	Advantage per MHz
Integer Iterations	44890	403950	8.99	2.99
Branch Iterations	27782	93552	3.36	1.12
While(1) Iterations	191536	6693086	34.94	11.64

Table 3.2: Speed comparison

Criteria	Atmega128RFA1	SamR21
Integer Iteration	274 nJ	49 nJ
Branch Iteration	442 nJ	208 nJ
While(1) Iteration	64 nJ	2.9 nJ

Table 3.3: Energy efficiency comparison

The SAMR21 micro-controller is almost the same micro-controller as SAMD21 [5], which is used in Arduino Zero boards. This allowed use to use exiting code, but unfortunately a not well written one.

Even thought the Arduino software is well designed, it was not designed with low power approach from the beginning. We will describe some of the problems encountered when trying to create the software stack.

The first problem noticed was that the Arduino Zero board had no sleep functionality implemented. The ideal idle current consumption should have been less than 5uA, tested and measured using a project created in Atmel Studio 7.0. The current consumption of the board was around 350uA. Further tests revealed that the USB device was always initialized, which accounted for the extra 200 uA. The rest of 150uA came from a default initializations of the pins as input pins, but this only lowered the current consumption to about 60uA. We kept searching for a cause, and discovered that the clock generators are never disabled at start-up, which accounted for about 30uA.

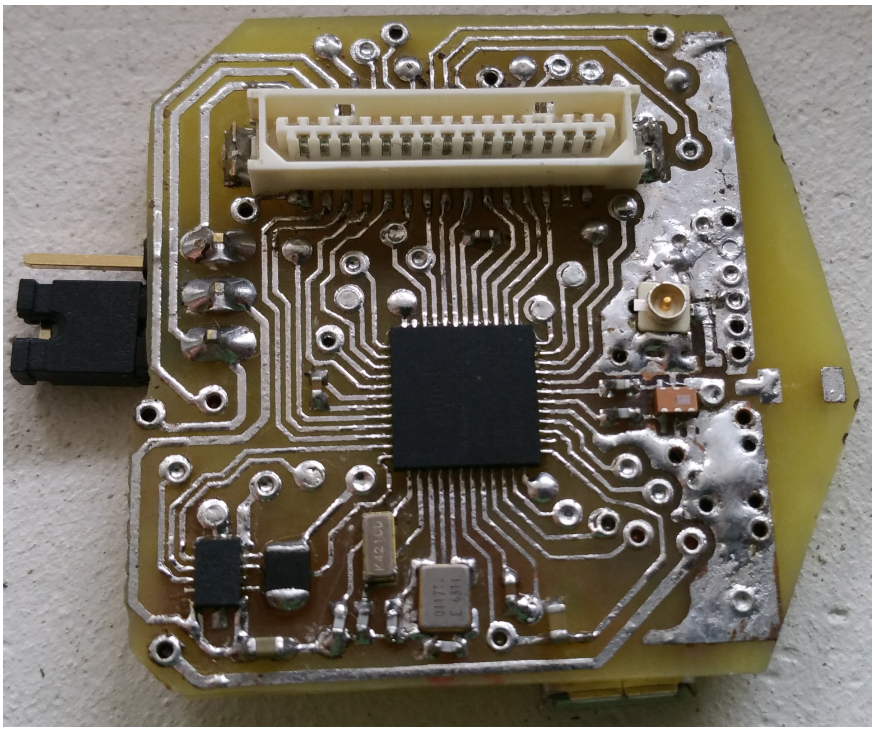

Figure 3.1: Sparrow R node

So far we managed to decrease the idle current consumption for the platform from 350uA to about 30uA @ 3v2, but it is still far from ideal. Surprisingly, lowering the voltage from 3v2 to 1v8 lead to decrease in sleep current consumption down to 3.3uA. When examining the power trace using a digital oscilloscope, we found that a very low frequency clock remains active, which at 3v2 has high spikes in power consumption.

