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ÚSTAV POČÍTAČOVÝCH SYSTÉMŮ

HOME SECURITY AND MONITORING SYSTEM

BEZPEČNOSTNÍ A MONITOROVACÍ SYSTÉM

RODINNÉHO DOMU

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Zadání diplomové práce

Řešitel: **Valach Lukáš, Bc.**
Obor: Počítačové a vestavěné systémy
Téma: **Bezpečnostní a monitorovací systém rodinného domu**
Home Security and Monitoring System
Kategorie: Vestavěné systémy

Pokyny:

1. Seznamte se s technologií "single-chip computer" a vyberte vhodnou platformu pro realizaci centrálního prvku systému monitorování a zabezpečení rodinného domu.
2. Prozkoumejte techniky "energy harvesting" a pokuste se jich vhodným způsobem využít v navrhovaném systému.
3. Navrhněte architekturu sítě bezdrátových senzorových modulů na bázi standardu IEEE 802.15.4/ZigBee. Zde uvažujte například pohybové senzory, senzory otevření oken/dveří, detektory škodlivých látek ve vzduchu a podobně.
4. Implementujte navrženou senzorovou síť a realizujte systém ve skutečném objektu.
5. Navrhněte a implementujte řídicí aplikaci pro správu systému.
6. Vytvořený systém ověřte v reálném RD vzhodnoťte jeho funkčnost a navrhněte případné vylepšení či rozšíření.

Literatura:

- Materiály dostupné na webových stránkách www.zigbee.org a dle pokynů vedoucího.

Podrobné závazné pokyny pro vypracování diplomové práce naleznete na adrese http://www.fit.vutbr.cz/info/szz/

Technická zpráva diplomové práce musí obsahovat formulaci cíle, charakteristiku současného stavu, teoretická a odborná východiska řešených problémů a specifikaci etap, které byly vyřešeny v rámci dřívějších projektů (30 až 40% celkového rozsahu technické zprávy).

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Abstract

The thesis elaborates on an implementation of wireless home security system. The wireless communication utilizes IEEE 802.15.4 radios and ZigBee communication protocol. The beginning of the thesis provides specification of the intended system followed by an evaluation of usable energy harvesting solutions and later by consideration of single board computer systems suitable for implementation of the control node of the sensor network. The rest of the thesis describes design, implementation and testing of particular components of the security system. Conclusion evaluates the achieved goals and offers suggestions for future work. The end products of the thesis are physical devices implementing wireless sensor nodes, control unit of the security system as well as a graphical user interface for the system management.

Abstrakt

Práce se zabývá implementací bezdrátového bezpečnostního systému rodinného domu. Bezdrátová komunikace je realizována rádii na bázi standardu IEEE 802.15.4, konkrétně využívá komunikační protokol ZigBee. Na začátku práce je sepsána specifikace systému, následuje rozbor technologií pro získávání energie z prostředí a přehled současné nabídky tzv. *single board computer* řešení, s elaborací jejich vhodnosti pro realizaci řídícího uzlu senzorové sítě. Dále pak práce popisuje samotný proces návrhu, implementace a testování jednotlivých komponent bezpečnostního systému. V závěru jsou zhodnoceny dosažené výsledky a navržena možná vylepšení stávající implementace. Výstupem práce jsou vyhotovená bezdrátové zařízení implementující senzory, řídicí jednotka senzorové sítě a implementace grafického uživatelského rozhraní pro její správu.

Keywords

ZigBee, wireless sensor network, security, monitoring, energy harvesting, single board computers, energy harvesting, IEEE 802.15.4, Atmel, BitCloud, Raspberry Pi, ARM

Klíčová slova

ZigBee, bezdrátová senzorová síť, bezpečnost, monitorování, mini počítače, získáváni energie z prostředí, IEEE 802.15.4, Atmel, BitCloud, Raspberry Pi, ARM

Reference

VALACH, Lukáš. *Home Security and Monitoring System.* Brno, 2016. Master's thesis. Brno University of Technology, Faculty of Information Technology. Supervisor Šimek Václav.

Home Security and Monitoring System

Declaration

I hereby declare that I have created this master's thesis independently under the supervision of Ing. Václav Šimek. All the materials and information sources the thesis is based on are listed in the text.

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Lukáš Valach
May 25, 2016

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I would like to express my gratitude to my supervisor Ing. Václav Šimek for professional help, useful comments and patience through the process of writing this thesis. Also, I would like to thank my family and friends for their support that helped me to keep a good morale for the entire time.

Contents

List of Abbreviations

a-Si amorphous silicon. 8

ACE auxilliary control equipment. 39, 48

ADC analogue to digital converter. 26, 31, 33, 43, 44, 47

AT Allwinner Technology. 19, 20, 22, 23

BBB BeagleBone Black. 24, 27

BBF BeagleBoard.org Foundation. 23, 24

BLE Bluetooth Low Energy. 18, 30

BOM bill of materials. 32

BPi Banana Pi. 21, 22

c-Si crystalline silicon. 7–9

CdTe cadmium telluride. 8

CIE combined interface. 39, 40, 42, 43

CIGS copper indium gallium diselenide. 8

CPU central processing unit. 18, 26

CU central control unit. 3–5, 28, 32, 37–40, 45, 48

DSSC dye synthetized solar cell. 9

EH energy harvesting. 6, 7, 14

ESR equivalent series resistance. 15

GPIO general purpose input output. 18, 32

GUI graphical user interface. 3–5, 17, 20, 29, 36, 37, 39, 40, 42, 43, 46, 48

IAS Intruder Alarm System. 39, 42

IC integrated circuit. 6, 7, 12, 20, 21, 25, 26, 30–32, 35, 47

IETF Internet Engineering Task Force. 29

IoT Internet of Things. 22, 26

LDO low-dropout. 34, 35

MCU microcontroller unit. 4, 20, 28, 29, 31, 32, 35, 47

MEMS microelectromechanical system. 11–13

MPPT maximum power point tracking. 35

NCPV National Center for Photovoltaics. 10

NiCd nickel-cadmium. 15, 46

NiMh nickel-metal hydride. 15, 16, 35, 46, 47, 50

OpAmp operational amplifier. 34

OPV organic photovoltaic. 9

PCB printed circuit board. 28, 32–34, 38, 42, 47, 48, 50

PEG pyroelectric generator. 11

PIR passive infra-red. 33, 38, 43, 44, 50

PMIC power management integrated circuit. 7, 15, 34, 35, 47, 50

PV photovoltaic. 6–10, 61

RF radio frequency. 6, 14, 28, 29, 31, 32, 48

RPF Raspberry Pi Foundation. 18, 23

RPi Raspberry Pi. 17–21, 26–29, 36, 38–40, 46, 48–50

RTOS real-time operating system. 22

SBC single board computer. 2, 4, 17, 19, 20, 23–27, 50

SoC system on chip. 18–26, 28–33, 39, 47, 48

TEG thermoelectric generator. 10, 11

TI Texas Instruments. 22–24, 31, 34, 35, 46

UPS uninterruptible power supply. 4, 28

WD warning device. 39

WSN wireless sensor network. 1, 11, 12, 14, 24, 27–30, 50

ZCL ZigBee Cluster Library. 30, 42

Chapter 1

Introduction

Information technology and computer based systems have evolved very rapidly over the past few years. Advances in science behind technology, miniaturization and enhancement of the manufacturing processes allow vendors to provide their products cheaper and packed with more features in smaller form factor. Terms such as wireless, energy efficient or energy harvesting are becoming prevalent among current IT products' specifications. People are, as a consequence, confronted with sophisticated technology on daily basis and it undoubtedly affects the way they live, work, relax and do many other activities in their everyday lives. Perhaps the most common reason why one is willing to let the technology affect his live to such extent is the convenience it provides. More and more tasks are delegated to automated systems, so that the user can pursue other, often more pressing or pleasurable business.

One particular area where the technology tend to take over the responsibilities which typically belonged to human is building management. Building automation systems are employed in many corporate buildings for a long time now. They regulate lightning, take care of power management, heating, ventilation, security or other parts of building operation, often with no or little need for human intervention. Analogical systems find their place also in many homes converting them to so called smart homes. The advantages of smart home systems over the regular ones are similar to those in their corporate counterparts. Tenants are provided with detailed information about their household operation, can set up policies for processes performed in the house and these systems can help to improve overall comfortability and cost effectiveness of living. Smart homes, or home automation systems in general, may also cover the security aspect of living in the house. The market offers systems that implement range of passive as well as active devices which contribute to elevation of the home security. They range from sensors as simple as electronic contacts on doors or windows through smart locks to motion sensor triggered cameras.

The motivation behind this theses dwells in a need for home automation system in the author's home. Available security systems are usually closed solutions with limited means for future expandability. Adding additional functionality besides the security may prove complicated and vendor depended. Current technology, as will be shown later in the thesis, provide good means to build custom system, tailored to provide desired functionality for a reasonable price. Security system discussed in this thesis represents only the initial subsystem of a broader, more versatile automation system planned to be employed. Content of the work is based upon the results of technology review and search for suitable components for low power wireless sensor network (WSN) conducted as a semestral project.

Structure of the thesis consists of eight chapters. All are ordered so that they chronologically follow phases necessary for the implementation of the system. After this introduction, the second chapter deals about the system specification. Chapters three and four provide overview of energy harvesting solutions and available single board computers (SBCs) usable within the system implementation. Chapter five describes the design process of the system and the resulting implementation fills the content of the chapter six. Testing and evaluation results with proposed system enhancements are stated in chapter seven followed by the thesis' conclusion.

Chapter 2

System specification

Foundation of successful design and implementation of a system of either software of hardware basis is its specification. Well formed specification may prevent issues later in the development process and thus make it much smoother. From the designer point of view, the specification should be as precise as possible in terms of interpretation of the used language elements. In the best case the specification is expressed in some formal language, which does not leave much space for multiple semantic interpretations. However this is not possible in every situation as not everyone who specifies the system is familiar with such formal language, therefore informal description in natural language is often used. The resulting unambiguity of the specification may cause that the intentions of the person specifying the system does not need to be picked up by the designer. It is hence useful not to underestimate this section and to provide as clear description of the system and its functionality as possible. This chapter provides the specification of the intended system in form of natural language.

On the highest level of abstraction, the system discussed in this thesis can be qualified as wireless security system. Naturally it should include sensor nodes for detection of various changes in the environment as well as central unit, which will act as information gathering and evaluating centre. Sensors themselves may include basic intelligence regarding to environmental changes processing but the main logic and assessment of risks will remain in the central unit. User should be provided by means to configure and control the system through graphical user interface (GUI) and the management application should be able to remotely warn the user about incidents. From the power management point of view only the central unit will have access to mains, whereas the sensor nodes will have to manage from batteries. For the sake of ease of use and low upkeep they should be designed to last long time without the need for user or maintainer intervention. Installation process of the whole system should be painless, thus other than wireless communication between sensors and central unit is not acceptable. Additionally, the system should be flexible enough to handle future functionality enhancements. General idea is to build a more complex home automation system with the security system acting only as the first of its many functionalities.

Above mentioned specification requirements are coarse, but they are there to provide overall picture of the supposed system. Price wise, the whole system should be affordable and use common, easily obtainable components. Price criteria are more strict when talking about sensor units than for central control unit (CU) for obvious quantity reasons of both device types. Therefore one time design and implementation of CU may cost slightly more than the sensors, up to the extent of providing solid base for the system. Adding every additional sensor device to the network should be however as cost effective as possible. The next sections of this chapter elaborate on the system specification from all the particular components' point of view.

2.1 Central control unit

CU will represent the brain of the system. All the processing of the inputs from sensors should be done by the CU, it should monitor their states and control the transitions among them. The perspective of the system extensibility beyond pure security functionality puts slightly higher performance requirements on the CU than ones, which can be met by a simple microcontroller unit (MCU). At the same time it will have to be operational ideally non-stop every day throughout the year, so the power requirements should be low. The ideal candidate for the role of CU seems to be one of the SBCs. They provide enough performance for relatively simple applications yet are not as energy demanding as regular desktop computer. The continuous supply of power to the CU will be realized by uninterruptible power supply (UPS) and for this reason the CU itself does not need to care of a lot about power outage.

Besides the role of the system brain, the CU should also fulfil a role of the network manager for wirelessly the connected sensors. In other words, it will handle nodes joining, remaining and leaving the network. It should be also aware of the operation parameters of the nodes, such us the time periods when the nodes are fully operational and when they are in power saving mode so that it is able to decide whether the node is not available because of malfunction or tamper, or it is simply sleeping.

CU will need to provide GUI for the user to control the sensor network. It should serve as the only interface point with full management access between user and the security system. The users of the system are not anticipated to have vast technical knowledge, therefore the integration and ease of its use are very important. Visualisation on home entertainment system or simple television or monitor are the is the preferable way. More detailed requirements for GUI, mainly from functionality point of view, are described in the section 2.3

2.2 Sensor nodes

One of the main requirements for the sensor nodes is to be energy sufficient for a long period of time. Ideally the user should not be required to actively take care of them at all once they are installed to intended location. In real life however, there will without any doubt have to be occasional service checks, battery changes or initial troubleshooting. Hence, autonomous operation of the nodes could be extended by employing some sort of energy harvesting technique. Expanding existing sensor network with a new sensor should be simple enough, so that a regular user would be able to add a new sensor to established network without major difficulties.

The sensors will sense various environment changes. Foremost, the range of supported sensor types should include motion sensor and contact sensors for detection of opened windows or doors. Small form factor of the actual devices is not a hard requirement, but they are expected to be as small as possible to be easily to manipulate with and install. In spite of their dimensions their wireless range should be able to cover maximal combined distance of 30m.

2.3 User interface

Every aspect of the security system should be manageable directly through GUI running on the CU. It should provide graphical elements to easily arm or disarm the whole system as well as only selected sensor nodes. It should maintain up to date list of active sensors with detailed information about the sensors, which will be editable by the user for easier management. At minimum, there should be elements allowing to specify location and description of a particular sensor. GUI should visualize the states of sensors clearly in order to quickly distinguish alarmed sensor among the others. User should have a possibility to store set configuration and device information he inserted, to make them persistent across multiple application runs.

Chapter 3

Energy harvesting technologies

The essence of energy harvesting (EH) (also known as power harvesting or energy scavenging) is to collect ambient energy of various forms and convert it directly into electric energy [21]. There are two main directions of EH systems, first one concerning large scale applications such as wind/watermills or various large scale solar power systems. The second one, which is the topic of this chapter, concerns small scale applications. In such applications the converted energy can be used to power small electric devices either solely without need for batteries, or to prolong their operating lives by continuously recharging their power sources. Exploiting full potential of EH then makes possible to design autonomous integrated circuit (IC), which are able to run without power source related maintenance for many months, even years. Combination of EH solutions together with utilization of wireless communication technologies in IC designs represent very desirable solution in applications, where any maintenance of the device would be difficult and/or expensive.

Ambient energy occur in many forms yet not every type is equally effective to harvest in all situations. Among the EH techniques, probably the most developed and widely used one concerns exploiting the energy from light, either sunlight or artificial light from various sources. Harvesting light energy and converting it to electrical power is possible thanks to photovoltaic (PV) effect and therefore the technology using this principle is commonly referred to as photovoltaics. Other types of EH include harvesting thermal energy, energy from movement or biological/chemical energy from chemical reactions. Nowadays, a broad usage of various wireless technologies based on radio frequency (RF) signals permits harvesting energy virtually out of thin air. Table 3.1 shows power density of several suitable ambient energy sources according to available literature [40, 5, 55, 42]. Power density determines how much energy can be potentially harvested from given energy source.

Ambient source	**Power density (μWcm^{-3})**
radio transmissions	< 1
artificial light	100
sunlight	100 000
vibration	4–800
thermal	10–60

Table 3.1: Power density of ambient energy sources

In order to successfully apply energy harvesting techniques within the IC design it is necessary to cope with various aspects and limitation of these techniques. Harvested energy have to be handled efficiently because not all the energy of the source can be harvest and turned into electric energy. In the best case scenarios only up to few mW of energy can be usually harvested. Moreover the amount of harvested energy fluctuates, as the sources of ambient energy are typically not stable. Therefore there usually have to be power management integrated circuit (PMIC), which takes care of proper storing and regulation of the harvested energy.

Energy storage itself is generally the biggest limitation and challenge concerning development of energy self-sufficient mobile solutions. The storage can be provided by various types of batteries or capacitors, each of them with different properties more or less suitable for specific harvesting application. Incorporation of EH techniques therefore requires understanding of this topic as well as careful planning with concerns about destination area and function of the design in mind.

3.1 Photovoltaic energy

Harvesting solar and light energy in general to power small or medium sized electronic devices is nowadays well established. Various solar powered wristwatches or calculators represent the typical application in consumer electronics for many years now. Properties of the solar cells empowering the devices however strongly depend on their manufacturing process and the type of the cell technology itself. Many different methods to produce PV cells exists and new ones are always a subject of research. One of the main research goals is increasing the conversion efficiency of existing technologies, which is even now relatively small. The efficiency of PV cell technologies may also vary significantly depending on light properties it intends to harvest energy from. The cell technology usually predetermines whether the cell is going to be used in direct (sun)light or operating in diffused light conditions. These conditions also affects lifetime of the cell technology and therefore careful consideration have to be made prior selecting the particular technology for a specific application. In the following section is discussed current state-of-art technology of PV cells, their principle of work, performance and availability in consumer market.

3.1.1 First generation

Historically the oldest generation of commercially usable PV cells is based on crystalline silicon (c-Si) and represent the majority of solar cells used worldwide (sales over 87% in 2011 and 90% in 2012, 92% of produced PV cells [35, 26, 10, 20]). The reason for that dwells in their generally high efficiency (commercially available about 16%) of transforming light to electric energy and long lifetime of operation. Moreover the technology itself is very mature. The electricity is generated by single layer P-N junction of crystal silicon semiconductor, which are produced on wafers, ribbons, ignots or other forms. Depending whether the cell is composed only of single crystal or multiple grains of crystals, the first generation of PV cells is further divided into monocrystalline and polycrystalline cells. Former are more expensive to produce in large dimensions as a growing process of one big silicon crystal is a peculiar thing. On the other hand it generally provides highest energy conversion efficiency for given cell area among the first (and also second) generation of PV cells. Their lifetime is proven over the long time of usage worldwide, yet their efficiency is decreasing as temperature of environment rises (loss of 12-15% for over 50 °C) or in diffuse light conditions [10]. They have also low absorption coefficient which causes portion of light to be reflected instead of converted to electrical energy. In order suppress this negative effect they are often treated with an anti-reflexive coating and their surface can be textured so that the light is trapped within the cell.

