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AALTO UNIVERSITY SCHOOL OF ELECTRICAL ENGINEER
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Perpetual battery life for Machine to Machine communication devices with cellular access

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ABSTRACT OF THE MASTER'S THESIS

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The advent of Machine to Machine (M2M) communication has opened up new avenues for the mobile operators and also for the equipment vendors. The ecosystem of communication is fast emerging in to a new dimension. However to make the new realm of M2M communication feasible, there is a need to reduce the power consumption of these devices.

Research is being carried out in several directions to reduce the power consumption. Research work has been done to develop new network topologies, architecture and also improve the electronics and embedded systems to reduce power consumption. This thesis explores the third direction which is concerned with developing a prototype using the existing electronics and cellular access techniques to explore the possibility of improving power consumption. This is concerned also with using energy harvesting for recharging the battery supplies. The development of the prototype is aimed at using a CPU, cellular access device and rechargeable power system to develop M2M device with battery time in terms of years.

We will be using the concept of sleeping devices to enable infinite battery times. The aim of the research is to find sleep times which may lead to sufficiently longer battery times and hence provide a prototype of M2M device with energy harvesting solution capable to have independent power source for years.

KEYWORDS: M2M, Low power, Cellular access, GSM, GPRS, Solar panel, LTE, solar power, Energy harvesting , Perpetual battery times

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Muhammad Waqas Mir

ABBREVIATIONS

2G	2nd generation
3G	3rd generation
4G	4th generation
ADC	Analog to digital converter
APN	Access point name
AT	Attention
BA	Broadcast allocation
BOD	Burn out detection
CPU	Central processing unit
DRX	Discontinuous reception
EHS	Energy harvesting systems
EGSM	Extended-GSM
FET	Field effect transistor
GPRS	General packet radio service
GSM	Global System for Mobile
HTTP	Hypertext transfer protocol
ICT	Information and communications technology
IP	Internet protocol
LAN	local area network
LTE	Long Term Evolution
M2M	Machine to Machine
MOSFET	Metal–oxide–semiconductor field-effect transistor
MPP	Maximum power point
OS	Operating system
PDP	Packet data protocol

SIM	Subscriber identity module
SPI	Serial peripheral interface
TCP	Transmission control protocol
TTL	Transistor–transistor logic
USART	Universal synchronous asynchronous receiver Transmitter
USB	Universal serial bus
USSD	Unstructured supplementary service data
VIN	Voltage input

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1 Introduction

1.1 Machine to Machine communication

The ubiquitous growth of cellular networks has opened up new avenues for devices which make use of the wireless networks for specialized purposes. For the last two decades, cellular networks have seen huge increase in traffic. However, for the past five years or so, data traffic has taken off and many experts see it as the future of ICT. The term M2M is mainly used for Machine to Machine communication but it has been used for Machine to Mobile and other concepts. In our work, M2M would refer to Machine to Machine communication. The concept of internet of things has been introduced for the new era of communication which would advance from the existing human to human communication to machine to machine and human to machine communication. Cellular networks are central to any such idea as they provide umbrella coverage and have more capacity as compared to the wireless LAN and other localized wireless networks.

M2M and internet of things has been described as the new technology revolution that would be generating business in billions in the next decade. Moreover it would increase the number of devices in magnitude of billions. This scenario has led to research work in interoperability of different systems, using low power devices and creating a new eco system for the communications industry [1]. With increased number of devices communicating with each other over the cellular networks, a new era of communication and social change would begin. However, this new technology revolution would require fundamental changes in the way we operate devices and cellular networks. The device communicating with the cellular network can be anywhere. It can be located at our home, offices, roads, market places or even remote areas. The communication performed by any wireless device consumes power and so is the case with machine to machine and machine to human communication. However there lies a fundamental difference between the power dynamics of internet of things and that of conventional communication. There is expected increase in the number of devices being used in a direct and indirect way by a person and their probable location. Therefore providing power to these devices would be the key factor in realizing the goal of a connected world and connected society. With the ever reducing power resources of the world, we need to look for alternate energy sources and power efficient devices to make the dream of connected world a reality. A lot of work is currently being done to reduce the power consumed by the cellular networks and the power load they produce on the communicating devices. A practical scenario that can result from a connected society is that a person might have to deal with tens or hundreds of devices which are to be powered for communication. In this case, wired power or regular charging will be not a practical scenario anymore. Therefore, we need to look for alternate power source options and ways to conserve power.