Tough we did not reach the goal of 5uA, we still managed a respectable 30uA @ 3v2 and less than 4 uA @1v8. Due to the time constrains and the need to use the nodes in order to implement and test new features, we decided that for now this is acceptable, and for future revisions, we will come back and find the extra clock source.

Even the run current consumption was not ideal, instead of achieving the promised 70uA/MHz @ 3v2, or around 3.5mA @ 48MHz, the micro-controller consumed 8mA @ 48MHz. We managed to reduce the current consumption to 5.5mA @ 48MHz, due to clock optimizations presented bellow.

The first change was to change the clock of the peripheral interfaces, instead of 48 MHz, we run them at 12 MHz. Also if peripherals are not used, we completely disable them. Due to this, we ran into problems related to SERCOM implementation, a generic module that handle USART, SPI and I2C. It was working on Arduino Zero, because the CPU and the BUS were configured to run the same

speed, but due to the previous clock source modifications, the SERCOM did not set the correct speed. Also, there are 6 SERCOMs, and instead of enabling the clock for each one only when it is used, all of them were enabled, which lead to extra power consumption during run time.

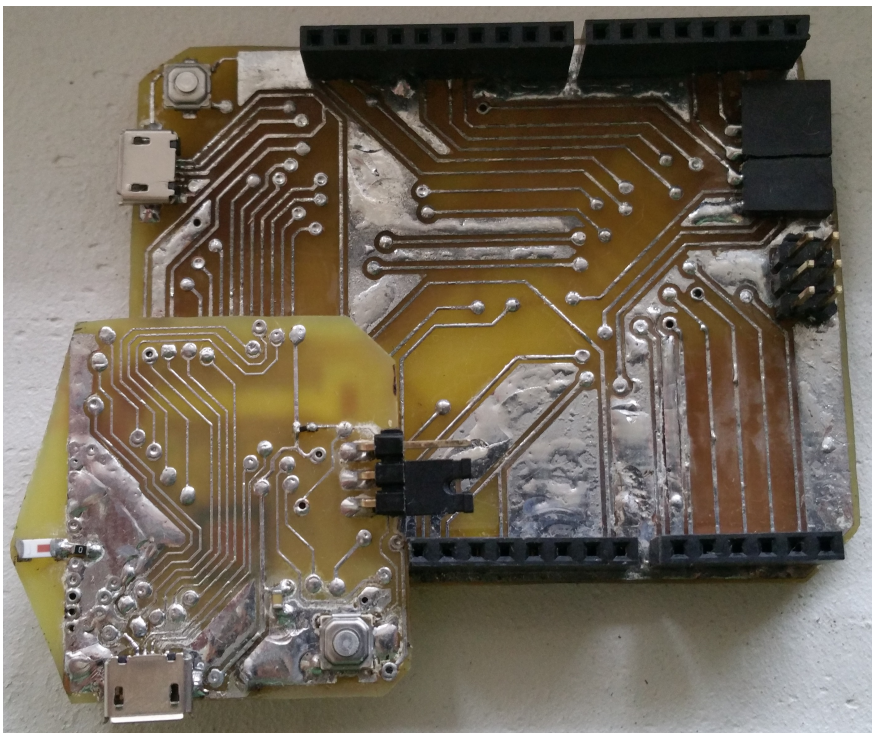

Figure 3.2: Sparrow R node mounted on Aduino compatible base

3.2 Hardware

Because not all sensors are designed to run at 1v8 up to 3v3, we need to be able to dynamically change the operating voltage of the node. We used TPS62742, a step-down switching DC/DC converter with up to 90% efficiency, voltage selectable output from 1v8 to 3v2 with 200mV step, 360nA quiescent current and a special mcu controllable load output, with push-pull transistors. In inactive state the load line is pulled to GND and when active is pulled to VCC. When active it consumes 12uA, but compared to the controlled sensors, this should not be noticeable. Because this allows to completely power down the sensors, the "stand-by" current consumption is 0uA and it also eliminates the previous design problem of floating GND which allowed the sensors to "steal" power from other pins and not be properly disabled.