Polycrystalline cells are generally less efficient, having approximately 80% of monocrystalline efficiency because of the impurities in cells. Their fabrication process is less expensive and material intensive. Instead of growing a single crystal of silicone, these cells are made by pouring molten silicon into a cast implanted with seed crystals, thus growing silicon forms multiple homogeneous areas when cooled down. This kind of cells can be recognized by „metallic effect“ pattern caused by visible grains of different silicon crystals. Other properties remains similar to the monocrystalline cells.

3.1.2 Second generation

Another type of silicon based PV cells are amorphous silicon (a-Si) cells. Unlike in the two previous, the silicon in this type of cells is not organized in crystal structure or anyhow regularly structured. The cell itself is only a thin layer of silicon deposited on backing substrate material such as metal, glass or plastic. A-Si PV cells together with non-silicon based PV cells made of cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) are commonly classified as thin-film solar cells and represent the second generation of PV cells. One of the advantages of thin-film cells is that they can be made flexible and transparent to some extent, therefore allowing more versatile usage than fragile c-Si cells. Thin-film technology uses much less material for manufacturing process which is also less expensive than for c-Si cells. However, they have lower conversion efficiency and therefore require more space to provide similar performance. In case of a-Si it is caused by its unorganized molecular structure resulting high recombination rate. To compensate, thin layers are often stacked on top of each other, creating multiple junction PV cell discussed in subsection 3.1.3. Each layer can target different spectral range of light to harvest thus increasing overall efficiency. Thin-film PV cells perform relatively well under poor lightning conditions and are not as much affected by shading. Those features predetermine them to be used indoors and indeed they are very commonly used in solar powered calculators or wristwatches. Big disadvantage of a-Si cells is, that their already low efficiency degrades over time significantly. Within first 1000 hours of operation it can loose up to 15% of its efficiency after which it remains relatively stable. Exposing them further to strong direct light cause efficiency degradation of up to 30% of original initial efficiency [16].

CdTe and CIGS cells generally perform better than a-Si in terms of conversion efficiency. Some commercially available CdTe cells are reaching up to 13% [20] conversion rate. They have also better heat resistance than crystalline silicon cells. As a matter of fact, thin-film cells, namely CdTe, represents second biggest market portion after crystalline silicon cells [20]. There are however other concerns regarding CdTe and CIGS. They both use cadmium compounds. CIGS uses CdS as one of its top layers, but in much smaller level than CdTe) which is rather toxic. Although the use of such cells should not bear risk for environment, there are concerns about effect on the environment when the cell is damaged and at the end of its lifetime [15]. Another concern regards the availability of some rare elements, namely tellurium and indium, in the future [27]. In spite of all the concerns, those two types of cells still represent competition for c-Si in specific applications thanks to their high light absorption coefficient with good matching to solar spectrum and low cost manufacturing process.

3.1.3 Third generation

Third generation of PV panels represents a new approach to PV technology, with focus on using abundant non-toxic materials and increase of conversion efficiency. The technology of this generation still mainly resides in laboratories. The cells consists of basically a several thin-film layers stacked on top of each other. The top layer uses high band gap (junction) cell to absorb high energy photons, allowing low energy photons to pass through to to the lower layers. Lower layers have each slightly lower band gap than the previous one and are able to absorb photons with longer and longer wavelenghts, hence lower energy. Without additional lower band those lower energy photons would be lost as heat.

The number of layers is usually two or three, recently four. Theoretical maximum efficiency generally increases with number of junctions. The highest conversion efficiency among all technologies is currently provided by so called III-V multi-junction PV cells. Material used to create thin layers of those cells were originally elements in the III and V columns of the periodic table therefore the name of the category. The same technique of using multiple junctions can be used also with second generation thin-film cells, while other materials such as organic molecules are being investigated as well [36]. Despite currently high conversion efficiency, these cells are not commercially wide spread. The manufacturing techniques and materials are still too expensive to allow them to become real competitors to crystalline PV cells in a production environment.

Another type of third generation PV cells are organic photovoltaic (OPV) cells [37, 45]. This technology aims to lower the cost of PV energy in contrast with first and second generation. It uses abundant carbon based polymer materials with different colours and transparency disposed in thin films. They are predetermined to be used in building integrated PV and on various surfaces with need for flexibility. Principle of operation of OPV technology is based on electro-chemical reaction, usually between multiple organic semiconducting materials commonly called acceptor and donor enclosed between two electrodes. Incoming photon is absorbed by donor layer, where it excites an electron of single molecule. The electron is bound together with hole and forms so called exciton. The exciton is transported to the interface of donor and acceptor materials, where due to materials' electro-chemical properties it is separated to free electron, which is accepted by acceptor, and a free hole. Both of them then contribute to difference in potential, create PV effect and the resulting charge is extracted by electrodes. Conversion efficiency of OPV cells is small, but they can compete with better already mentioned technologies due to the simplicity of their fabrication process and usage of eco and cost friendly materials.

On the edge between organic and inorganic PV cells are dye synthetized solar cell (DSSC). They utilize three components to operate. First is organic absorber material, dye, used for absorbing photons and generating excitons. Second component is metal-oxide material which transports free electrons from excited dye molecule to anode. Last component is liquid electrolyte which transports free holes from dye to cathode. Benefits of DSSC are as well as in case of OPV cells in simple and low cost manufacturing process and materials. However, they also share their low conversion efficiency and shorter lifetime than c-Si technologies. There are not any available product in commercial production yet.

Different approach to increase cell efficiency and lower the manufacturing cost can be achieved by using optical systems of mirrors and lenses called concentrators. Role of a concentrator is to gather and focus light from broader region into small area and therefore increase its intensity. This way the light can be directed to much smaller PV cell, which reduces amount of needed material and eventually its manufacturing cost, especially if rare elements are used. In case a high efficiency solar cell such as multi-junction solar cell is used, the harvested energy from small area is significantly higher than without the use of concentrator. The highest conversion efficiency, 46%, among all PV technologies was achieved in laboratory environment using highly concentrated multi-junction solar cell. Concentrator can be static or mounted on tracking system which accommodates the movement of the Sun, hence provides the best position and angle for concentrator to achieve its maximum performance. Obviously, this technology is intended for outdoor use. Although concentrators can provide much more energy to be converted by PV cell, it also heats up the cell itself. High temperatures may lower cells efficiency so it has to be cooled down by some active cooling system.

Despite provided classification of PV cells into categories in the text above, the classification is not as simple and clear. Various groups of researchers and manufacturers may use different criteria for classification. At top of that, many groups overlap and technologies used in one group are being researched in other in order to be applied in a different way. New research ideas can be applied to old technologies, upgrade them and create a new technology covering features of multiple stated groups. When it comes to conversion efficiency of respective technologies and their improved versions, National Center for Photovoltaics (NCPV) of USA maintains up to date chart of PV technologies efficiency along with world record numbers and companies that hold them. The chart is shown in the figure D.1.

3.2 Thermal energy

Harvesting energy from heat is possible thanks to Seebeck (thermoelectric) effect. It was first observed back in 1826, that two dissimilar metals with different temperatures kept together would generate electric charge [38, 53]. The simplest unit using thermoelectric effect is composed of two metals of different materials — nowadays P-type and N-type semiconductors — connected by metallic interconnections. Such structure is called thermocouple. When different temperatures are applied on the top and bottom of the thermocouple it generates open circuit voltage between not interconnected ends of semiconductors. In order to increase the harvested power, more thermocouples are used and enclosed between two electric insulator plates usually made of ceramic material. Individual thermocouples within the structure are connected together thermally in parallel and electrically in series. Such system is called thermopile and it is a core component of thermal energy harvesters commonly referred as TEGs (see figure 3.1). The voltage output of TEG depends on the temperature difference between its hot and cold sides as well as material dependent coefficients (Seebeck coefficients) of semiconductors. In order to increase temperature difference

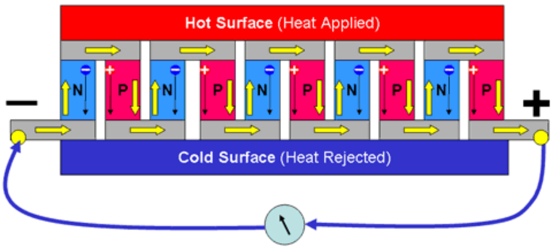


Figure 3.1: Thermoelectric generator (TEG) structure
(taken from `http://www.mpoweruk.com/thermoelectricity.htm`)

between hot and cold plates of TEG, various heat sinks and radiators might be used to direct heat to hot plate or dissipate the heat from the cold plate more efficiently. Operational performance also depends on thermal resistances of materials used in thermopile. Higher thermal resistance is creating larger effective temperature drop and eventually, the harvester generateis more power. Improvement in TEG technology came with new materials and miniaturisation. Emerge of microelectromechanical system (MEMS) technology allowed TEGs to become thin-film devices and broaden their field of application into areas such WSN, where compact dimensions matter. Shrinking the manufacturing process also increased the amount of integrated thermocouples per TEG, therefore making them more powerfull while still retaining the size.

Alternative approach of harvesting thermal energy uses pyroelectric effect of certain materials. Those materials exhibit spontaneous electrical polarization which is a function of temperature. Unlike previous TEG principle, pyroelectric material is heated up as a whole and electrical charge is only temporary over the time. Variations of temperature then cause correspondent variations in charge. Principle of generating and harvesting electrical energy using pyroelectric generator (PEG) is similar as the one used in conventional mechanical heat engines. The PEG is continuously heated up and cooled down in a cycle which causes the electrical current in attached external circuit to change its flow direction. Resulting alternating current is then usually regulated to direct current. Problem of this approach is that environment with such alternating temperatures, so called thermal vibrations or thermal transients, is not very common.

One option to achieve needed thermal vibrations can be realized by thermally connecting pyroelectric material on a tip of bi-metallic strip, which is then carefully placed between heat source and heat sink. Bending of the bi-metallic strip is designed to touch alternately the hot and cold surface every time it is cold or hot enough. Due to the oscillation of the bi-metallic strip caused by temperature rise and fall, the pyrroelectric material is alternately forced against heat source and heat sink, therefore experiencing thermal vibrations and generating the needed charge [46, 47]. On the other hand, issuing moving parts to harvesting system can limit device reliability and negatively affect its lifetime.

Although pyroelectric effect based harvesting has big potential and can operate better even with high temperature source, there is still need of research to be done prior their commercial success. The main advantage of TEG over PEG is, that they need only steady state temperature gradient and does not require any moving parts. However TEG has lower theoretical maximum efficiency for given temperature difference than PEG. Modelling and experimental measurements indicates that PEG system conversion efficiency could be in range of 10-20% whereas TEG systems are in range of 8-10% [22, 47].

3.3 Energy from vibrations and motion

Vibration energy harvesting includes transducers exploiting electrostatic, electromagnetic or piezoelectric effects [53]. In a general scheme, the kinetic energy of environment is usually firstly converted into relative motion between two elements using mass-spring system. Actual mechanical-to-electric converter exploiting one (or several) previously mentioned effects is then coupled to it and generates electric energy. Thanks to the mass-spring system's resonance phenomenon, the amplitude of relative movement of the system is increased compared to ambient vibrations' amplitude, which increases the amount of converted energy by transducer. However, the resonance frequency of the system has to be tuned to match the characteristic frequency of the application environment thus if that changes, the harvesting system efficiency decreases. One of the aims of further research is to widen the frequency range in which a system is efficient or develop techniques for adaptation to this changes. Harvested power is usually delivered in alternating current therefore the final part of a harvester is usually AC/DC converter.

3.3.1 Electrostatic converters

Electrostatic harvesting system's mechanical-to-electric converter is based on variable capacitors system. It generates electric charges from capacitance variation, which is caused by relative motion of two polarized electrodes separated by air, vacuum or any dielectric material [43]. They can be further divided into two types, electret-free and electret-based. Electret is a dielectric material that has a quasi-permanent electric charge or dipole polarisation, which can last for years. The former are passive structures and require active electric circuit in order to provide necessary polarization to the electrodes. The system then converts energy in energy cycles and have to be either re-polarized after each cycle or supplied by constant voltage which takes care of the polarisation. Part of the harvested electric energy can be used for the polarisation in the latter case, it renders there to be peculiar to use. They have to be started up using external power source and to maximize the efficiency, the polarization source has to have high voltage ($>$100 V). On the other hand, the electret-based ones are already polarised and therefore mechanical energy can be directly converted to electrical energy without any need for initial starting electric energy. Their output powers also depend on electret's surface voltage and their lifetime is determined the by their charge stability, which is on average at least 200 years [28].

Output voltage of electrostatic harvesters is usually high (hundreds of V), whereas the generated current is rather low (hundreds of nA). Hence there has to be step-down voltage regulator or similar power management IC circuit to be able to power up WSN nodes. Electret-free harvesters can produce power of hundreds of $\mathrm{nWcm^{-3}}$ up to few tens of $\mathrm{\mu Wcm^{-3}}$, whereas the electret-based deliver tens and even hundreds of $\mathrm{\mu Wcm^{3}}$ [43].

Electrostatic transducers are less known option for energy harvesting from movement compared to for example piezoelectric devices. However they have potential to become low cost devices as they do not require any magnets or expensive piezoelectric materials. They are suitable for low frequency vibration environments ($<$100Hz) and thanks to MEMS technology can be miniaturized into dimensions appropriate to use with WSN nodes. Unfortunately, currently there are not any commercial solutions on the market so the technology still resides in research laboratories.

3.3.2 Piezoelectric converters

Piezoelectric materials are able to generate electric charges proportional to mechanical strain applied to them. Inversely, they deform when they are exposed to an electric field [44]. Piezoelectric materials are usually anisotropic, which means that their properties differ with respect to the direction of the applied forces, orientation of polarization and electrodes. In the first type of piezoelectric converters the electric power was generated by applying compressive strain perpendicular to electrodes on the material. In other words, a direct pressure or force from an impact was applied to the material. This way of harvesting movement energy is suitable for e.g. shoe sole harvesters, gathering energy from impacts of shoe and ground, but it does not have many practical applications in vibration abundant environment. Energy from vibrations is much more efficiently harvested by a system, where piezoelectric material is under traverse strain parallel to the electrodes, i.e. forces bend the material rather than compress it. This set-up usually uses layer of piezoelectric material attached to cantilever structure as in figure 3.2.

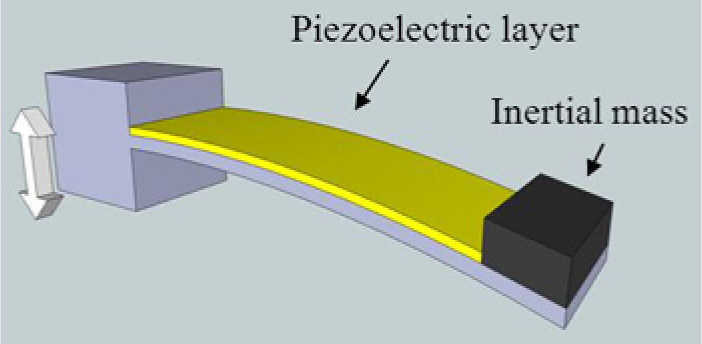


Figure 3.2: Piezoelectric energy harvester
(taken from www.npl.co.uk)

The free end of cantilever is fixed with mass, so that the whole system's vibration amplitude, and therefore the strain to piezoelectric element, is amplified due to resonance of a mas-spring system when exposed to ambient vibrations. It was concluded, that the mass on the cantilever should be maximized with respect to size limits and strain constrains in order to maximize the harvester's output at resonance. Depending whether the cantilever is composed of only one piezoelectric layer or two, they are called unimorph and bimorph respectively. The former shows better performance in low frequency vibrations and the latter in mid-range. Piezoelectric conversion principle is well suited for micro-scale integration and MEMS technology. Properties of piezoelectric material varies with age, stress and temperature. Over the time they tend to stabilize, but the ageing is accelerated with the amount of stress applied to them over time and they can lose its piezoelectric properties after heating up over certain temperature. Output voltage of piezoelectric harvesters is relatively high at low electrical currents. This technology typically reaches output power in tens, even hundreds of $\mu\mathrm{Wcm}^{-3}$ depending on the vibration conditions and size of the harvester system.

3.3.3 Electromagnetic converters

Principle of operation of electromagnetic transducers is based on exploiting Faraday's and Lenz's law in a system composed of magnets and coils. Electric current is induced in a coil exposed to a variable magnetic field thanks to effect known as electromagnetic induction. It is well established electricity generation technique, especially in history of electricity generation within macro-scale power plants. Variation in magnetic field is achieved by motion of a coil in a magnetic field of a magnet, which causes the coil to be affected by changing magnetic flux depending on a relative distance between the magnet and the coil. The faster the motion is, the faster the change rate of magnetic flux in coil is, and therefore the higher current is generated.

Electromagnetic converters are usually bigger in size/volume due to need for coils with sufficient number of windings and magnets, hence they are more difficult to miniaturize in a way that they still generate sufficient amount of energy [53]. Although they provide lower voltage, they usually delivers higher output current than piezoelectric and electrostatic harvesters [5]. MEMS based harvester was able to produce output with power of about hundred nW but bigger devices can deliver high hundreds of µW of power.

3.4 RF energy

Development in wireless communication technologies filled the environment of cities and even villages with RF energy of various parameters. It includes digital TV, GSM, 3G/4G cellular signals and WiFi operating on wide range of frequencies (300kHz - 5GHz) [41]. Those are major contributors to ambient RF energy which has potential to represent essentially free power source for small WSN nodes. Although this energy is abundant in urban environment, it has low power density and suffer from attenuation through its propagation, reflections and absorptions by various obstacles. It may also be very unreliable, fluctuating power source as in case of WiFi, where transmissions depend on active use.

Actual amount of harvested power is then affected by multiple conditions. The efficiency of the receiving antenna system along with the distance of harvesting system from RF signal origin are the key determining factors. Antenna system efficiency is relatively high but vary from system to system and application. It can reach even over 50% [34] depending on the input signal power. But even if the transmit power of source is high, the energy effectively harvested lowers significantly as the distance from the signal origin increases. In case of WiFi router RF source the transmit power is about 100 mW. But according to [39, 1] harvesters can typically provide power in order of units or tens of µW if situated relatively close to it. This amount of power is admittedly sufficient to power simple WSN with long duty cycles of wakeup-sense-transmit, but for more active or functionally complex wireless nodes it is still quite limiting. Similar numbers of harvested energy are also obtainable by harvesting energy from more powerful power sources such as GSM or digital TV signal. The relative distance from them can be usually larger, e.g. tens or hundreds of m. Another possibility for increasing energy output is to use a bigger antenna, but it may become impractical for small WSN nodes [34].

Some applications may exploit another approach for harvesting RF energy to power their operation. Instead of gathering the ambient energy, which was emitted by other devices as a part of their operation, a device may prefer to focus on harvesting RF energy from a dedicated source [7]. In such case the amount of harvested energy can be higher as both the harvester as well as the RF source can be fine tuned to work in synergy. Distance related attenuation however remains, moreover this approach brings additional cost to WSN design for dedicated RF sources, which have to comply with country specific maximum wireless power regulations.