The node can be connected to an extension daughter board which fully respects the Arduino pinout. The advantage of this approach is that it allows to

easily test and prototype new configurations in order to be prepare the project in the shortest time possible. Also existing hardware designed for Arduino can work with this board, which increased the number of compatible hardware. In total, 20 I/O pins are available, pins that can be used for connecting sensors, either on the daughter board, or directly on a specialty designed board.

A jumper can select whether the Node is powered from USB or from other 2v1+ voltage supply. Through the same jumper a power measuring device can be used to monitor the total power consumption. In case the DC/DC converter is not needed the node can use other power source.

3.3 Software

We implemented new modules designed for low power like sleep, power management which can dynamical change the running voltage between 1v8 to 3v2 when requested and enable or disable the LOAD power line. This allows the user to select which voltage is better required for applications. For example, some sensor must be powered at exactly 2v8 while others at 2v5 or lower. This module allows for precise voltage selection with 200mV increments, use the sensor and then switch to the lowest voltage in order to obtain the best power consumption possible.

The RF module is AT86RF233, integrated into the micro-controller. An Arduino library [4] exists for the RF but in order to add new features, we integrated the module for the RF in the core of the platform. This allowed us to let the user focus on what to do with the platform and not how to do something with it. Furthermore, extra futures and bug fixes are easier to be implemented if the module is integrated in the platform. For example, in case the RF is constantly running in receive mode for more than 5 minutes, it is recommended to do Fine Tuning of the PLL clock in order to eliminate possible clock skews. Feature wise, when the module automatically receives a packet, it saves it locally together with RSSI and LQI, which can be later read and used buy the user. The internal buffer is designed for 8 packets of 127KB of data, which amounts for 1 KB of ram. The buffer is cyclic, so in case the buffer is not read, the oldest data is discarded and replaced by a new one. This should not happen very often, because the buffer is large enough to handle all request, even for high bandwidth transfers.

If the user has a need to save the data in case of power failure, the micro-controller has an EEPROM like functionality which allows a 16KB region of flash to emulate EEPROM write endurance. The flash contains pages of 64 bytes, and the EEPROM has an overhead of 4 bytes, which leaves 60 bytes for actual data. Also, for each page, another page must be reserved for further use. The results is that out of 16KB used, the total amount of usable space left is $\frac{16*1024}{2} * \frac{60}{64} = 7680 bytes$. This should be more than enough for normal use

because the normal endurance of 25k cycles of flash write and erase are increased to at least 150k, with typical values reaching 600k cycles. If a new software is uploaded, the EEPROM zone is completely erased.

For timekeeping when sleeping, RTC functionality was implemented. Besides keeping the time, RTC provides alarm interrupts for a special date, which can be configured to be triggered every minute, every hour, every day, every month, every year, or only once. Together with another peripheral named EventSys, periodic interrupts are provided and the interrupts interval can range from once every second up to 128 times per second, with increments of power base 2.

Because the software and hardware are never perfect, a watchdog functionality is also implemented, in order to avoid code lock-up or hardware failure due to extreme environment conditions.

The software can be installed as a new board for Arduino 1.6.x, latest iteration to date, May 2016. It was tested using Windows 8.1, but it should be fully compatible with other operating systems as well.

The node has native USB which allows for code upload and also serial interface over CDC. Because no extra components are needed, the same node can be configured to act as a gateway or as a leaf.

3.4 Power Consumption

Because the node was designed with low power in mind, we can obtain a very low deep sleep power consumption of 5uW. A small solar panel together with a small capacitor can be used as the main power supply.

For example, when a 1F capacitor is used with the voltage ranging from 3v3 to 2v1 the equivalent battery capacity would be

$$\frac{F * (Vi - Vf)}{t} = \frac{1F * (3.3V - 2.1V)}{3600s} = 0.333mAh$$

The node is equipped with a DC/DC converter that can bring substantial power savings, depending on the voltage of the power supply. A LDO wastes a lot off energy as the delta between the voltages increases, were as DC/DC works best when the delta increases, or putting it simple, if an LDO ouputs 1v8 and a chip consumes 5mA, the input current is almost the sam 5mA regardless of the input voltage. So even though the chip consumes 9mW, the total power consumed is actually 25mW. If in the same situation, a DC/DC with a 90% efficiency is used, then the input current would be :

$$Iin = \frac{Iout * Vout}{Vin * Efficiency} = \frac{5mA * 1.8V * 100}{5v * 90} = 2mA$$

we can ignore the quiescent current because it is very small, around 360nA. The total power consumption in this case is 10mW for an output power of 9mW

compared with the LDO which consumes 25mW in order to output just 9mW, a 250% difference between them.

In a real world situation, when a battery or a capacitor is used, the difference between them is smaller. We will present two cases, in order to better understand the influence of higher voltage supply.

The minimum voltage will be 2v1 for DC/DC and 1v9 for LDO. The current consumption of the chip is 5.5mA, and a capacitor of 1F.

Case 1: Capacitor charged to 3v3.

$$T_{LDO} = \frac{C * (V_i - V_f)}{I} = \frac{1F * (3.3V - 2.1V)}{5.5mA} = 218.2s$$

$$E_i = \frac{C * V_i^2}{2} = \frac{1f * (3.3V)^2}{2} = 5.445J$$

$$E_f = \frac{C * V_f^2}{2} = \frac{1f * (2.1V)^2}{2} = 2.205J$$

$$E = E_i - E_f = 3.24J$$

$$P = V * I * E_{fficiency} = \frac{1.8V * 5.5mA * 90}{100} = 11mW$$

$$T_{DC} = \frac{E}{P} = \frac{3.24J}{11mW} = 294.54s$$

$$Advantage = \frac{T_{DC} - T_{LDO}}{T_{LDO}} = \frac{294.54s - 218.2s}{218.2s} = 35\%$$

Case 2: Capacitor charged to 5v.

$$T_{LDO} = \frac{C * (V_i - V_f)}{I} = \frac{1F * (5V - 2.1V)}{5.5mA} = 527.27s$$

$$E_i = \frac{C * V_i^2}{2} = \frac{1f * (5V)^2}{2} = 12.5J$$

$$E = E_i - E_f = 10.295J$$

$$T_{DC} = \frac{E}{P} = \frac{3.24J}{11mW} = 935.91s$$

$$Advantage = \frac{T_{DC} - T_{LDO}}{T_{LDO}} = \frac{935.91s - 527.27s}{527.27s} = 77.5\%$$

At 3.3V the advantage is not that big, but at 5V we nearly double the battery life. Furthermore, using a LIPO battery which does not discharge as linearly as the capacitor will increase the advantage of the DC/DC.

In real world testing, we charged a 1F capacitor up to 3v3 and let it discharge by transmitting data every second. Even though the software was not optimized for low power, the node managed to run for 8 hours before the capacitor was completely discharged which translates to an average power consumption for almost 112uW.

Chapter 4

Energy Harvesting

This chapter presents the energy harvesting platform.

It is difficult to chose the best solution for solar energy harvesting, due to power requirements of different applications. In this chapter we will present the hardware that we used to generate and store solar energy.