3.5 Energy storage

Above described EH techniques represent only front end of EH system. The harvested energy is usually not consumed by the load right away as it comes from the harvester. In the most cases the energy is stored into some kind of energy storage, either capacitor, rechargeable battery or both at the same time. Those then provide power for the application load. Choice of energy storage type plays an important role when designing EH system as its properties may predetermine or limit the specific application area of the result.

The table 3.2 contains only few of may types of the energy storage technologies. They were selected based on available literature research, mainly [4, 24, 23], and the scope of the thesis. Every type has its pros and cons to be considered. The following paragraph discuses

Storage type	Capacity* (mAh)	Voltage (V)	ESR* (mΩ)	Recharge cycles
(Super) Capacitor	tens of F	up to 2.5	10	unlimited
Thin-film	1	3 to 4.1	10000	10^4
Li-Ion	100	3.3 to 4.2	100	up to 500
NiMH/NiCd	100	1 to 1.3	10	500 to 1000

Table 3.2: Energy storage types overview. Columns marked with asterisk (*) show the order of the units.

suitability of each listed storage type for the purpose of this thesis.

All storage types store the charge exploiting electro-chemical reaction except for capacitors. They are based on electrostatic principle and hold their charge thanks to the difference of potentials among electrodes separated by insulator. Thanks to that they withstand virtually unlimited amount of recharge cycles, but they are unable to hold the charge for long time periods. Their self discharge rate is highest from among the others. Very small equivalent series resistance (ESR) enables them to discharge the charge to load at very high currents without significant voltage drop. However, their inability to hold charge for long time as well as usually low nominal voltage render them useless as a stand-alone energy storage for the purpose of the thesis. On the other hand, they are suitable as power surge source when energy storage with high ESR is used as main energy source. Thin-film batteries would be a good match to such combination. They provide higher capacity and reasonable amount of recharge cycles. The drawback of using this technology is mainly its relatively high price. The choice of storage type was therefore narrowed to Li-Ion, nickel-metal hydride (NiMh) and nickel-cadmium (NiCd) batteries. They all provide enough capacity and their ESR should not cause any problem when powering the wireless nodes. Price wise are NiMh batteries the way to go with Li-Ion as the second best which leaves the last place to NiCd, which are also probably because of use of cadmium slowly being replaced by NiMh. NiMh batteries are also more durable when it comes to over and undercharge tolerance and also provide more recharge cycles.

Along with the selection of battery type and harvesting technology, has to be selected the PMIC. Its role is to manage the charging of the battery, protect if from damage by draining it dry or on the other hand overcharging it. Different battery types may have various charging strategies. Li-ion batteries are for instance charged by constant voltage charging and they do not tolerate almost any overcharge when they reach their full capacity. They also have a point of the lowest voltage at witch the load must be removed from the battery to prevent permanent damage. NiMh batteries on the other hand handle continuous charging by small currents, which is typically referred to as trickle charging. They tolerate over and undercharging and the original capacity can be restored [24].

3.6 Conclusion

With respect of the discussed in this chapter, the most viable option for employing energy harvesting technique to prolong operation of wireless sensors seems to be light energy harvesting. The family house environment where the devices are going to be deployed does not provide many other ambient energy sources, at least not in a form for meaningful harvesting. Light energy harvesting is also the cheapest to realize which will matter a lot as the sensors are intended to be deployed in more than small quantities eventually. The quick research of energy storage in local market selected NiMh as the most competitive battery technology to include in the security system. Although they come only with 1.2 V nominal voltage, there are packs of triple cells in series providing sufficient resulting voltage.

Chapter 4

Overview of single board computer platforms

SBCs are pocket-sized devices, which provide PC functionality for many low cost applications. They are well established among community of do-it-yourself enthusiasts for various hobby projects as well as among specialists for more serious applications, research related experiments or for educational purpose. Their computational power usually can not be compared to the one of regular PCs, but PCs are for many applications unsuitable or simply provides much higher performance than is actually needed. SBCs usually outperform them in power consumption, cost and in some cases set of I/O interfaces for low level interaction with analogue or digital world (ADC, SPI, etc.).

With respect to the aim of this thesis, selected SBC will have to fulfil the requirements stated in the chapter 2. In short, it will have to handle GUI, run energy efficiently and because not many SBC integrates IEEE 802.15.4 radios, it have to be capable of low level serial communication with external component providing wireless access.

Market with SBC has experienced a big development recently and is relatively full of SBC of various capabilities for diverse areas of application and in many price ranges. According to the basic requirements above were selected few solutions which could be utilized and the following sections discuss their advantages and disadvantages. Golden mean for price was set to 40 €, but without any doubts there are solutions providing necessary features while meeting the price limit. The information about boards were collected mainly from official pages of manufacturers of the solutions or official community support wiki pages.

4.1 Raspberry Pi

Clearly the best known product within SBC category is Raspberry Pi (RPi), which undeniably brought the concept of SBC up among the general public [19]. Although several different solutions have already been around at the time when it emerged, it dragged the attention of media and public as a low cost hardware development board. It still remains very popular and has well established community of users, who develop and share their solution among each other. What have started as a means to provide an affordable device for education purposes, have spread to the whole world covering a whole spectrum of applications.

Currently there are many versions of the board. The first, generation 1.0, started

<table>
<tr><th></th><th>B (Rev 2.0)</th><th>B (Rev 3.0)</th></tr>
<tr><td>SoC:</td><td>Broadcom BCM2836</td><td>Broadcom BCM2837</td></tr>
<tr><td>CPU:</td><td>900 MHz 32b quad-core Cortex-A7</td><td>1.2 GHz 64b quad-core Cortex-A53</td></tr>
<tr><td rowspan="5">GPU:</td><td colspan="2">Dual Core Broadcom Videocore IV Multimedia Co-Processor</td></tr>
<tr><td colspan="2">MPEG-2 and VC-1 (with license)</td></tr>
<tr><td>@250 MHz</td><td>3D @300 MHz, video @ 400 MHz</td></tr>
<tr><td>OpenGL ES 2.0 24 GFLOPS</td><td>28.8 GFLOPS</td></tr>
<tr><td>H.264 encode/decode 1080p@30</td><td>1080p@60</td></tr>
<tr><td>Memory:</td><td colspan="2">1GB DDR2 (shared with GPU)</td></tr>
<tr><td>USB:</td><td colspan="2">4x USB2.0 (on-board 5-port USB hub)</td></tr>
<tr><td rowspan="2">Video out:</td><td colspan="2">composite video (3.5 mm TRRS shared with audio out)</td></tr>
<tr><td colspan="2">HDMI rev 1.3/1.4</td></tr>
<tr><td>Audio out:</td><td colspan="2">analog (3.5 mm phone jack), digital (HDMI, I^{2}S)</td></tr>
<tr><td>Storage:</td><td colspan="2">microSDHC card slot</td></tr>
<tr><td rowspan="2">Network:</td><td colspan="2">10/100 Mb/s Ethernet (on the fifth port of the USB hub)</td></tr>
<tr><td></td><td>802.11n wireless; Bluetooth 4.1, LE</td></tr>
<tr><td rowspan="3">Extra pins:</td><td colspan="2">40-pin 2.54mm connector</td></tr>
<tr><td colspan="2">17 GPIO pins</td></tr>
<tr><td colspan="2">SPI, UART, I^{2}C, I^{2}S, +3.3/+5.5V/GND</td></tr>
<tr><td rowspan="2">Others:</td><td colspan="2">15-pin MIPI camera interface (CSI-2)</td></tr>
<tr><td colspan="2">digital audio input via I^{2}S</td></tr>
<tr><td rowspan="2">Power:</td><td>600 mA (3 W, switching regulators)</td><td>800 mA (4 W)</td></tr>
<tr><td colspan="2">5V in via microUSB (or GPIO but bypassing fuse protection)</td></tr>
<tr><td>Price:</td><td>35 €</td><td>32 €</td></tr>
</table>

Table 4.1: Raspberry Pi model B revisions 2.0 vs 3.0 comparison [19]

with two different board models, model A and model B. Model A was developed as a lightweight version of model B, providing the cheapest option lacking on-board networking capabilities and with only 256 MB of RAM memory in contrast with full featured model B with 512 MB of RAM. Raspberry Pi Foundation (RPF), the organisation behind RPi, then issued enhanced versions of both models labeled A+ and B+. The new versions featured more USB ports, more general purpose input output (GPIO) pins and lower power consumptions. At that point the development of model A+ had reached its end and RPF decided to continue to develop only model B+ product line.

Generation 2.0 brought the system on chip (SoC) replacement for newer one containing quad-core ARMv7 core, also enhanced on board RAM memory to 1 GB. The latest product, generation 3.0 model B uses 64 b ARMv8 quad core central processing unit (CPU) and provides many new features. The most interesting ones are on-board wireless connectivity support through WiFi, Bluetooth 4.1 and Bluetooth Low Energy (BLE) or more aggressive clocking of GPU, RAMs or even CPU itself. Comprehensive comparison of latest RPi 3.0 model B and generation 2.0 model B is elaborated in table 4.1.

Along with main models A and B, RPF offers a product called Compute Module, which is build of basically the same basic components as the generation 1.0 models, but intended for industrial application to shortcut the development process. It provides only SoC with memories on a relatively small form factor board which can be connected by SODIMM connector. It is not well suited for the intended application, and it is mentioned here only to provide complete overall overview. For the completeness, there is also Pi Zero model acting as even cheaper and smaller version of the model A+. In comparison with A+ it has more memory but does not include LCD and camera ports.

Any of the B+ models would fulfil the system requirements of the project. They provide networking solution for remote management and means for visualisation of the graphical management application through HDMI output. One advantage of generation 3.0 against 2.0 is the presence of the wireless connectivity.

4.2 Allwinner Technology SoC based boards

Commercial success of RPi was followed by emerge of new SBCs, form which many were basically just its more or less enhanced clones. The common denominator of all these new boards could be that they are based on Allwinner Technology (AT) SoC solutions. AT is a Chinese based fabless design company which licences ARM cores and designs SoCs mostly for Android tablets or various smart devices [52]. Popularity of their SoCs in SBCs is supported by the fact, that these boards practically can not be bricked as there is always possibility to boot into low level USB recovery mode (FEL) and repair the system. In addition, AT initiated communication with the growing open source software community linux-sunxi, which in turn started to provide open source operating system support for AT SoCs. Many companies producing SBCs rely on linux-sunxi's ecosystem, but only a few contribute back to it. They have in return the best support for their boards (Olimex, Cubietech). Linux-sunxi's support mainly concerns A10, A20 SoCs as their technology is available open source. Some AT chips are using proprietary solutions with only binary software available which are most likely not going to be released in open source world. However, thanks to this community the boards utilizing AT SoC are quite viable competitors in SBC market. Their functionality can be extended by various software and hardware hacks, often revealing functionality not directly intended to be available by the design company.

The computational power of these boards is competitive to RPis boards. Both AT and Broadcom SoCs use ARM cores and it is mostly only matter of time when one or the other company build a new generation of SoCs with more powerful ARM core, which forces the other company to catch up with the equivalent competitor. Therefore the real added value is in the peripherals and added features for the particular SBC.

4.2.1 Cubieboard

Cubieboard was developed in 2012, after RPi was already out, by embedded technology team situated around former AT employee Tom Cubie in China. Its relative success on market and praise by the open software community resulted in establishment of Cubietech Ltd. The aim of the company is to provide open source solutions and they already came with several Cubieboards and Cubietruck with enhanced feature set. They gained a firm position as an open source hardware producer on contemporary market. Among the product portfolio of Cubietech there are two feasible candidates, Cubieboard 1 and 2, presented in table 4.2. They are fully compatible with each other and differ only in used SoCs. Newer products, Cubieboard 4 and Cubieboard 5, are, although very interesting pieces of hardware, out of the price range set for this thesis.

Cubieboards do not belong to a category of RPi clones, but rather alternatives. The pinout of extending connectors is not compatible with RPi and therefore they provide their

<table>
<tr><th></th><th>Cubieboard 1</th><th>Cubieboard 2</th></tr>
<tr><td>SoC:</td><td>Allwinner A10</td><td>Allwinner A20</td></tr>
<tr><td rowspan="2">CPU:</td><td colspan="2">1 GHz ARM, ARMv7-A architecture</td></tr>
<tr><td>Cortex-A8, single core</td><td>Cortex-A7, dual core</td></tr>
<tr><td rowspan="2">GPU:</td><td>Mali 400</td><td>Mali 400 MP2</td></tr>
<tr><td colspan="2">OpenGL ES 1.1/2.0</td></tr>
<tr><td>Memory:</td><td colspan="2">1 GB DDR3</td></tr>
<tr><td>USB:</td><td colspan="2">2x USB 2.0, 1x microUSB 2.0 OTG</td></tr>
<tr><td>Video out:</td><td colspan="2">HDMI rev 1.4</td></tr>
<tr><td>Audio out:</td><td colspan="2">analog (3.5 mm phone jack), digital (HDMI)</td></tr>
<tr><td>Storage:</td><td colspan="2">SATA 2.0 connector, 4 GB NAND flash, microSD card slot</td></tr>
<tr><td>Network:</td><td colspan="2">10/100 Mb/s Ethernet</td></tr>
<tr><td>Extra pins:</td><td colspan="2">2x 46-pin header, GPIO, SPI, I^2C, RGB/LVDS,
CVBS, VGA, ADC, CSI, FM-IN, SPDIF-OUT, ...</td></tr>
<tr><td>Others:</td><td colspan="2">IR receiver, microphone jack</td></tr>
<tr><td>Power:</td><td colspan="2">5V/2A in via DC connector or microUSB OTG</td></tr>
<tr><td>Price:</td><td>42€</td><td>49€</td></tr>
</table>

Table 4.2: Cubieboard 1 and 2 comparison [31, 30]

own expansion boards for various purposes. Being around approximately the same time as RPi, it has developed relatively strong community and support.

4.2.2 OLinuXino

Variety of SBCs, not exclusively based on AT SoCs, is provided by the company named Olimex through their open-source hardware boards called OLinuXino. Along with them, they provide great deal of miscellaneous development and prototyping boards including Arduino like solutions and system on module boards consisting of processor, power control IC and memories integrated on board for fast modular design and development. They also provide many boards integrating different MCUs from the various renown manufacturers only with routed pins for easy integration and programming for hobbyists, together with lots of extension modules supplying more functions to all previously mentioned solutions. To sort out all offered SBC solutions from Olimex there is a table providing insight on few of their SBC families according to the used SoC. The table does not mention the most low-end boards based on Freescale iMX233 SoC because although they would be probably able to run Linux distribution or another means for GUI, their memory parameters (64MB) and CPU speed (454MHz) indicates that the performance may not need to be good enough for it. AT A13 based boards were excluded from the considerations because they lack the onboard networking, which is only available through expansion boards or USB devices. All the other boards are based on other AT SoCs and differs mainly in number and types of interfaces integrated on the specific boards. Most of them is also manufactured in versions including 4GB NAND flash on board for additional charge.

Although Olimex has started with production of OLinuXinos in 2013, they have much longer history. They have established the company in 1991 in Bulgaria and are gaining experience in designing development boards for embedded market ever since.

	OLinuXino (various models)			
SoC:	Allwinner A10	Allwinner A20		
Model name:	LIME	LIME	LIME2	Micro
CPU:	1GHz Cortex-A8, ARMv7-A architecture, single core	1GHz Cortex-A7, ARMv7-A architecture, dual core		
GPU:	Mali 400, OpenGL ES 1.1/2.0	Mali 400 MP2, OpenGL ES 1.1/2.0		
Memory:	512MB DDR3			1GB DDR3
USB:	2x USB 2.0, 1x microUSB 2.0 OTG			
Video out:	HDMI 1.4, 40-pin LCD connector			
Audio out:	via HDMI			via HDMI, 3.5mm phone jack
Storage:				SD card
	microSD, SATA connector, optional 4GB NAND flash onboard			
Network:	10/100 Mb/s Ethernet			
Extra pins:	3x 40-pin headers, 1x 20-pin header			3x 40-pin headers, 2x 10-pin headers (UEXT)
	GPIO pins, UART, I^{2}C, SPI, VGA out			
Others:	3 android buttons			10 android buttons, mirophone jack
	power/reset/wake up buttons, 2KB EEPROM, battery connector with charging capable IC, GPIO/power/battery status LEDs			
Power:	5V/1A in via DC connector			6-16V/0.8-0.3A in via DC connector
	5V via USB OTG, 3.7V LiPo via battery connector			
Price:	30 €	33 €	45 €	55 €
	+10 € for optional NAND memory			

Table 4.3: OLinuXino board families [32]

4.2.3 Other companies

Banana Pi (BPi) is perhaps the most obvious case of RPi clone, which is also confirmed by its Chinese developers [50]. They are using very similar design with slightly larger form factor and providing some more powerful components and few improvements over generation 1.0 RPi. Main changes include using different SoC with dual-core ARM, bigger RAM, more interfaces and gigabit ethernet. The pinout remains compatible for RPi extension boards although some are reported to not fit anyway. Few months after BPi mass production began in April 2014, LeMaker team, which was also invited to co-operate on the development of BPi, announced more enhanced version, Banana PRO, whose initial release was in October

2014. It is based on the same SoC, though as an addition to BPi it has WiFi chip on board.

Product line of Banana Pi is a little bit confusing to follow. It seems that LeMaker's Banana Pi Pro is not anyhow related with later SinoVoip product line, who was also invited to cooperate on development of the original BPi and is currently developing and enhancing BPi products. Relative success of BPi was followed by a release of a new board version called Banana Pi M2 which was followed by M2+ and later by the latest M3 model [49]. Version M2 have a quad core ARM processor inside AT A31 SoC, includes onboard WiFi and provides similar interfaces as BPi M1 and Pro except for the SATA support. Later versions enhance the specifications even more using more recent SoCs and technologies, but their prices push them out of the possible candidates list. Hence the table 4.4 compares Banana Pi (M1) and Banana Pro models.