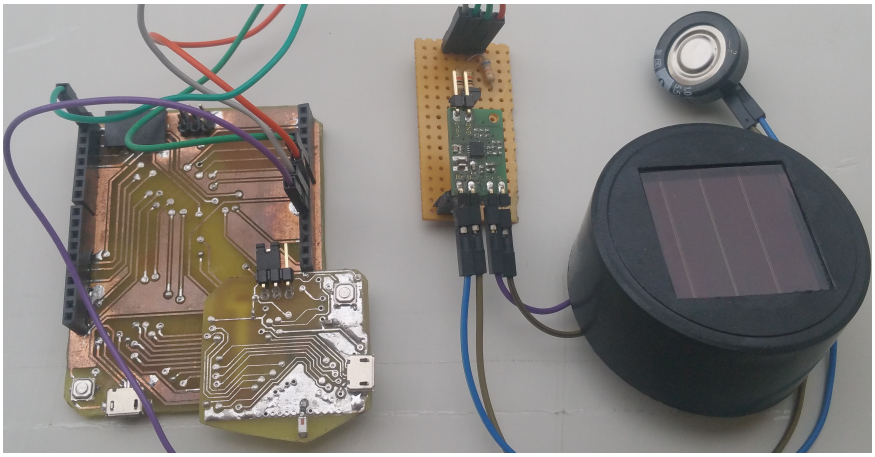

Figure 4.1: Setup for solar energy harvesting

4.1 TI BQ25504

The main component of an energy harvester is the boost converter needed to raise the voltage of the solar cell in order to be able to charge a battery or a super-capacitor. The chip selected by us is TI BQ25504, a very efficient boost converter with battery management for energy harvesting.

The chip can begin charging from a low voltage of only 330mV, has a very small quiescent current, less then 360nA and once started, it can harvest energy until to voltage drops to 80mV or less.

Another advantage is that the output voltage can be selected from 2.5V up to 5.25V, which can be used, as demonstrated in previous chapter, to charge a capacitor to a higher voltage in order to exponentially increase the total amount of stored energy.

Four our experiment, we have selected an output voltage of 3380mV.

4.2 Super-capacitor

The advantages of the super-capacitor over the rechargeable battery are as follows:

- it can charge and discharge almost instantaneously
- it has a very high number of charge/discharge cycles
- it does not suffer from the same aging symptoms as a battery
- it is far less pollutant than a standard battery
- it will allow a longer maintenance-free time than a battery

The disadvantages of the super-capacitor are :

- it is bigger than a battery
- it can store a much smaller amount of energy than similar sized batteries
- it is very expensive
- it operates at low voltages and may require a charge pump to rise the voltage
- much higher current leakage.

The main problem of a capacitor is current leakage. The bigger the capacitor, the bigger the current leakage. Also the technology with which they are built can also have a profound effect on leakage current.

Even though it does not seem much, if a 1F capacitor has self discharge rate of 6uA [7], this is more than the sleep power of the Sparrow R. Even more, if using a 25F capacitor, the leakage current is increased to 45uA, which can be equivalent to the same power consumption of the node sending data every few seconds. Because of this, the total energy that can be stored is greatly affected by the duration needed for the node to use the super-capacitor as power supply.

Charging is also a problem. If for 1F capacitor, a panel that can supply 50uA is more than enough to charge the capacitor and supply the power to the node, for a 25F capacitor that power is barely enough to maintain the stored energy, without even powering the node.

For our experiments we have chosen two 1F capacitors rated at 5V.

4.3 Solar Panel

We can use any solar panel, as long as it is rated up to 3V and has enough power to charge the selected capacitor.

Because we do not need a large amount of energy, a small solar cell of just 60mW is more than enough to fully charge the capacitor in just 5 minutes of sunny weather. This means that regardless of the meteorological condition, we would be able to charge the capacitor daily.

Chapter 5

Software Implementation

In this chapter we will present a simple yet efficient scheduling algorithm for single users.

State-of-the-art algorithms require a lot of feedback in other to dynamically schedule transmission task, the feedback being the consumed energy, the remaining energy. This is not very desirable in real world, where a lot of variables can generate a big error in the estimated energy left

- Large changes in temperature can alter the total energy stored
- Leakage currents, that can vary between charges and different levels of stored energy
- Differences between supposed identical super-capacitors.

In order to simply the algorithms for the user to deploy them faster in a real EHWSN applications, we have implemented and tested a simple dynamic scheduling algorithm for transfered data.

The algorithm can be considered to have very basic water-filling policy, with one slot that is the current discharge period. This simplifies the implementation and reduces the computational requirements. It is designed to be run with an energy harvesting module that has a super capacitor as energy storage unit. Because of this, we simplified the predictor in order to obtain O(1) complexity.

The capacitor does not discharge very linear, but in the tests we have conducted, the error is small enough to allow us to estimated de remaining time without the requirement of measuring how much energy did the capacitor stored and how much energy is was consumed or without a discharge curve.

The algorithm has a total time that it needs to respect, while trying to maximize the total number of packets sent. In order to achieve this two simple

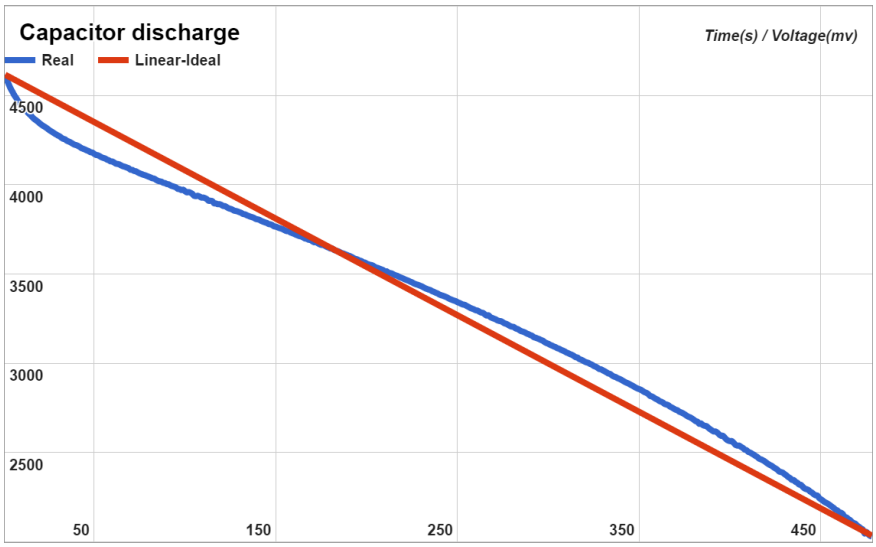

Figure 5.1: 1F capacitor discharge

requirements, it dynamically estimates the remaining time and according to the difference between the estimation and the remaining time, it keeps the same send frequency or alters it. Because when lowering the speed, the total consumed energy will not be halved, due to leakage and sleep current, a penalty is imposed, one that we selected at 75%. Also, in order to make sure that the deadline is respected, under a certain voltage level, the speed is halved and kept until the energy is depleted or the capacitor is recharged.

The algorithm is very versatile, with customization options, depending on the type of hardware and requirements of the application in which it is used.

What can be changed and it is recommended to be changed is presented in the list bellow. Other customization options exists, but it is not recommended to changed them.

- DEFAULT_TARGET_TIME The default deadline for the algorithm. After one iteration it is dynamically adjusted.
- TIME_PERCENTAGE_PENALTY Reduce or increase the estimation time.
- SPEED_DECREASE_PENALTY When the transmission speed is decreased, a penalty must be applied because it is not linear.
- MIN_SEND_FREQ Minimum packets per hour for the algorithm. Minimum value that can be set is one per hour
- MAX_SEND_FREQ Maximum packets per hour for the algorithm. Maximum value that can be set is one per second, or 3600 per hour.