<table>
<tr><th></th><th>Banana Pi</th><th>Banana PRO</th></tr>
<tr><td>SoC:</td><td colspan="2">Allwinner A20</td></tr>
<tr><td>CPU:</td><td colspan="2">1 GHz ARM Cortex-A7
(ARMv7-A architecture, dual core)</td></tr>
<tr><td>GPU:</td><td colspan="2">Mali 400 MP2
OpenGL ES 1.1/2.0</td></tr>
<tr><td>Memory:</td><td colspan="2">1 GB DDR3 (shared with GPU)</td></tr>
<tr><td>USB:</td><td colspan="2">2x USB 2.0, 1x USB 2.0 OTG</td></tr>
<tr><td rowspan="2">Video out:</td><td>composite video (RCA jack)</td><td>composite video (3.5 mm TRRS shared with audio out)</td></tr>
<tr><td colspan="2">HDMI rev 1.4, LVDS</td></tr>
<tr><td rowspan="2">Audio out:</td><td></td><td>I^{2}S</td></tr>
<tr><td colspan="2">analog (3.5 mm phone jack), digital (HDMI)</td></tr>
<tr><td rowspan="2">Storage:</td><td>SD card slot</td><td>microSD card slot</td></tr>
<tr><td colspan="2">SATA 2.0 connector</td></tr>
<tr><td rowspan="2">Network:</td><td></td><td>WiFi 802.11 b/g/n</td></tr>
<tr><td colspan="2">10/100/1000 Mb/s Ethernet</td></tr>
<tr><td rowspan="2">Extra pins:</td><td>26-pin header
8 GPIO pins</td><td>40-pin header
28 GPIO pins
I2S, SPDIF, LRADC,
LINE-IN, FM-IN, HP-IN</td></tr>
<tr><td colspan="2">SPI, UART, I^{2}C, +3.3/+5.5V/GND</td></tr>
<tr><td>Others:</td><td colspan="2">IR receiver, camera interface, on board microphone
3 buttons (reset, power, U-boot)</td></tr>
<tr><td>Power:</td><td colspan="2">5V/2A in via microUSB</td></tr>
<tr><td>Price:</td><td>32 €</td><td>43 €</td></tr>
</table>

Table 4.4: Banana Pi and Banana PRO comparison [50, 51]

Initial BPi models are often criticised for poor manufacturing quality, but SinoVoip seems to push the development of the product the right way from this point of view. With the boom of the Internet of Things (IoT) market they started to offer their BPi G1, which is primarily focused on home automation market. It integrates Texas Instruments (TI) chips to support IEEE 802.15.4 radio with ZigBee connectivity and other chips for Bluetooth Low Energy and WiFi connectivity. It may serve as a gateway for interconnecting all those networking technologies, however it is able to run only some kind of real-time operating system (RTOS), which is not very suitable for the purpose of the thesis.

As you can see from comparison tables 4.3, 4.2 and 4.4, AT based boards provide relatively similar set of interfaces and functionality, which is determined by the used SoC. Therefore, the next few companies providing SBC with AT chips are mentioned for only overall overview, emphasizing the focus on the major differences and interesting features they provide.

Interesting option represents LinkSprite company with their pcDuinos [29]. All models are based on A10 and A20 chips, offering models with WiFi, 1Gbps ethernet, 1 GB to 4 GB NAND flash storage or SATA support. As the name may suggest, the main trademark is its pin headers interface compatible with Arduino. The prices start at approximately 50 € without taxes in European vendor stores which means that the boards are not absolutely unsuitable for intended application, but do not provide any advantages over the other mentioned boards. Haoyu electronics provides MarsBoard SBCs with integrated WiFi modules and 8 GB NAND flash storage. Prices starts at about 30 € for A20 board without WiFi module and around 55 € for A10 and A20 with WiFi included. Other than that they also offer SBC based on Rockchip SoC (1.6GHz dual core Cortex-A9) with similar equipment for comparable price. Generally there are many new SBC based on cheap AT SoCs which mimics other boards capabilities. They try to compete with the other boards mainly by price, whereas often the support and quality of manufacturing falls behind.

	BeagleBone Black (rev. C)
SoC:	TI Sitara AM3358BZCZ100
CPU:	1 GHz Cortex-A8, ARMv7-A, single core 2x PRU 32-bit MCUs NEON floating point accelerator
GPU:	PowerVR SGX530
Memory:	512 MB DDR3
USB:	1x USB 2.0, 1x miniUSB 2.0 OTG
Video out:	microHDMI rev 1.4a
Audio out:	via HDMI interface
Storage:	microSD card slot, onboard 4GB eMMC
Network:	10/100 Mb/s Ethernet
Extra pins:	2x 46-pin headers 65 GPIO pins, 2x I^{2}C, 2x SPI, 5x UART, 8x PWM, ADC (7ch available), 4x TIMER, 25x PRU I/O, CAN, +3.3 I/O on all signals, GND, ...
Others:	3 buttons (reset, power, boot)
Power:	5V/1A in via DC connector, pin header, miniUSB
Price:	45 €

Table 4.5: BeagleBone Black details [11, 18]

4.3 BeagleBoard

BeagleBoard.org Foundation (BBF), similarly as RPF, aims to provide education for masses in embedded computing through their SBC. Although they are closely involved with TI and use their hardware components in their boards, they focus on truly open-source nature of their hardware and software solutions. The community and the support within it is on a very good level, in addition TI allow one of their employee and a designer of all the boards to provide additional support within the company time. BBF is non-profit organization and does not earn money from board sales. Rather they are spend mainly for manufacturing and distributing the boards [17]. Currently they offer one board, which by its price and capabilities could serve as the central unit for intended WSN. In contrast with the other SBCs it provides much more low level peripheral interfaces and some interesting features not present in the other boards.

One of such features is so called PRU, which is basically a small programmable units with its own instruction and data memories, interrupt controller and resource unit for interconnection with SoC resources. There are multiple PRU units on BeagleBone Black (BBB) which can operate independently from host processor or each other as well as work together in coordinated way. They can be used for tight real time constrained tasks, designed for efficient custom data manipulation and therefore system performance acceleration, or just for more intelligent environment status evaluation before waking up the main processor from power saving mode. Thanks to presence of multiple channels of analogue IO (ADC/PWM), there is no need to interface analogue sensors and actuators through additional expansion boards. Other SBCs usually have only up to one channel of each, therefore extension board is needed should more than one such device be interfacate. BBB boards ship with Linux distribution Angstorm, tailored for embedded systems and can be used for validation and diagnostics of the board.

	HummingBoard-i1	**HummingBoard-i2**
SoC:	Freescale i.MX6 Solo	Freescale i.MX6 Dual Lite
CPU:	1 GHz ARM Cortex-A9, ARMv7-A	
	single core	dual core
GPU:	Vivante GC880 + GC320 OpenGL ES 2.0, many accelerated formats enc/dec	
Memory:	32 bit, 512MB DDR3 @ 800Mbps	64 bit, 1 GB DDR3 @ 800Mbps
USB:	2x USB 2.0 (shoud be able of OTG host	
Video out:	HDMI rev 1.4	
Audio out:	analog mono (3.5 mm phone jack) digital (HDMI, SPDIF through RCA)	
Storage:	microSD card slot	
Network:	10/100 Mb/s Ethernet	
Extra pins:	26-pin header, 8 GPIO pins SPI, UART, I^{2}C (more by muxing SoC pins)	
Others:	MIPI camera interface (CSI-2), reset pin	
Power:	5V/2A in via microUSB	
Price:	47 €	70 €

Table 4.6: HummingBoard i1 and i2 comparison [33]

4.4 HummmingBoard

Interesting approach providing some system modularity is offered by Israel based company SolidRun with their HummingBoards. They provide three basic models of boards, which consist of so called carrier board and microSOM system on module. The earlier is basically just a base board carrying various interfaces, connectors and supplementary ICs without any computational unit. Depending on the set of features and connectors they distinguish among four models – basic, pro, gate and edge. Computing unit, Freescale i.MX6 SoC, is then integrated into microSOM along with operating memory, power management unit and networking system. MicroSOMs are providing normalised system interconnectivity to carrier board and can be interchangeable among each other. SolidRun provides four models of microSOMs differing in amount of operating memory and used SoC, which further defines set of features such as wireless connectivity or support for storage interfaces.

User is allowed to create his own combination of microSOM and carrier board to provide the best fit for the intended use-case. Moreover, their interchangeability gives the user vast possibilities for scaling up or down the resulting SBC performance and features. Custom build combinations are rather expensive, but there are pre-built boards offering just about right functionality required for this thesis. They are available for more favourable prices and their hardware specification can be found in table 4.6.

4.5 Odroid

Hardkernel company started its operation in 2009 as an Android hardware developer as the Odroid stands for Open and Android. Over time they have transformed into multi-

<table>
<tr><th></th><th>Odroid C1+</th><th>Odroid C2</th></tr>
<tr><td>SoC:</td><td>Amlogic S805</td><td>Amlogic S905</td></tr>
<tr><td>CPU:</td><td>1.5 GHz Cortex-A5, 32b
ARMv7-A quad core</td><td>2 GHz Cortex-A53, 64b
ARMv8 quad core</td></tr>
<tr><td rowspan="2">GPU:</td><td>Mali 450 MP2 @ 600 MHz</td><td>Mali 450 MP3 @ 700 MHz</td></tr>
<tr><td colspan="2">OpenGL ES 2.0</td></tr>
<tr><td>Memory:</td><td>1 GB DDR3 @ 792 MHz</td><td>2 GB DDR3 @ 912 MHz</td></tr>
<tr><td>USB:</td><td colspan="2">4x USB 2.0, 1x microUSB 2.0 OTG</td></tr>
<tr><td>Video out:</td><td>HDMI rev 1.4a</td><td>HDMI rev 2.0 4K @ 60 Hz</td></tr>
<tr><td>Audio out:</td><td colspan="2">via HDMI interface or I2S</td></tr>
<tr><td>Storage:</td><td colspan="2">microSD card slot, eMMC module socket</td></tr>
<tr><td>Network:</td><td colspan="2">10/100/1000 Mbs^{-1} Ethernet</td></tr>
<tr><td>Extra pins:</td><td colspan="2">40-pin header
GPIO pins, I^2C, SPI, PWM,
UART, ADC (2 channels)</td></tr>
<tr><td rowspan="2">Others:</td><td>RTC, backup battery
connector</td><td></td></tr>
<tr><td colspan="2">power switch port, IR receiver,
status and power LEDs, boot selector port</td></tr>
<tr><td>Power:</td><td colspan="2">5V/2A in via DC connector or USB OTG</td></tr>
<tr><td>Price:</td><td>40 €</td><td>50 €</td></tr>
</table>

Table 4.7: Odroid C1 details [8, 9]

OS hardware platform developer. In the summer 2014 they have introduced RPi like SBC called Odroid-W. Instead of being just a clone of the RPi they designed their board in much smaller platform with more efficient power management suitable for integration to smart wearable products and IoT devices. Despite smaller form factor, it provides extended set of features including RTC and power management IC enabling it to run on battery and manage re-charging process. With the price of approximately 35 € it represents attractive alternative to RPi. However, the product is built on the same SoC as RPi's, Broadcom BCM2835, for which they did not succeed to ensure future supply of chips, therefore the product production is discontinued. Despite the fact, that the company will provide support for the current owners and still have some volumes available for sale, it would not be very reasonable to select it for the role of central unit, especially when the market is full of products in active development.

The popularity of Odroid W by the feedback by the community motivated the company to design a product that fits more the category of general purpose mini computers than miniature development board for IoT. Odroid C1 is significantly more powerful than generation 1.0 RPi and even generation 2.0 or similar boards for very competitive price. After huge success of C1 model and the fact that it got sold out relatively quickly, Hardkernel enhanced it into version C1+ and shortly after RPi 3.0 was out, they came with Odroid C2. Hardware wise C2 integrates the same ARM core as RPi 3.0 differing only in SoC manufacturer, which is in Odroid case Amlogic. Paper performance should therefore be very similarly to RPi, but many user reviews claim that C2 outperforms RPi in many ways. Most significant ones are the network speed due to RPi's connection of gigabit ethernet through USB hub in contrary to direct connection to SoC in C2, CPU performance due to 800 MHz faster clock speed or built in analogue to digital converter (ADC). At the same time the O2 lacks on-board WiFi connectivity solution. The price tag slightly above the price of RPi makes it very strong player among SBCs. For the purpose of the project it may be a little bit over-powerful, but with future extensibility considerations in mind, both C1+ and C2 models provide to be very relevant solution to go with. Their hardware specification is shown in comparative table 4.7.

4.6 Conclusion

Before summing up the specifications of the presented boards and driving conclusions about their suitability for the project, it has to be said, that they all would be sufficient with a little bit of compromise. The network connectivity with at minimum 100Mbit ethernet will cover all necessary interconnection requirements to already established home network infrastructure with internet access. Because the data flow will not be big, consisting mainly from simple monitoring and management commands for an application running on the board, enhanced speed of 1Gbit ethernet of Banana Pi/Pro or Odroid C1+ does not represent a necessity, but rather extras. WiFi modules would only add a degree of mobility, yet central unit is not meant to be moveable and will have its stable position so that on-board WiFi is not a big decision forming factor either.

When it comes to software equipment and processing power to back it up, they all are able run either some Linux distribution or Android. However there are differences in performance where mainly multi core based SBCs have a clear advantage, especially when it comes to multi-threaded performance. Moreover the rise in price for dual core boards, or even for quad core Odroid C1+/C2 or RPi 3.0, is not very significant. Hence, with enhanced future expansion and possibility of higher computing needs in mind it would make more sense to go for multi core system.

Graphic performance of all mentioned boards is sufficient. GUI of management application will run easily on any of the boards. The lowest 2D/3D graphic performance board has BBB and the best performance goes to Odroid C2 with Mali 450 MP3. For the multimedia encoding/decoding, should it ever be used within the security system, is in these systems dedicated processing module outside of GPU units, with one exception of Broadcom Videocore IV which integrates 2D/3D and multimedia encoding and decoding together in the GPU and BBB. BBB does not have this unit, consequently its multimedia performance is limited. All the other boards have dedicated hardware support for multimedia processing and can handle video decoding in 1080p, the best even in 4K. All of them provide basic audio output through HDMI interface, some of them through analog 3.5mm phone jack or other interfaces not directly present on board, but with pinout in extra pin headers.

Power consumption requirement is not as easily evaluated, because maximum power ratings in boards' specifications are not to showing the real use case average consumption of the boards. Some numbers can be obtained from community forums, unfortunately not for all the boards, providing sufficient overview. RPi B boards are told to have average consumption of 1.9 W to 2.5 W, which was improved with model B+, and from 1.04 W to 1.72 W when no devices are connected to its interfaces except for ethernet connection. BBB is told to have comparable numbers from 1.05 W to 2.3 W, and it seems that other boards are oscillating in similar range. In most cases their average power consumption does not exceed 3 W, but the numbers depends on CPU/GPU activity, number of connected devices and intensity of communication with them. The central unit is not intended to be powered from batteries and the offsets within the consumptions of the boards are too small to rule any of them out just because of it.

Prices of the boards in text above are just approximate without VAT and shipping costs, but reflect the state of the market in May 2016 for various Europe based retailers. Although it is not a parameter with the biggest impact, it surely matters. Therefore HummingBoard i2 drops out from the further consideration with its price significantly higher than the rest of the boards, which usually fall within a category under 50 €. Reasonable price tag of RPi does not belongs solely to it any more because there are more boards with very similar price often offering better overall performance and features than RPi. Within them there is Odroid C2 which is, although only barely within the 50 € price tag, providing quad core performance, 64b architecture, powerful graphics and possibility to use fast eMMC. Moreover it provides balanced set of features on extra pins for analogue and digital interaction, therefore represents a very viable solution.

In conclusion, currently the best candidates are probably Odroid C1+/C2 or RPi 3.0 B. Odroid's still growing community and support is becoming as huge as the one of RPi or BBB. On the other hand it may still look like overkill looking at its specifications and the requirements of the system. For the very fundamental requirements of the thesis is even old version of Raspberry Pi 1.0 B board very sufficient, and the fact that the author is in possession of such hardware makes the purchase of additional, yet better equipped SBC, not reasonable for the purpose of the thesis. In comparison with other boards it does not lack any project crucial features, hence it will be used for the implementation of central unit for WSN. The future may prove it to be not satisfactory any more, but at the time of writing, considering the intended application, it is a viable option.

Chapter 5

System design

The specification of the sensor system to be designed accounts for one CU connected to many sensor nodes, which should cover the area of a family house. The range requirement of the system can be met in various ways. Either by using a technology which provides long wireless range, or it will rely on higher density of wireless nodes within the network, thus covering desired area. The essential feature of selected technology is its ability to form more complicated than point-to-point networks, ideally the ones allowing star, tree or mesh topologies. A few of the currently trending protocols for low power WSNs are discussed in section 5.1.

Following the choice of wireless protocol, the section 5.2 discusses available components for the implementation of the core of the wireless nodes. For the sake of simplified mounting of the components on printed circuit board (PCB) they were restricted to only SoC solutions integrating RF part with MCU in one package. On one hand this choice limits the ability to customize the connection between MCU and RF to zero, but on the other hand the purpose of the project does not account for any other connection between them than the one already integrated in the package. Moreover the SoC solutions are usually offered for lower price than their respective standalone versions.

In order to further optimize the implementation process and increase the re-usability of the components, every designed network device will consist of tree separate building blocks. Every sensor device will consists of wireless node board integrating the wireless SoC with the application firmware, sensing block connected to the pins of wireless node block and both will be powered by a power management block. This way the wireless node can be complemented with various types of sensing blocks and its operation will need to be adjusted accordingly only by modifying the running firmware. Should happen, that a sensor type is not needed any more, the wireless node can be re-used for another sensor type or even different application. Power management block will regulate the energy harvesting from light source, take care of recharging the connected battery and delivering the power to the wireless node and the sensing block. For better aesthetics of resulting sensor nodes, every type of block will have matching holes in the PCB, through which these blocks can be fasten together to form a final device. The sections 5.3, 5.4 and 5.5 provide details for wireless node, sensing and power management blocks respectively.

The CU is different than sensor device with respect to above stated. Thanks to the fact, that its functionality will be partially implemented by a RPi which is going to be connected to stable power source, there is no need to include power management block or even a sensing block to the unit. The wireless node will be ideally powered through extension header pins of the RPi. The RPi itself should then be powered through UPS. Functionality wise, the wireless core will manage the underlying sensor network and report any changes to RPi through a serial interface. RPi will be able to evaluate the received messages and visualise their meaning through GUI to the user. Should the user perform management action in the GUI, the command will be sent through RPi serial interface back to to the wireless core to execute desired action.

5.1 Communication protocol

The choice of communication protocol is important part of system design. Its selection directly restricts the range of possible hardware manufacturers and their MCUs. Moreover even if particular manufacturer provides devices which support selected communication protocol, they do not necessarily need to provide the firmware development tools for it to build user applications for free. There are nowadays many network protocols designed to be used for low-power WSNs. Some are more widespread than the others for various reasons. ZigBee protocol for instance is on the market as an open standard for more than a decade, it is adopted by many vendors and has become the protocol against which the other protocols are usually compared. Currently there are several network protocols which are considered to be the most suitable and preferable for low-power WSN character of this thesis:

- 6LoWPAN
- Bluetooth Low Energy (also called Bluetooth Smart)
- Thread
- Z-Wave
- ZigBee

For the purpose of the discussed security system the Z-Wave system has to be ruled out right away. The reason is that there is only limited number of Z-Wave supported SoCs manufacturers, namely, Sigma Designs and Mitsumi, and the Z-Wave stack is proprietary and closed source. That would make the development process tricky and expensive as there are only few devices supporting the protocol. From a different point of view, it is meaningless to use proprietary technology unless there is a clear advantage or reason to do so. Z-Wave looks very appealing from the end user perspective, declaring their flawless compatibility even over the range of different end device vendors. But for the purpose of relatively small WSN project like this it is certainly a not the wisest choice.