Algorithm 1 Send frequency scheduling Algorithm

```
1: procedure ALGORITHM,(voltage, time)                                    ▷
2:     determine current state Charging/Discharging
3:     if changed from Charging to Discharging then
4:         Calculate the new target time
5:         Calculate the frequency based on total number of sent data
6:         changedVoltage ← voltage
7:     end if
8:     if current state is Discharging then
9:         if voltage < MIN_COMPUTE_DELTA then
10:            sendFreq ← sendFreq/2
11:        end if
12:        deltaVoltage ← changedVoltage − voltage
13:        if deltaVoltage > MIN_VOLTAGE_DELTA then
14:            Estimate the new remaining time
15:            Calculate remaining time until deadline
16:            newSendFreq ← sendFreq ∗ estimated ∗ percentagePenalty/remaining
17:            if newSendFreq! = sendFreq then
18:                Change the speed
19:                changedVoltage ← voltage
20:            end if
21:        end if
22:    end if
23: end procedure
```

- DEFAULT_SEND_FREQ The default packets per hour before the algorithm stabilizes.
- MIN_VOLTAGE_COMPUTE The minimum voltage under which the algorithm will stop adjusting the frequency
- MIN_VOLTAGE The minimum voltage considered by the algorithm when computing the estimated time and the new send frequency.
- MIN_VOLTAGE_DELTA The delta voltage over which the algorithm will start to compute the estimated time and the new send frequency.

The algorithm will recalculate the new deadline every time, so in case the sun will rise sooner or later the target time will be automatically adjusted. In order to compensate for the situation in which the sun will rise later or for a raining day, the algorithm always tries to keep the node alive for a longer time than the given deadline. How much, depends on the deadline.

Chapter 6

Evaluation

Our goal was to deliver a solution that could be deployed in an application as fast as possible, so instead of running software simulations, we decided to implement and test the algorithm on the new node Sparrow R. The algorithm is implemented in C, and compiled with gcc-arm-none-eabi-4.8.3-2014q1 on Arduino 1.6.4.

We selected 2 super-capacitors of 1F and 5V maximum rating. We fully charged the capacitor and then let the algorithm decide how fast the data should be transmitted in order to reach the time deadline.

The only input needed is the current voltage of the capacitor, read using a voltage divider that is control by an n-mos transistor in order to reduce the power dissipated by the divider. The node will run a task that simulates sensors readings and other processing through a delay of 100 ms. The network is configure as single-hop, and the data sent through RF has the length of 45 bytes.

When beginning with a deadline of 4 hours, in the first run, the node manages to execute 1593 task and be functional for a total time of 4 hours and 18 minutes. The second run, with a new deadline of 4 hours and 11 minutes, the node ran 1631 tasks for a total time of 4 hours and 35 minutes.

With a longer, more realistic deadline of 8 hours, the node managed to transmit 785 times for a duration of 8 hours and 14 minutes. We ran into problems when a longer deadline of 12 hours was tested, mainly because the self discharge of the capacitor combined with the idle current consumption of the node is high enough to waste more 75% of the energy. This had a significant impact on the total number of executed tasks.

TODO - add the 12 hours test and talk more about it.

The 12 hour test meant that 1F capacitor is barely enough for 12 hours with our demo test and that a bigger capacitor might be needed. Because we had two types of 1F capacitor, we were curios to see if there is a difference between them. What we found was a bit of surprise, especially the lowest voltage at which