Another candidate, 6LoWPAN, was designed by Internet Engineering Task Force (IETF). The acronym stands for IPv6 over Low power Wireless Personal Area Network. Unlike the other mentioned protocols, 6LoWPAN fulfils only the function of a network layer without any functionality defined on the application layer. Thus to chose 6LoWPAN as a basis for wireless communication would imply creating all the logic above network layer. Such development for one use case WSN would be surely a great exercise but otherwise a waste of effort and time. Furthermore when there already are technologies which are build on top of 6LoWPAN focusing on providing of WSNs functionality.

One of such technologies is Thread, relatively new networking protocol with specification for members available since July 2015. RF SoCs supporting Thread are currently offered only by Silicon Labs and NXP which were among the founding members of Thread Group (in fact it was Freescale before acquisition by NXP). But because Thread operates on top of IEEE 802.15.4 physical layer, which is a standard for low-rate wireless personal area network solutions already supported by many major IC vendors, it is only a matter of time when there will be more Thread supporting SoCs on the market. On the application layer Thread group promises to provide the very best way to connect and control products in the home automation network. Another reason for deeper consideration of Thread is that together with ZigBee Alliance, the Thread group announced support for applications written using ZigBee Cluster Library (ZCL), which will run transparently on Thread networking protocol. To sum it up, Thread looks like an ideal networking protocol for the security system this thesis is about, however it is a cutting edge technology which was not taken into account in the beginning of the project as it was not anywhere near production ready at that time.

The only protocol among the above mentioned, which does not rely on IEEE 802.15.4 physical layer is BLE. The advantage of BLE network protocol is that the devices operating on top of it are able to directly communicate with newer mobile devices. This may be convenient for remotely controlling the security system by application written for mobile phone, on the other hand it exposes the security system to wider range of attackers. That does not mean that that the other protocols are safer to use because there is lower probability that someone will walk around with for example ZigBee enabled mobile device. BLE allows the devices to achieve extremely low power consumption. It has recently adopted the means to overcome the range limitations of star network topology and implements mesh topology by what is called scatternet. Scatternet is a group of interconnected piconets, which in turn consists of one master node and up to 7 slave nodes. Scatternets are formed when one slave node decides to act as a master node for another piconet. BLE fulfils the requirements of the network needed for the security system. It is scalable, low power and would easily handle the required data throughput. Despite that it is not the best possible from among the mentioned protocols. The fact that it is not based on IEEE 802.15.4 physical layer leaves the possible future updates of the discussed WSN restricted by the underlying Bluetooth hardware.

Whereas if the selected protocol is ZigBee which runs on top of the IEEE 802.15.4 physical layer, the future upgrades of the system could switch to any other of the mentioned protocols in case the ZigBee itself proves to be unsuitable for the task for some reason. From overall point of view however, ZigBee seems to be the best match. It is very well established and over the years of its existence the market provided many suitable SoCs by various manufacturers. ZigBee represents the standard network protocol in scope of WSN, although its way to market may have been slower than for some of the new WSN protocols mentioned above. Various products of different manufacturers should be able to communicate among each other and that may prove to be useful if there was a need to extend discussed sensor network with already established product. Some sources claim, that interoperability among ZigBee products of different manufacturers do not cooperate as flawlessly as in case of Z-Wave for example. This could be compensated by the possibility to tweak discussed security system behaviour should that issue occur. ZigBee may not offer any extra functionality worth mentioning when compared to other mentioned protocols (except for 6LoWPAN) and could prove to be uselessly overcomplicated for the scope of the project. Its selection however brings much more hardware SoCs variety into play, thus bringing down the cost of whichever components are going to be selected. On the other hand, not all of the manufacturers offer free ZigBee protocol stack for application development. This aspect is discussed in more details in the following sections.

5.2 Components selection

Trends in MCUs employing applications tend to incline to use ARM based MCUs. Many and more applications are using Cortex family ARM MCUs instead of legacy 8/16/32bit MCUs. They provide similar functionality with higher processing power for relatively the same price. There is no practical reason not to use ARM based SoC also in this project, even so that the ARM technology is growing and find application in numerous areas of information technology. Especially well-suited appears to be Cortex-M0 and Cortex-M0+ cores, which aim for ultra low-power applications.

Every available major IC manufacturer provides ZigBee based RF solutions in many cases build around ARM MCUs. The defining factor for choosing suitable SoC will therefore be the combination of the following:

- the lowest energy consumption
- ARM based
- SoC integrating RF and MCU in one package
- the availability of the free development tools
- the availability of free ZigBee Pro protocol stack implementation
- cost effective

Very interesting product line is offered by Atmel with their SAMR MCUs product line. They are SoCs integrating RF and already mentioned Cortex-M0+ cores which come with 64/128/256KB of flash memory. They come in two variants regarding the features such as number of pins with analogue capabilities, number of ADC channels, and overall feature set. Atmel offers their Atmel Studio as a development environment and although it is free, it only supports Windows operating systems. Their ZigBee Pro stack implementation called BitCloud is available for free as well and it is delivered as a combination of closed binaries and open sources. The MCUs themselves are available from 4 € – 7 € depending on the flash memory capcity (updated in May 2016). In order to fit full featured BitCloud into the MCU, Atmel recommends to use the 256 kB version.

TI offers IEEE 802.15.4 RF ARM SoCs based on Cortex-M3 cores. They are bigger than Cortex-M0+ cores, provide more processing power but at the same time they need more power to run. The extra processing power does not mean any significant advantage for discussed sensor system, hence the increased price of approximately 10 € is not justified compared to the Atmel offer. TI provides their implementation of ZigBee Pro stack called Z-Stack only for IAR IDE, which is other than free 30-day evaluation period a paid tool. There is also a possibility to use IAR IDE with code size restriction, namely 16KB for Cortex-M0+ devices, which will for even the most optimistic estimations of resulting code size be surely insufficient.

Freescale, now NXP, offers their Kinetis W SoCs based on Cortex-M4 cores, which are even one step more powerful and energy demanding than Cortex-M3. At the time before acquisition by NXP they offered BeeStack as their free implementation of ZigBee Pro stack. NXP also has their ZigBee stack implementation but it does not offer ARM based wireless SoCs. NXP is preparing Kinetis W MCUs based on Cortex-M0+ cores in the near future, which could be interesting when they are released. For the time being however, NXP or Freescale do not have better option to offer than TI or Atmel.

The other investigated big IC manufacturers failed to fulfil one or more of the above mentioned requirements. Microchip provides their ZigBee Pro stack implementation for over 870 € or alternatively offer to contact their sales department for ZigBee Smart Energy profile suite. Microchip does not offer any ARM based SoCs, but rather offer the RF module as a separate chip. Silicon Labs offer their EmberZNet Pro Stack implementing ZigBee Pro feature set only as part for particular product purchases. Their range of ZigBee enabled SoCs includes only Cortex-M3/M4 devices. STMicroelectronics offers SoCs integrating IEEE 802.15.4 radios with Cortex-M3 ARM cores, but information about their ZigBee protocol stack implementation are very sparse on their website.

In conclusion, Atmel's SAMR family SoCs meets all the criteria without any unnecessary compromises. The big advantage is the price of SoCs already mentioned in paragraph earlier in the text. The feature set of SAMR MCUs is satisfying every possible need of the project. As a bonus, Atmel provides functionality which they call *Sleep walking*. It enables the developer to control clocking domains of SoC very precisely and leave the peripheries enabled and working while the MCUs is in a sleep mode. This functionality will allow the sensors to sense the environment changes in armed mode, while the MCU will only wake up occasionally to perform keep-alive actions with regards to CU.

5.3 Wireless node

Wireless node block represents application and network brain of sensor nodes. The design of the block will be built around Atmel's SAMR21E18 SoC, which compared to SAMR21G18 version offer less features, but with better pricing. The PCB layout was designed according to official recommendation from the datasheet and related application notes with one exception [13, 14]. Atmel recommends 4-layer PCB for flawless wireless connectivity and performance in opposition to 2-layer PCB layout design used in the thesis. The reasoning for 2-layer design is that it proved to be more cost cost effective with regards to necessary layout specifics such as controlled impedance traces in combination with available components' sizes than 4-layer design.

The resulting design was inspired by the Atmel's reference board implementation *SAMR21-Xplained Pro*. The bill of materials (BOM) used for the custom design is listed in appendix B.1. Few components were however difficult to obtain, hence they were replaced with the next best ones attribute wise. Reference design used a lot of 0402 sized components which are difficult to solder by hand. Those were replaced by the larger 0602 packaged components, which in the end have shown up to be more cost effective than 0402 ones. The smaller ones seem to have extra price margin for additional miniaturization. The signal traces were then adjusted accordingly to fit the components sizes.

All GPIO pins, which were not essential for the proper internal SoC operation were driven to extending header, therefore full SoC pinout can be used should the application require it. Resulting schematics can be seen in the appendix C.2. Poured layout is shown in the figure 5.1.

5.4 Sensing block

Depending on the complexity of the sensing block, the resulting design may or may not be necessary to be implemented in PCB. Sensing element may be simple enough to be directly connected to appropriate pins of the node board, eliminating the need for integration into

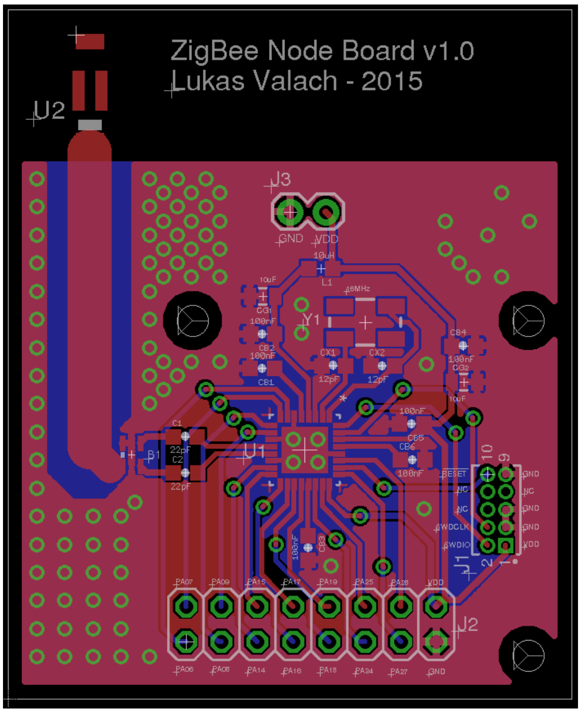


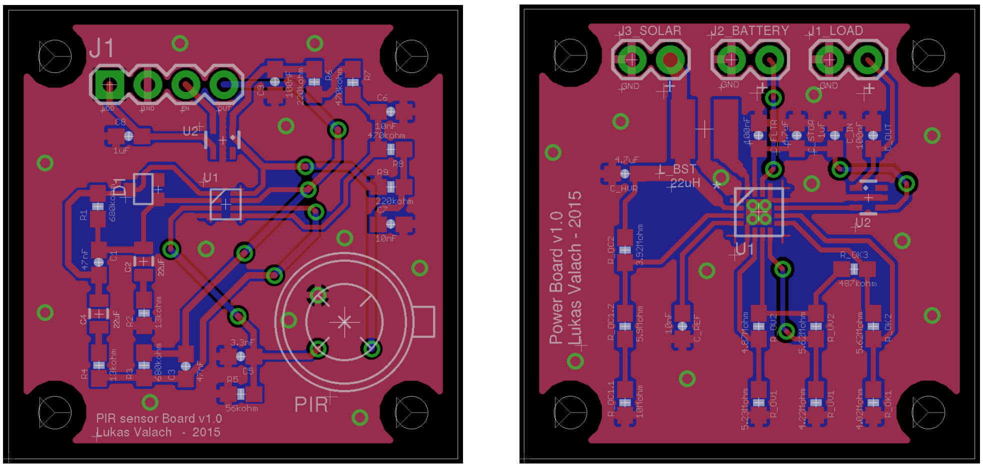
Figure 5.1: Node board poured layout

PCB at all. The most essential sensor type for the scope of this project is motion sensor. Its relatively complex design is integrated into PCB and described in the following subsection. On the other hand, contact sensor is so simple that it can be connected to the node board directly. It only features two wires opening and closing electric circuit and does not require complex seasoning as in case of motion sensor.

5.4.1 Motion sensor

Search for suitable motion sensor module did not yield the desired results, despite there are many full featured modules available on the market. The problem was usually in overcomplicated design of a module which may serve reasonably well for design on higher level on abstraction, but failed to fulfil low power consumption requirement for the purpose of this thesis. Very many solutions offered motion sensors providing digital output with already pre-implemented thresholds of motion sensing. Considering the capabilities of SAMR21 SoC, mainly the presence of ADC, is digital output of a sensor rather drawback than advantage. Analogue output offers possibility for finer tuning of the motion sensing threshold on the side of the SoC, allowing for setting up an individual sensors with custom thresholds setting. That may prove to be useful in different deployment scenarios.

The decision was made to design a custom motion sensor module almost from scratch. As a base sensing element was selected dual element passive infra-red (PIR) sensor IRA-E700ST0 by Murrata. This element is available even in single quantities for reasonable price, including vast offering of fitting fresnel lenses. To avoid re-inventing the wheel, the design is based on application note [12] with few modifications. Original design from the document provides digital output by clipping the second stage amplification and filtering output of the sensing element. This final, clipping stage is removed in the designed sensing block and the amplified and filtered analogue output is driven to an output pin.



(a) PIR board

(b) Power board

Figure 5.2: Poured layouts

The original design consumes 24 µA according to the application note. Very similar consumption is expected also from the presented modified design, although the use of only 2-channel version of the operational amplifier (OpAmp) from the original design should lower its consumption by approximately 1.2 µA [48]. The sensor operation is expected to be halted for a long period of time during the day, only to be active during the night. Therefore the design integrates a load switch controllable through an input pin for further lowering of power consumption. Quiescent and shutdown currents of the load switch are less than 1 µA which could significantly improve power management and battery life of the whole sensor node. Full design schematics is shown in the appendix C.1 and poured PCB layout is depicted in the figure 5.2a.

5.5 Power management block

Selecting ambient light as an energy harvesting source is expected to provide only small currents for a limited period of time. Used cells has to be small to fit the overall size of the sensor devices but large enough to provide sufficient power to re-charge accumulators during day. The requirements for small form factor and short light exposition time while still providing reasonably enough power are contradictive, thus it is necessary to add a PMIC which will be able to utilize the maximum out of the panels. Search for a suitable PMIC resulted in selection of BQ25504 by TI. Other interesting candidates among the considered ones included LTC3108 by Linear Technology, MAX17710 by Maxim and another solutions form TI, BQ25505 and BQ25507.

Maxim's PMIC is an interesting piece, which fits the purpose of the project, but at the time of decision making was not available. It is universal PMIC for either high or low voltage power sources. It provides unregulated as well as low-dropout (LDO) regulated outputs and includes over and undervoltage battery protections. Although it is twice as expensive as selected BQ25504, it represents very generic solution which would also accommodate various harvesters of other types should they be utilized in the future.

LTC3108 is another suitable candidate. It achieves the smallest quiescent and leakage currents of all mentioned options and includes 2.2 V LDO regulated output. Problem with LTC3108 is that it does not include under and overvoltage battery protections. The sensor devices are supposed to be left unmaintained for long periods of time, therefore the absence of such protections is a deal breaker. On top of that the LDO output is limited by maximum of 11 µA, primarily intended for low power MCUs. Any additional more power hungry ICs such as wireless radio has to be powered from main output. But because SAMR21 integrates the wireless radio in the same package the LDO output current limits will not cover the power needs when radio is transmitting, rendering the LDO circuitry useless for the application.

TI PMICs represent the most reasonable options. They all provide under and overvoltage protections of battery and additionally programmable maximum power point tracking (MPPT) circuitry for better solar cell output utilization. Respective version differ in features they offer with BQ25504 being the base model. BQ25505 extends the base model with additional pinout for primary battery and appropriate switching circuitry to extend the operating time when there is no energy to harvest. BQ25570 on the other hand includes step down regulated output with high enough maximum output current limit for the purpose of SAMR21. Both versions are slightly more expensive and do not provide any extra functionality necessary for the design, therefore the base, BQ25504, model was selected for the appliction.

BQ25504 can be tailored for intended application very well through resistor networks configurations for every individual feature. Detailed instructions to do so are described in the datasheet [25], and correct values of particular resistors were computed using official helper spreadsheet available online on TI webpage. Values specific to the thesis are shown in the filled spreadsheet included in the enclosed CD. Used labels of individual resistors are consistent with ones in the schematics in the appendix C.3.

Configuration of MPPT depends on and has to be configured for particular solar cell. The PMIC has a maximum input power rating of 510 mW which happens to fit very well with 2 V/250 mA solar cell by Optosupply available at local distributor. The solar cell ratings are stated for direct sunlight in ideal conditions, therefore lower average power output can be expected from the cell in a real situation. Datasheet of the solar cell does not include power charts to determine maximum power point, therefore the MPPT circuitry value is set to neutral 80% of the maximum cell voltage [25].

Settings for over and undervoltage protection depend on used rechargeable battery. BQ25504 supports various rechargeable batteries types from Li-ion through Thin-film to regular capacitors. Considering the analysis of battery types in section 3.5 and its conclusion a decision was made to use NiMh battery. They are quite tolerant to over and under charging as well as to higher working temperatures. Although this battery type does not maintain its current as long as for example Li-ion batteries, they will be charged regularly during daytime periods. Specifically, chosen battery has nominal voltage of 3.6 V at 360 mAh capacity. Resulting undervoltage protection settings cuts the load of the battery when its voltage falls below 2.9 V. On the opposite side the overvoltage protection triggers and cuts of input power from solar cell when battery voltage rises above slightly more than 3.6 V. The resulting layout of the power board is shown in the figure 5.2b.

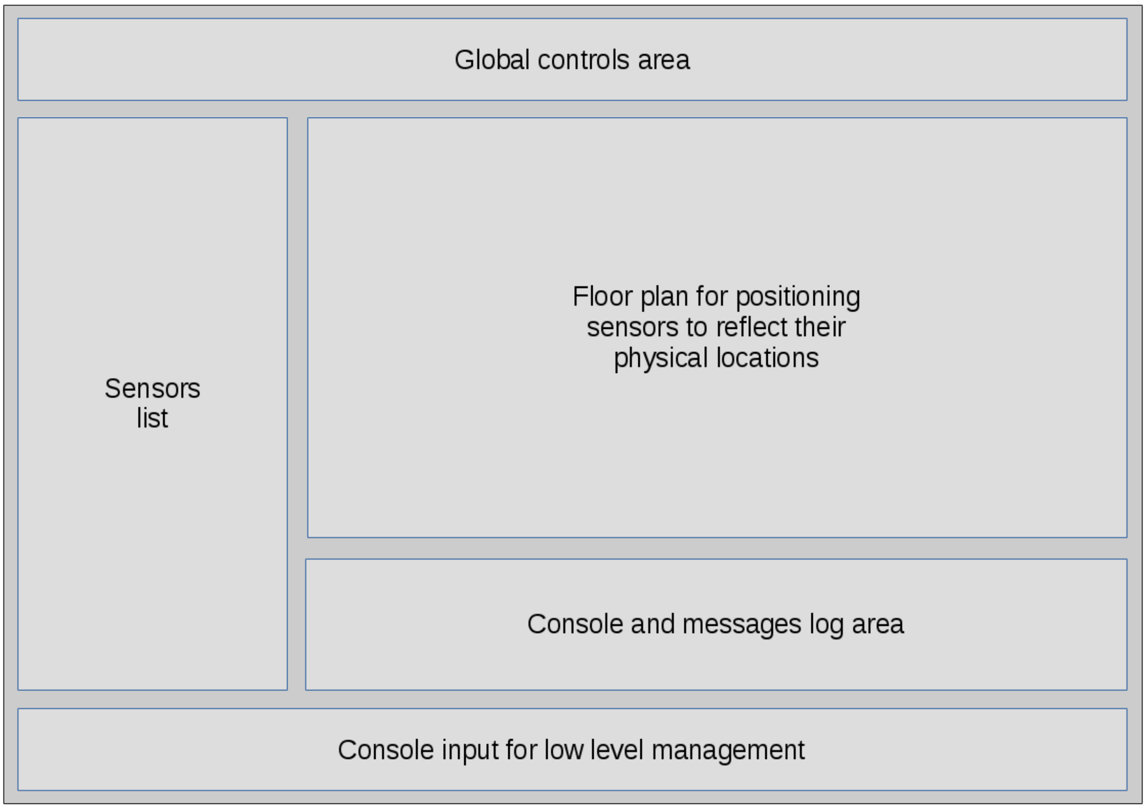


Figure 5.3: Sketch of GUI design

5.6 Graphical user interface

Design of GUI for management of the sensor network need to be clear and simple, so that it is easy to work with and does not overwhelm RPi with is processing power requirements. In order to achieve a smooth running on the RPi the resulting application will be compiled directly for OpenGL ES which is natively supported by RPi's hardware. This way it will not require X-Server to run on the device and will be able to utilize the whole processing power.

GUI will consist of only one application window. Its layout is shown in the figure 5.3. The left side of the application window is vertically filled with a list of registered sensor nodes. The items of the list will indicate the actual state of the sensor, its name and short textual description of location, whereas the name and location labels will be modifiable by the user.

The main element of the application window will be building floor plan with graphical markers for enrolled sensors. It will fill the rest of the application window from right edge of sensor list to the right edge of screen. User will be able to manipulate with graphical representations of the sensors on the floor plan. Intended object where the sensor network will be deployed has two stories, so the user will be able to move sensors between the stories as well. Graphical elements representing sensors will visualise sensor status in the same way as it is done in sensor list. For better orientation and placement of the elements the whole floor plan will be zoomable and movable. The positions of the sensors on the plan will be storable to permit later manual or upon start up restore.

In the lower part of the application window, under the floor plan, will be console log window with input prompt field. The console window will log every event in the network and distinguish error messages from user input and CU messages by different font colour of particular logged message. The input field will serve for low level communication with CU's wireless core over the serial interface. It will act as a means for debugging or troubleshooting the network.

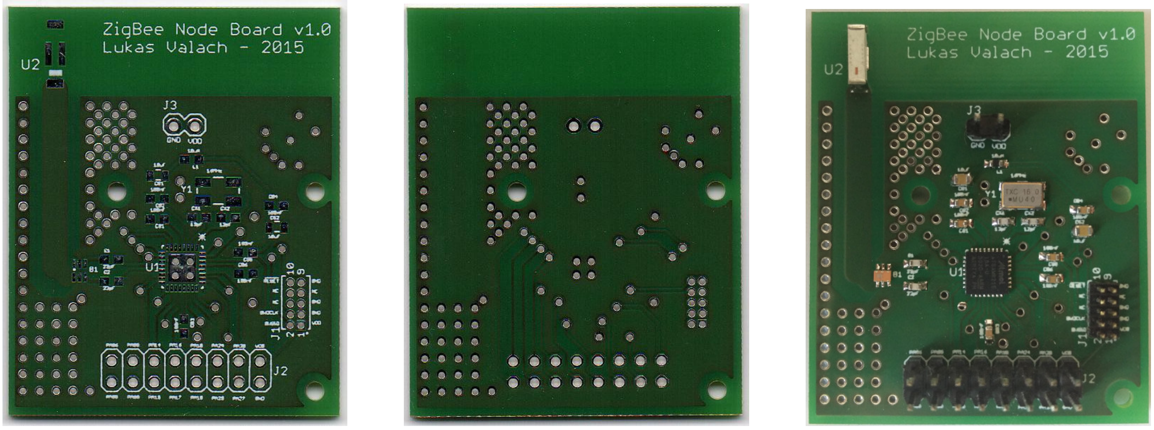
The top part of the window will contain toolbar or menubar with controls allowing to change the state of the sensor network or settings of the application itself. At minimum it will include buttons for arming and disarming all sensors and buttons for saving and restoring the floor plan state.

It is anticipated that during testing phases of the development process will be revealed some problems or not optimal solutions for control elements as stated in previous paragraphs. Any additional enhancements or additions to the GUI application will be considered and endorsed on the fly, rationale behind it discussed in the implementation chapter.

Chapter 6

Implementation

Designed PCBs were sent for fabrication to a local PCB manufacturer. After the boards were ready they were assembled by hand in the university laboratory. Resulting products before and after assembly are shown in the figures 6.1, 6.3 and 6.4.



(a) Top view (b) Bottom view, mirrored (c) Assembled board

Figure 6.1: Node board pre and post assembly photos

All PCBs have issues with silkscreen layer being unreadable. It roots from the design stage, when the actual size of the characters was not considered well enough and resulting texts are blurry. PIR sensor boards have an additional issue, a missing trace. At some point between designing the board and sending resulting gerber files to PCB house for manufacturing an error was made, and the incriminated trace was removed from gerber by accident. This fact was revealed during testing phase and was fixed by replacing the missing trace with a piece of wire as seen in the figure 6.4c. Other than those two, there were no issues with the PCBs, therefore the works could continue by implementing and testing the firmware for respective board types. The rest of the chapter describes this process as well as implementation of management application.

6.1 Control unit

CU consists of serial port interconnected RPi and SAMR21 wireless node board. The board has very low power consumption, therefore it can be powered directly from RPi's

ID	Message type	Payload
1	device joined	extended address (2 B)
2	device left	
3	zone enrolled	extended address (8 B), enrolment status (1 B), zone type (2 B), manufacturer code (2 B)
4	zone went down	extended address (2 B)
5	zone back up	
6	status report	extended address (8 B), status (1 B)
7	address conflict	conflicting short address (2 B)
8	zone table	table size (1 B), item size (1 B), items ((table size * item size)B)
9	short address	extended address (8 B), short address(2 B)

Table 6.1: Messages' types from SAMR21 to RPi

pins as shown in the figure 6.2. The biggest portion of implementation work on control unit functionality was dedicated to the firmware for SAMR21 SoC. Rather than starting from scratch, the implementation is based on provided ZigBee's Home Automation profile example by Atmel. It implements so called combined interface (CIE) device which serves as central management node within the ZigBee network. The example provides basic implementation for client side of various ZigBee clusters. The main interest for the purpose of this thesis lies in Intruder Alarm System (IAS) zone cluster [2], which defines an interface between sensor node (server side) and node to which the sensor reports occurred changes in observed environment area, CIE. Conventionally, IASs also include another clusters besides zone cluster, most commonly auxilliary control equipment (ACE) cluster and warning device (WD) cluster. The former is filling up the functionality of remote control equipment such as keypads for typing arm/disarm passwords. WD implements warning indicators, strobe lights, siren, etc. Both functionalities are however implemented directly in CU and do not rely on a dedicated ZigBee nodes, therefore the mentioned clusters are not necessary, hence not implemented. SAMR21 is able notify the RPi about alarm or other situations using binary messages sent over serial connection. The table 6.1 shows all the possible messages sent from SAMR21 node board to RPi. Each message consists of its id, which is 1 B and the payload as stated in the table. RPi's application logic evaluates those messages, identifies suspicious activity and, if necessary, notifies the user by e-mail. SAMR21 can be controlled by another set of messages (see table 6.2) sent from RPi through serial interface. For user convenience are those commands abstracted by the GUI control elements, which are discussed further in the subsection 6.1.1.

The client side of the zone cluster functionality, which is the side running in CIE, has been partially pre-implemented in BitCloud. It maintains table of enrolled zone devices (i.e. sensor nodes) and accepts status update notification only from those devices enrolled in the table. These notifications represent current status of the zone device (see section 6.2). They can be one time or regular notifications and in the latter case the CIE is able to determine whether the remote sensor device is operational or not by detecting missing

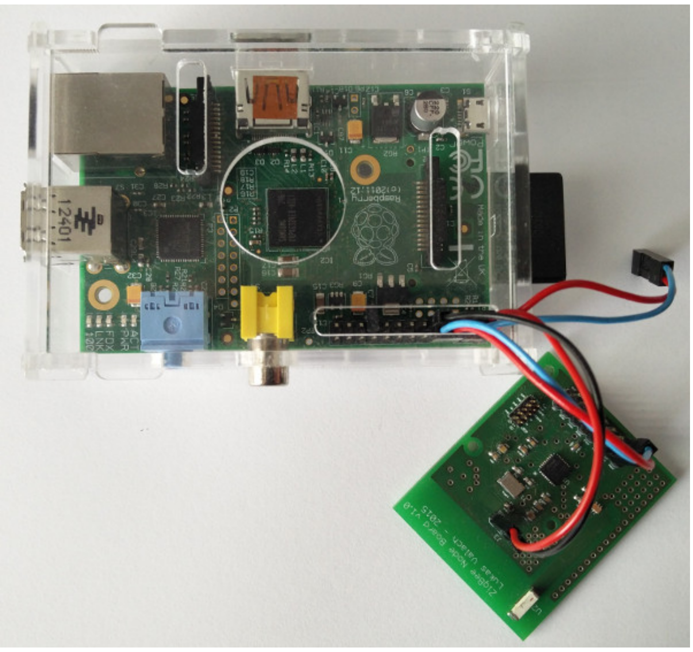


Figure 6.2: CU – RPi interconnected with node board

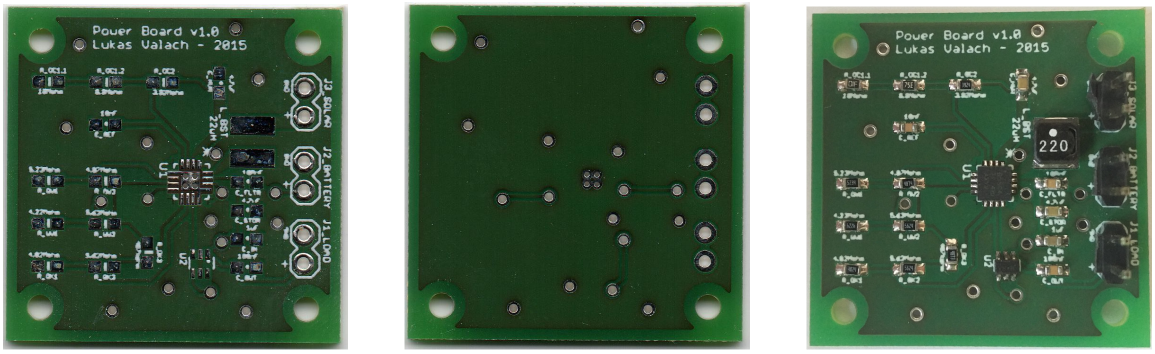
ID	Command type	Payload
1	arm device	short address (2 B)
2	disarm device	
3	reset device	
4	enrol device	
5	get short address	extended address (8 B)
6	get zone table	
7	allow joining	number of seconds (1 B)
8	remove device	extended address (8 B)

Table 6.2: Command types from RPi to SAMR21

reports. This feature is utilized in the project and should any sensor not send an expected status notification 3 times in a row, the CIE announces it being down and notify the management application. The sensor may come alive again, which is also dully reported to the management application, leaving the interpretation of the event in broader context to the application logic on RPi.

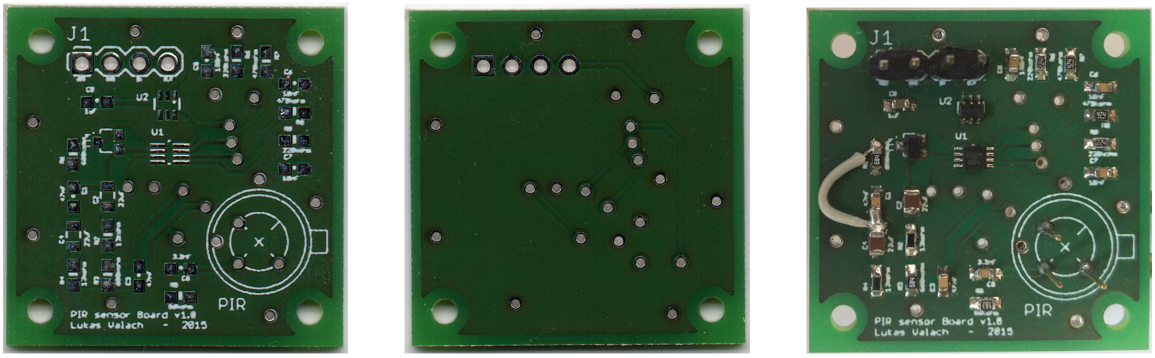
6.1.1 Management application

GUI application for the whole system runs solely on RPi. It is implemented using Qt framework (see [54]), while the main application logic is written in C++, and the graphical interface itself is written in QML declarative language. C++ provides direct access to the serial interface, maintains the model of the sensor network and provides hooks to access the model and serial interface from QML. QML visualizes the model to the user and provides controls for the network and sensors management. In the screenshot of application in the figure 6.5 are shown all possible states of the sensors. The names provides textual descrip-



(a) Top view (b) Bottom view, mirrored (c) Assembled board

Figure 6.3: Power board pre and post assembly photos



(a) Top view (b) Bottom view, mirrored (c) Assembled board

Figure 6.4: PIR board pre and post assembly photos

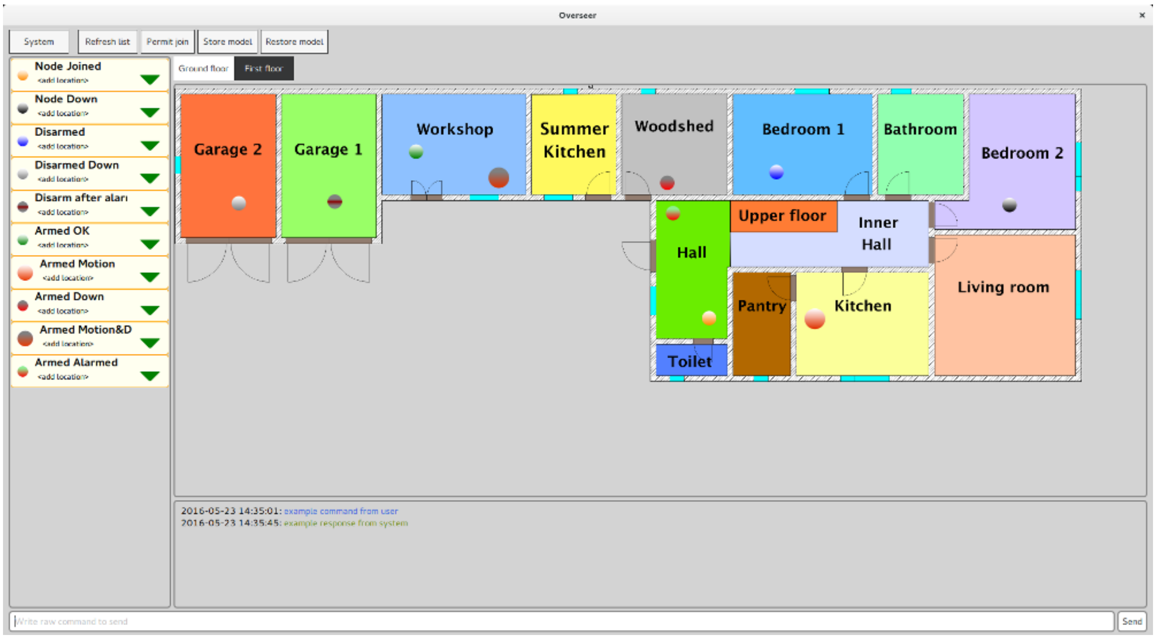
tion of given state for the purpose of the example and status lights represent visualisation of the state. Should any sensor be in alarmed state the status light is animated, it is flashing red and pulsing its dimensions. Thanks to that the user is able to locate the sensor which triggered the alarm quickly. On top of that, alarm is sent to the set of e-mails configured by the user through system configuration menu.

For finer grade management the user can open the details of individual sensors from sensor list by clicking on particular list item. Details subwindow is opened as shown in the figure 6.6 and allows the user to fill in information about the sensor, arm and disarm it individually or reset it to state before enrolment.

Besides the control using provided graphical elements the user can use the direct access to the serial port thorough command line in the bottom of the application window. It accepts ASCII messages and provides access to low level management of the sensor network. For the normal operation it is not necessary to use it, however should any problems occur it may come handy for troubleshooting. The full list of supported commands is listed in the user manual available in enclosed CD.