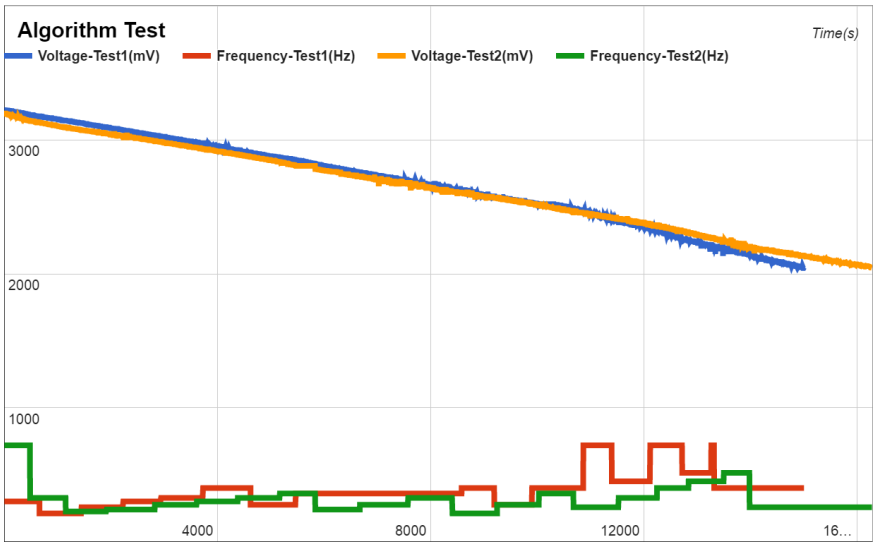

Figure 6.1: Two runs of the algorithm

the node stopped working. The blue capacitor had a lower voltage of 1950mV compared to the black of 2050mV. However, the black one managed to transmit data more times than the blue one, even when the algorithm was tweaked to take into consideration the lower working voltage of the blue one. The black managed to send 1642, while the blue one manage a 1254.

Figure 6.2: 1F differen capacitors, Left Black - Right Blue

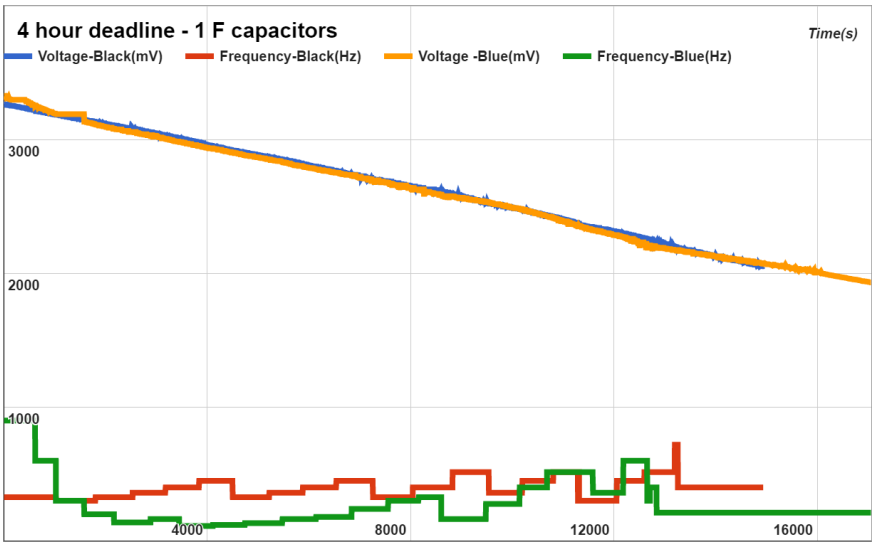

Figure 6.3: 1F different capacitors test, blue vs black

Chapter 7

Conclusions

The main goal of this thesis was to present the complete architecture of a Energy Harvesting Wireless Sensor Network. We have presented a brand new node designed to be new development platform that can be used to bring new ideas to life. On of those ideas is dynamically varying the transmission speed in order to keep alive a node until the capacitor can be recharged. We implemented an algorithm that we tested on the node, something that our research found that is rarely done, and proved that it is able to keep the node alive and use efficiently all the stored energy.

Because the algorithm needs to be able to read the voltage of the capacitor, the hardware requirements are very small and it can be easily deployed on existing hardware with little to no modification.

7.1 Future Work

Even though the algorithm is functional, there is always room for improvement. We would like our work to be continued with an optimization of the algorithm for better time estimation. Also, taking into account past weather in order to predict when we can start to generate power could help us to better determine the new target time, so that in case of a very cloudy weather, we could adjust the deadline and hopefully, keep the node alive until the sun will be able to recharge the super-capacitor.

Another point not covered in this thesis is multi-hop network. We tested the algorithm in a simple single-hop scenario, but a multi-hop test is needed to know if the algorithm needs improvements for this scenario.

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