6.2 Sensor units

Sensor device consists of 3 units as described in chapter 5. Implementation of sensing and power management blocks consist solely from soldering selected components on the



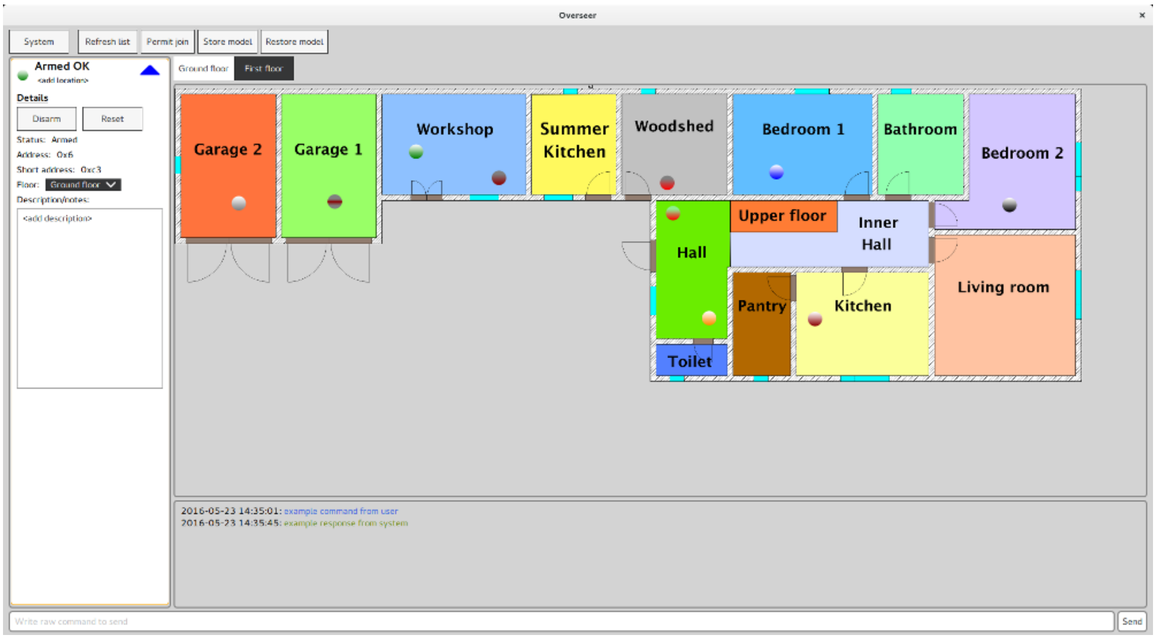
```
2016-05-23 14:35:01: example command from user
2016-05-23 14:35:45: example response from system
```

Figure 6.5: GUI application design

fabricated PCB. Wireless node additionally need a firmware implementing specific sensor operation. The general principle of sensor device operation is provided later in this section, while the specifics for particular sensor types are discussed in subsections 6.2.1 and 6.2.2.

Firmware for sensors incorporates the actual handlers for sensing block as well as few ZigBee clusters providing communication interface across devices. The ZCL specification [3] determines minimal cluster support for particular device types. IAS zone devices are mandatory to implement only server side of basic, identify and zone clusters. First two mentioned are necessary for rather fundamental wireless device operation as they provide information about the device, resetting and remote identification features. Server side of the zone cluster then complements the client side of the same cluster on CIE and provides sensor enrolment and status notification reporting functionality. As a matter of fact, zone cluster does not seem to support any command for arming or disarming the sensor hardware on the device and make it reactive to environment changes in [2]. Perhaps the intention was to consider device armed right after it has been enrolled by CIE, and disarmed by simply ignoring any status notifications incoming to CIE. This approach however does not suit the needs for low power operation and smart duty cycles in this thesis. More complex sensors may draw substantially more energy in armed state than in disarmed. Hence an additional commands for arming and disarming are implemented through ZigBee On/Off cluster.

While the sensor is armed, it sends regular status notifications to the CIE even if no alarm situation is detected. This behaviour enables the CIE to detect power source failures or tamper attempts. Sensor itself is not able to distinguish between those two, therefore it can not provide any additional information about the nature of the incident when it is back in operational state. The sensor communicates its immediate state through setting of various flags in status notification messages [2, p. 353]. Right after the sensor receives arm command it responds with initial status notification containing set supervision notifications flag. That particular flag is sticky and remain set for all subsequent notifications until the



Status: Armed
Address: 0x6
Short address: 0xc3
Floor: Ground floor
Description/notes:
<add description>

```
2016-05-23 14:35:01: example command from user
2016-05-23 14:35:45: example response from system
```

Figure 6.6: GUI application - sensor details

device is disarmed. Disarming command leads to sensor sending status notification with supervision notifications flag unset, as an indication that no more status notifications are going to be sent. If sensor detects environment change which triggers an alarm, it sends the status notification with alarm1 flag set. The flag remains set for any following notifications which happen to occur while the alarm trigger condition is still true. When the environment changes back to its normal state, the flag is unset and a notification is sent.

Every received message's source address is inspected whether it matches the CIE address set during commissioning phase, when the sensor first joins the network. This check provides additional layer of protection against unauthorized sensor manipulation by rouge network node. It allows only device which commissioned the sensor to set the authorized CIE details.

6.2.1 Motion sensor specifics

The role of sensing block for motion sensor is implemented by the board with PIR sensor described in previous chapter. Its output is connected to the wireless nodes's ADC input pin. If the sensor device is armed, the board is powered on and ADC on SAMR21 is started in free running window mode [14, p. 802]. ADC is watching that the voltage on its input is within a specific voltage range corresponding with no alarm condition. Should it get out of that range, an interrupt is issued, ADC operation is suspended for a while and application task is scheduled to report alarm condition. Every ADC interrupt re-starts one shot timer responsible for reporting that the sensor get back to original, unalarmed state. Hence if the timer expires, there was no alarm situation during past time and the threat is no longer present.

Wireless node controls the powering of the PIR board as well. It is done so through output pin which is driving the enable pin of PIR's board load switch. Arming closes the switch making the PIR board operational. Disarming command disables ADC and cuts power to the PIR board. It helps to conserve energy when the sensor is disarmed as neither

ADC nor PIR board consume power. Arming and disarming, therefore powering and cutting the power of the PIR board has one disadvantage. The PIR output seasoning circuit needs some time right after the board was powered up to stabilize. This time is experimentally determined to be around 6 s, after witch the output voltage does not experience spikes which would trigger an alarm. To accommodate to this limitation the arming and disarming is separated into two steps. First the power is enabled to the PIR board and then the ADC is enabled when arming, disarming happens in reversed sequence.

6.2.2 Contact sensor specifics

Contact sensor implementation is much simpler than motion sensor implementation. It consist of simple magnetic switch which closes and opens the electric circuit depending on whether it is in magnetic field or not. The switch has two outputs, which are connected to two pins on the wireless core node. One of the pins is set as output pin driving the switch low. The other pin is set as input with internal pull-up enabled and it detects whether the switch is closed driving the voltage to low or open, when the pull-up holds it high. In disarmed mode are both pin inactive with internal pull-ups enabled for the lowest energy consumption [14, p. 1060].

Chapter 7

Testing and evaluation

Basic testing of the functionality of the sensor network was done during implementation phase of the work. After tuning in the basic functionality the system was brought to supposed deployment environment to conduct use case testing of the system. In section 7.1 are described the features of the testing environment and conditions present at time of testing. Revealed issues are described later in subsection 7.1.2 and addressed in section 7.2, which also discusses possible improvement for the next revisions.

7.1 Testing

Testing was conducted in two stories family house from mid sixties. The perimeter walls of the object are approximately 35 cm thick, while inner walls are slightly thinner, about 20 cm. The weather conditions were relatively consistent over the time of testing, it was sunny during the day which manifested in increased illuminance inside the object. For the purpose of testing were used only motion sensors, as they represent the more complex of the two types of designed sensors.

7.1.1 Assembled devices

The devices were completed using appropriate parts, yet the appearance was still rather makeshift. Pictures of the devices are shown in figures 6.2 and 7.1. Every designed board includes drill holes intended for tightening the boards together so that they make up the final form of particular device. However, fitted pin headers in combination with used wire fittings did not match well for intended final form. They were too big and would require much bigger spacers than those available. This aspect of the physical design was underestimated during the design phase, but on the other hand it is easily fixable by re-soldering more suitable, 90° angle pin headers. The interconnecting wires will fit naturally and the form factor will be relatively the same.

7.1.2 Operation tests and issues

Networking wise the sensors were able to join network created by CU, send messages and receive commands. The wireless range range between two adjacent devices is approximately 10 m, which is for initial batch of custom wireless boards in environment with many obstacles well enough. Initial tests however did not include any test cases for more complicated network topology such as tree or mesh and only star topology with CU acting as a hub was

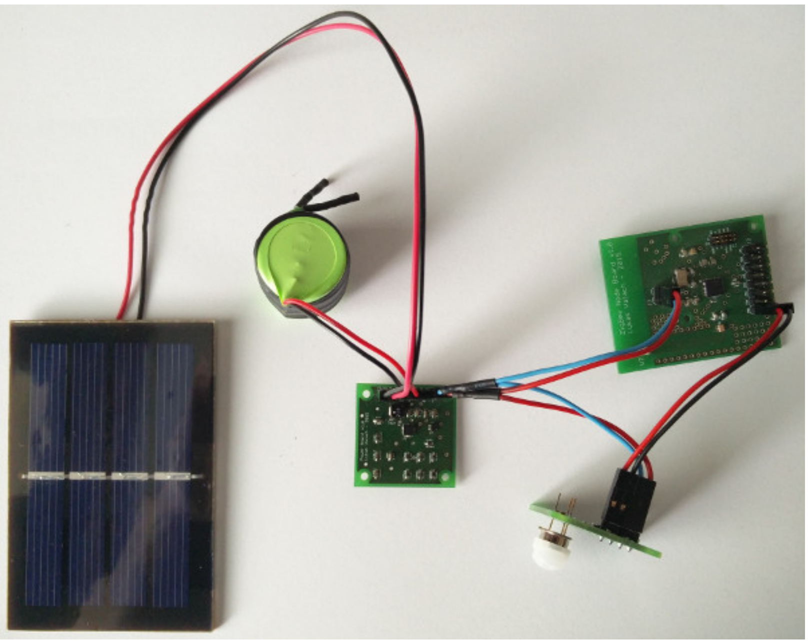


Figure 7.1: Motion sensor device

tried out. More advanced network topology capabilities are however directly implemented in Atmel's BitCloud, hence there should not be any hiccups utilizing the functionality.

Control through GUI of management application proved to be working well, however there were some lagging issues while receiving long messages from SAMR21 trough serial interface. The cause of the problem probably dwells in a combination of low, single core processing power of RPi and the way the serial interface input is internally processed by the application. Other graphical elements are working smoothly and the layout of the application window provided to be very practical on the connected widescreen television. The controls are simple and the floor plan spans almost across the whole screen allowing to have overall view of the monitored area at a convenient zoom level.

Devices were operating as expected also regarding the sensor and monitor functionality. Implemented reporting system worked well, actual values for keep-alive timers and sleep periods would need longer testing so that all the practical aspects of these settings show off by everyday use.

The major issue observed during testing concerned the powering and energy harvesting systems. Although the solar panel provides reasonably enough power to charge up the battery during the day, the battery dies anyway after some time and is unable to maintain its charge. It could be caused by charging by very small current, which over time causes building up an internal resistance in used batteries, hence rendering them empty. However, TI document [24] mentions that this flaw should only affect NiCd batteries, while the used batteries are of NiMh chemistry. The state can be reverted and the battery capacity can be restored by applying considerably higher than nominal voltage and high current to the batteries for a short time period, which is referred as zapping in the document. After that they can be slowly charged by C/10 current until full capacity is reached, however in order to do that the battery has to be removed from the sensor device and charged manually. Another possibility is possible low quality level of the used batteries.

In relation to above mentioned, the selected batteries do not suit the best the charging IC. They consists of three cells with nominal voltage of 1.2 V connected in series, providing the resulting 3.6 V and 320 mAh. Because the individual cells may have slightly different characteristics, they may not be charged equally by the PMIC, which considers them to be one big cell. One small cell therefore may be charged or build internal resistance faster than the others causing others deteriorate faster. Separate charging of individual cells would work much better, but it is not achievable by the used PMIC. For bigger part of the testing of the functionality of the devices, the energy harvesting part with rechargeable batteries were replaced by regular non-rechargeable battery pack meeting the voltage level.

Problems with power source revealed another important flaw in design. SAMR21 SoC has maximum input voltage rating of 3.6 V to which the selection of rechargeable battery was subjected. No voltage regulator was designed to be used in the power line between the input power source and the MCU itself. During the design phase it seemed redundant to use such regulator as the discharge curve of NiMh batteries is very flat, and it was assumed not to be a big issue anyway as the SoC is able to operate at 1.8 volt to 3.6 volt range, and the voltage drop should not be significant enough to be an issue. In practice on the other hand, this assumptions backfired and it is very clear now that the voltage regulator providing stabilized voltage output is a crucial part of the design. Its integration on the wireless board would allow the PMIC use higher voltages, possibly helping with NiMh batteries management as well. As a quick fix to this issue, the power regulation IC could be placed directly on the wires interconnecting output of PMIC and input power pins of wireless core board. The right solution is to redesign the PCB of wireless node boards to integrate voltage regulator on it directly.

Another area which would need additional attention is sleep operation of the sensors. The sleep operation as it is works on the nodes, they can be put to sleep and they are awaken in case they need to interact with the other nodes. This basic functionality is already pre-implemented in BitCloud core. However the SAMR21 offers possibility for *sleep walking* (see section 5.2 or [14] for details). It would enable to keep the sensor in a sleep mode for the most of time even in armed state, when only ADC would remain awake to sense environmental changes and provide wake up interrupt. Regardless, BitCloud provides its own functions abstracting the user from low level settings of sleep modes. Attempt to use BitCloud sleep management alongside with sleep walking did not bear the desired results and was working very unreliably, hence it was disabled for the current implementation and will need to be addressed in the next development iteration.

As a temporary solution, there is also a possibility to not use automatic BitCloud sleep management and use the raw access to sleep management through appropriate registers. Such solution may however prove to be overly complicated, possibly re-inventing the wheel provided by BitCloud. More feasible middle ground solution could be achieved by using BitCloud sleep management with application timers for polling. They would wake up the MCU to perform sensing/measurements from time to time in a similar fashion as it was usual for programming old 8bit MCUs. Such solution would be working to some extent but either the timers would need to be set for very fine granularity or the application could have showcased delayed reactions to trigger conditions or miss the trigger conditions at all by not sensing at the right time. Hence none of those temporary solutions were implemented as they would only turn one kind of a problem to a different kind without actually solving anything.

7.2 Future improvements

The basic functionality of the created system was proved during its testing. As a proof of concept it worked well. Although, there are some issues which need to be resolved for flawless functionality as described in the previous section as well as a few improvements, which may help to enhance the features of the system. These improvements are described in this section.

7.2.1 Improve radio performance

Achieved wireless reach of approximately 10 m is enough for deployment in medium sized family house, yet its improvement could probably decrease the resulting price for the system as a whole. Longer wireless range would allow more sparse deployment of sensor devices and places distant from location of CU would be reachable over less intermediate wireless devices.

The design of the wireless node accommodates 2-layer PCB, which according to Atmel's application note [13] is not as efficient for wireless devices build around SAMR21 SoCs. In the same application note Atmel recommends to use 4-layer PCB as for better separation of various grounds of SAMR21 SoC. The proposed PCB stacking allows for microstrip design for controlled impedance regions and it miniaturizes down the whole design by using mostly 0402 sized components. Switching to 4-layer stacking could therefore improve the wireless performance for slightly increased manufacturing and assembly costs. To be certain that the 2-layer stacking is so much worse in wireless performance it would be appropriate to conduct measurements of the RF performance. Radiation diagram would provide the best indication whether the designed RF related traces synergy with the RF components. A degree of improvement could be also achieved by replacing current chip antenna with bigger and more powerful antenna. It may be reasonable to consider adding SMA connector on the next board revision to be able to use external antenna.

7.2.2 Remote management application

Another improvement which will be needed for convenient use of the system is developing an application for mobile devices, which could perform certain management tasks of security system remotely. The architecture of the current management application is designed with the possibility for adding remote management extension already. The only requirement is to add networking support class and connect it to the core of the application through already prepared hooks and handlers. GUI of the remote application could copy the design of management application for RPi as the Qt allows cross-compilation for all major mobile operating systems.

Remote access could be provided with two levels of trust, both with only limited security system management abilities. The lowest capability would be provided to remote clients connecting through internet. They would be only able to monitor the sensor network and check status of individual sensors. Remote client accessing the central managing application from within the home network (WiFi or wired LAN) would have additional rights for arming and disarming the security system. The disarming could last for only limited time period after which the system would go back to armed state. During that brief time the user would be able to get to the CU and disarm the system permanently. Remote management application could therefore replace physical remote terminal or similar ACE, or simply enhance its functionality, while the user could choose to use either or both.

7.2.3 Internet connectivity independent notifications

The system so far provides only e-mail notifications if anything suspicious happens in monitored object. As an extension to this type of notification, and in order to make the alarm system more fail proof, it would be useful to provide SMS notifications. This would require GSM module with SIM card slot in order to connect to some of the local carriers' network. The feature would also require active either data or SMS package for the connectivity and every notification would naturally cost user some money. On the other hand, the incidents should happen very rarely as it is indeed unnatural state of the monitored object. In order to further reduce the frequency of sending SMS notifications the system could be enhanced by set of settings allowing the user to configure severity levels of particular issues and alarms. Those severity levels would then directly imply whether or not the system sends SMS notification or not, should that given trigger situation happen.

The GSM module would be probably connected to the RPi directly through some of the remaining serial connections or it could be using USB port in form of USB dongle. The latter would require deeper support on the operating system and drivers side as opposed to only serial communication library needed for the former. In any way, adding another channel of communication with the user could strengthen the security of the security system itself and provide redundancy to the system of alarm reporting.

Chapter 8

Conclusion

This thesis reports about design and implementation of a ZigBee based home security system with a RPi SBC as its central management unit and user interface gateway. Nodes of the WSN are based on custom designed PCB boards providing the wireless, sensing and power management capabilities. The custom boards are result of technology review, which was conducted in order to select the best suitable components for the purpose of this thesis. Firmware part of the boards is partially based on existing solutions, which were modified and extended to be able to better provide desired functionality.

Central management unit of the sensor network is implemented by synergy of RPi, which provides high level management and application, and designed wireless board providing low level application logic and networking capabilities. The communication between the two is realized by serial communication, through which is the RPi able to manage the sensor network using designed communication protocol. Graphical user interface, which provides single point of user management and monitoring interaction, is implemented by Qt framework utilizing C++ core with QML layer for actual graphical design.

Sensor nodes utilize the same wireless boards, but in connection with power management and sensing units. As an exemplary model was selected the implementation of motion sensor board utilizing PIR element with seasoning circuitry to provide analogue output for the application to process. Power management units are realized by PCB boards with PMIC targeted for harvesting ambient light energy to recharge the attached NiMh accumulator.

The thesis provides overview of energy harvesting technologies with considerations about their suitability as the operation time extender of the designed wireless sensor nodes. The ambient light energy source was selected based on the evaluation of the intended deployment environment properties, where the ambient light is the most redundant energy source. Although the conversion efficiency of contemporary solar cells available on the market is relatively low, the abundance of light makes it a perfect candidate. Another research of technology was conducted regarding SBCs solutions currently on the market, comparing their fitness as a central unit of the system. As the requirements for the SBC serving as central unit of WSN are not high, the determining factor for selection was the price of particular SBC. Final selection of the RPi was subjected to the fact, that the author got into possession of a free piece.

Working proof of concept was confirmed by testing the system in laboratory conditions as well as in real environment with a set of few sensor devices and a central unit forming a star network topology. The sensing functionality was able to alarm of ongoing situations by e-mailing messages to defined addresses. Energy harvesting and powering subsystems were however underestimated in the design phase, therefore they would need an additional iteration of development works in order to address revealed flaws. The same applies to sleep modes, which require more tuning after the powering issues are resolved. Networking capabilities proved to be sufficient with the estimated reach of approximately 10 m between adjacent wireless devices. As a whole, the resulting implemented system can be declared functional, but in order to be usable in a real environment without any issues it still needs a further development effort.

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Appendices

List of Appendices

Appendix A

CD content

- Thesis Latex source codes and text in PDF
- Management application:
  - user manual
  - source codes
  - instructions for setting up cross-platform development environment
  - binaries for Raspberry Pi 1.0 B
- Network devices:
  - source codes for control unit and sensor nodes' firmware
  - binary firmwares for control unit and sensor nodes
  - instructions for setting up development environment
  - Eagle sources of developed boards
  - gerber files for PCB manufacturing
  - complete BOM spreadsheet with prices
  - duty cycle and power consumption estimations

Appendix B

Bill of materials

B.1 Wireless node board

Symbol	Part number	Quantity	Value	Package	Description	Manufacturer
U1	ATSAMR21E18A-MU	1	SoC	QFN-32	Cortex-M0+ with IEEE 802.15.4 radio	Atmel
U2	2450AT43b100E	1	Antenna	7x2x2 mm	2.4 GHz	Johanson Technology
Y1	7B-16.000MEEQ-T	1	16 MHz	5x3.2 mm	10 pF, 10ppm stab./tolerance	TXC
B1	2450BM15A0015E	1	Balun	2x1.25x0.8 mm	2.4 GHz to 2.5 GHz, 50 Ω	Johanson Technology
J1	M50-3500542	1	2x5	1.27 mm pitch	for SWD debugger and programmer	Harwin
J2	—	1	2x8	2.54 mm pitch	available SoC pinout	
J3	—	1	2x1		input power and ground	
L1	BLM18PG221SH1D	1	10 μH	0603	RF inductor 220 Ω@100 MHz	Murata
CX1, CX2	MC0603N120J500CT	2	12 pF		ceramic, COG/NPO, 50 V, 5%	Multicomp
C1, C2	MC0603N220J500CT	2	22 pF			
CG1, CG2	MC0805X106K160CT	2	10 μF		ceramic, X5R, 16 V, 10%	
CB1, CB2, CB3, CB4, CB5, CB6,	MC0603B104K250CT	6	100 nF		ceramic, X7R, 26 V, 10%	

Table B.1: Wireless node board BOM

B.2 PIR board

Symbol	Part number	Quantity	Value	Package	Description	Manufacturer
PIR	IRA-E700ST0	1	PIR element	∅: 9.2, h: 4.7 mm	infrared sensor, dual element, max. 15 V	Murata
PIR_LENS	IML-0658	1	Fresnel lens	∅: 11, h: 8.65 mm	fresnel lens fitting the PIR sensor	Murata
U1	TSU102IQ2T	1	OP amp	DFN-8	dual channel op-amp, 9 kHz, 1.5 V to 5.5 V	STMicroelectronics
U2	SIP32431DR3-T1GE3	1	Load switch	SC-70	load switch, 1.1 V to 5.5 V, 1 A	Vishay
R1, R3	ASC0603-680KFT5	2	680 kΩ	0603	thick film, 0.1 W, 1%	Welwyn
R2, R4	ERJP03F1302V	2	13 kΩ		thick film, 0.2 W, 1%	Panasonic
R5	CRGH0603F56K	1	56 kΩ		thick film, 0.2 W, 1%	TE Connectivity
R6, R9	MCWR06X2203FTL	2	220 kΩ		thick film, 0.1 W, 1%	Multicomp
R7, R8	CRGH0603F470K	2	470 kΩ		thick film, 0.2 W, 1%	TE Connectivity
C5	MC0603B332J500CT	1	3.3 nF		ceramic, X7R, 50 V, 5%	Multicomp
C6, C7	VJ0603Y103KXACW1BC	2	10 nF		ceramic, X7R, 50 V, 10%	Vishay
C1, C3	MC0603B473K160CT	2	47 nF		ceramic, X7R, 16 V, 10%	Multicomp
C9	MC0603B104K250CT	1	100 nF		ceramic, X7R, 25 V, 10%	
C8	MC0603X105K100CT	1	1 µF		ceramic, X5R, 10 V, 10%	
C2, C4	C2012X5R0J226M/1.25	2	22 µF	0805	ceramic, X5R, 6.3 V, 10%	TDK
J1	—	2	2x1	2.54 mm	pin pair cut off of bigger header	Harwin
D1	DA3J101A0L	1	Diode	SC-85	80 V, 0.1 A	Panasonic

Table B.2: Wireless node board BOM

B.3 Power Board

Symbol	Part number	Quantity	Value	Package	Description	Manufacturer
U1	BQ25504RGTT	1	PMIC	QFN-16	power management unit for solar powered battery charging	Texas Instruments
U2	SIP32431DR3-T1GE3	1	Load switch	SC-70	load switch for under-voltage protection	Vishay
J1, J2, J3	—	3	2x1	2.54 mm	pins for battery, solar panel and load power	Harwin
C_REF	VJ0603Y103KXACW1BC	1	10 nF	0603	ceramic, X7R, 50 V, 10%	Vishay
C_FLTR C_OUT	MC0603B104K250CT	2	100 nF		ceramic, X7R, 25 V, 10%	Multicomp
C_IN	MC0603X105K100CT	1	1 µF		ceramic, X7R, 10 V, 10%	
C_HVR C_STOR	GRM188R61A475KE15D	2	4.7 µH		ceramic, X7R, 10 V, 10%	Murata
R_OK3	CRCW0603487KFKEA	1	487 kΩ		thick film, 0.1 W, 1%	Vishay
R_OC2	CRCW06033M92FKEA	1	3.92 MΩ			
R_OK1	CRCW06034M02FKEA	1	4.02 MΩ			
R_UV1	CRCW06034M22FKEA	1	4.22 MΩ			
R_OV2	CRCW06034M87FKEA	1	4.87 MΩ			
R_OV1	CRCW06035M23FKEA	1	5.23 MΩ			
R_UV2 R_OK2	CRCW06035M62FKEA	2	5.62 MΩ			
R_OC1.2	MC0063W060315M90	1	5.9 MΩ		thick film, 0.063 W, 1%	Multicomp
R_OC1.1	MC0063W0603110M0	1	10 MΩ			
L_BST	VLCF4018T-220MR49-2	1	22 µH	4x4x1.8 mm	shielded, 0.49 A, 20%, 0.369 Ω, Irms 900 mA, Isat 490 mA	TDK
BATTERY	B-3XN320BC2	1	320 mAh^{-1}	⊘: 2 h: 2 cm	3x B-N320BC in series, wire connectors	Vinnic
SOLAR_PANEL	OPL20A20101	1	2 V, 250 mA	90x60x3 mm	small polycrystalline solar panel	OptoSupply

Table B.3: Wireless node board BOM

Appendix C

Boards schematics

C.1 PIR board

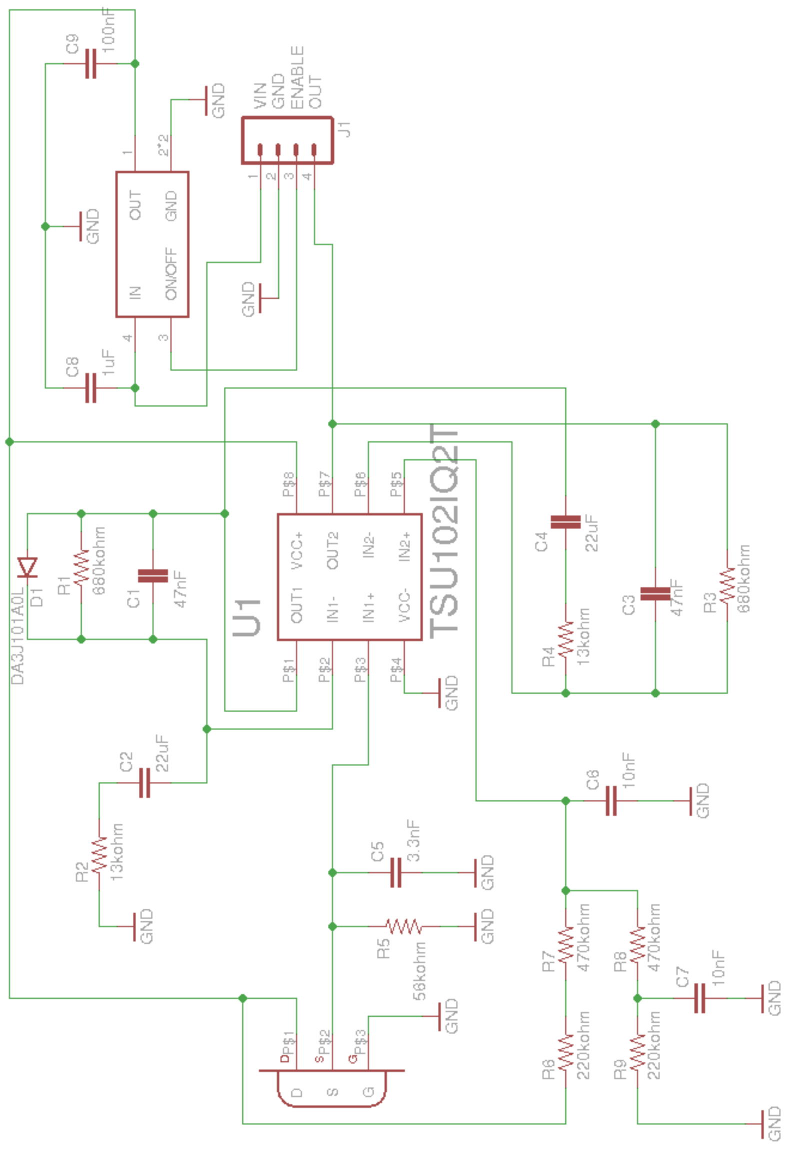

Figure C.1: PIR board schematics (modified [12])

C.2 Wireless node board

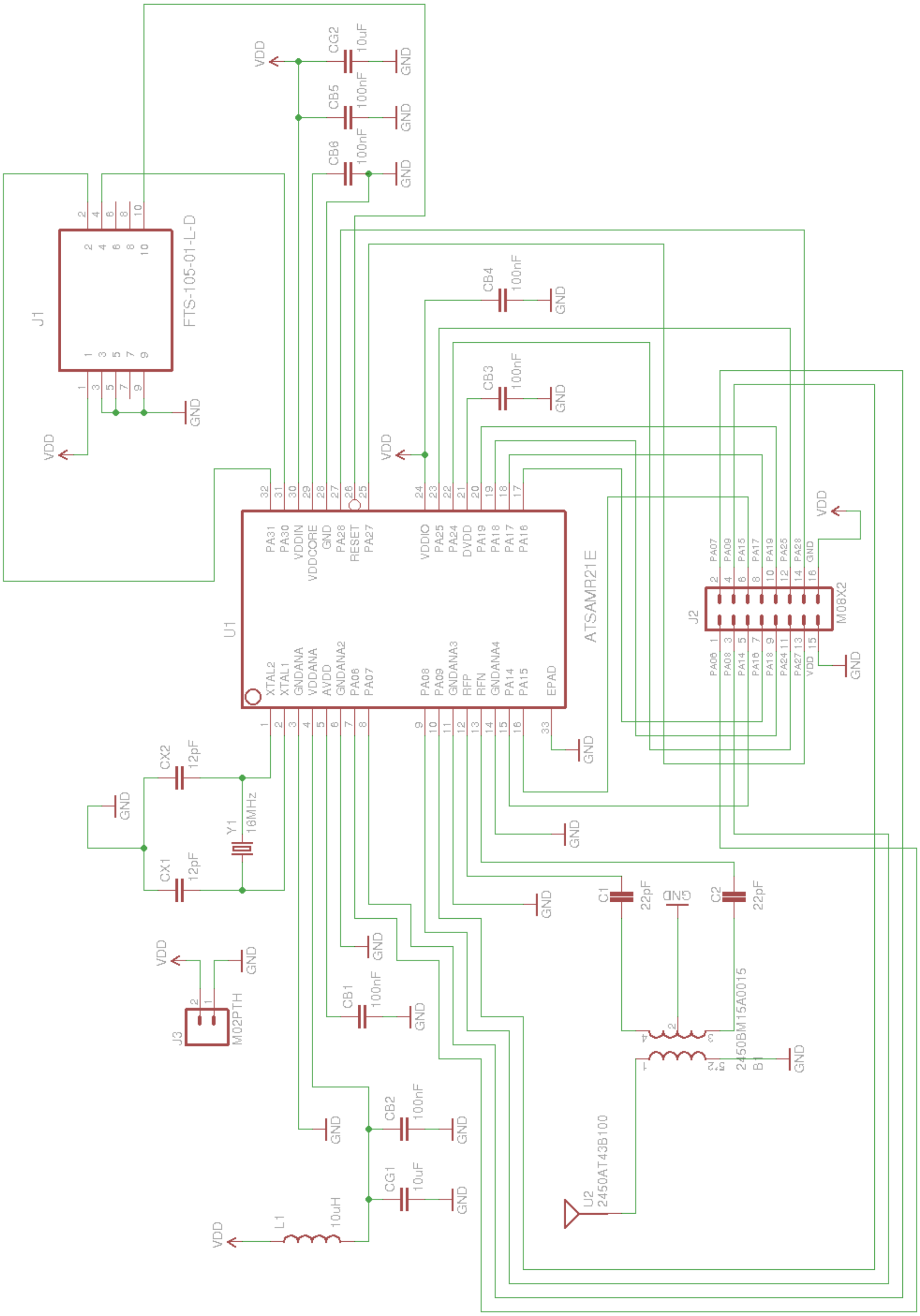

Figure C.2: Node board schematics

C.3 Power board

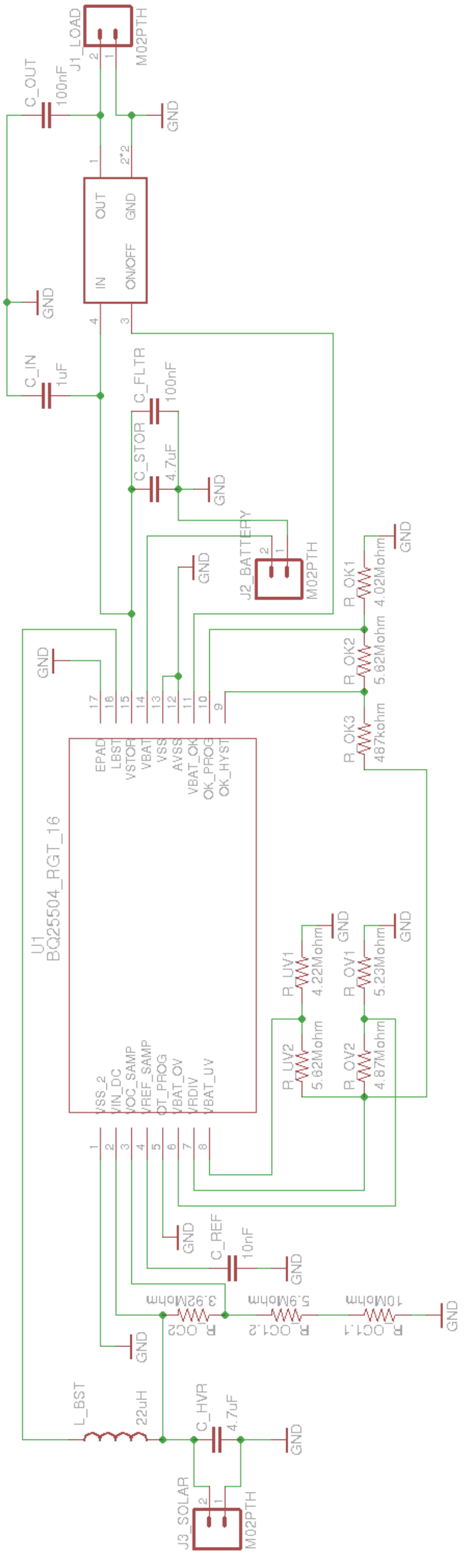

Figure C.3: Power board schematics

Appendix D

Photovoltaic efficiency chart

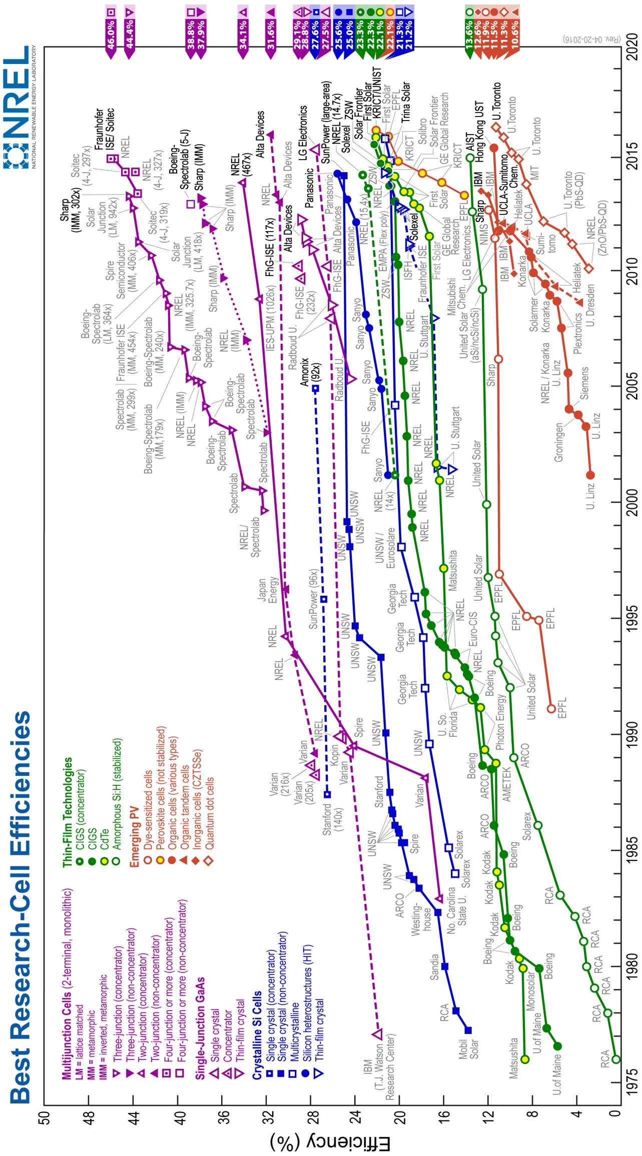

Figure D.1: PV technologies' efficiency.

This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.