M2M devices are a key factor in linking up the information of the physical world with the communication networks and other platforms. However, the battery life time of devices sending and processing sensor data is a very important factor in implementation of ubiquitous M2M devices for a range of applications.

1.2 Scope and contribution

The scope of this thesis is to evaluate and analyze possibility of infinite battery times for a cellular sensor platform. We shall devise a prototype which is able to communicate with cellular network and post data on the internet cloud. We shall use power conservation techniques such as sleepy nodes and low power processor to analyze the power gains that can be realistically achieved. The results would be in the form of expected life time of a solar powered battery sensor. The results would reveal the amount of battery times that can be achieved by using the current commercial products. We wish to establish the fact that the battery times can be extended to limits of years and decade with current technology. Thus the technology enabler for wide scale deployment of M2M devices is already available in the form of commercial products and smart use of power saving techniques.

The aim of the research is to assess the possibility of infinite battery times for sleepy M2M devices with ability to communicate with cellular network. A prototype for sleepy M2M device has been developed. The prototype uses a sleep strategy for power conservation. It has the ability to communicate with cellular network. With optimized sleep times, the prototype has battery times in range of years. The analysis of solar powered charging reveals that we can employ energy harvesting to have battery times in terms of decades.

The first chapter includes the introduction and scope of the work. Second chapter describes the research work that has been carried out in energy harvesting, low power microcontrollers and sensor platforms. In third chapter, the system architecture of the proposed prototype has been detailed. Implementation of the proposed prototype is included in the fourth chapter. Results and discussion has been included in fifth and sixth chapters respectively. Seventh chapter is about the future work and references are included in the eighth chapter.

2 Background and technology evolution

Before going in to the details of our work and analysis of solar powered sensor, it is essential to have a look at the background work that has been conducted in the field of solar powered sensors and communication devices. Moreover, the research work carried out on sleeping nodes would also help us understand and build a system that is power efficient and has battery times in range of months, years if not in decades.

2.1 Energy harvesting and solar powered devices

The advent of internet of things has brought the idea of Machine to Machine communicate in the fore front. The future expansion of such Machine to machine networks and communication is in part dependent on the battery life time of the devices in use. A lot of work has been carried out to minimize the power consumption and enhance the battery lifetime. There are several directions to solve the problem of energy conservation. Research has been carried out in the field of electronics to reduce the size and power consumption of the devices. A lot of work has been carried out in optimizing the protocol over the radio and other interfaces to provide energy efficient solutions. Another dimension to the energy conservation solution is the use of energy harvesting techniques.

With ever decreasing energy reserves of the world, energy harvesting is becoming increasingly significant. In particular for the low power electronic devices such as sensors and mobile phones, energy harvesting is being considered as the next energy solution. In [2], the recent advances and developments in the field of energy harvesting have been discussed in detail. The use of piezoelectric, kinetic, magneto-electric, biomechanical, electrostatic and solar power are being researched and developed in to workable solutions [2]. Research has also been focused on the design of efficient energy harvesting systems (EHS). In [3], a tier based model has been described for the design of

EHS. The tiers have independent functions of device or load handling, energy measurements, power control and conditioning, energy storage access and energy storage itself. In [4], optimized schemes of rectifiers and other electrical components have been described to improve the power management and efficiency of the EHS subsystems. The use of energy harvesting has increased in particular with embedded systems. This is largely because of the low power required by these systems to function. In [5], a model has been discussed for storage, dissipation and provision of harvested energy for real time embedded systems. Energy harvesting is being considered as one of the energy solutions for current low power embedded computing systems [6].

Energy harvesting involves techniques and methods used to convert ambient energy present in the form of wind, movement or solar light in to electrical energy. Energy harvesting techniques are increasingly becoming popular for all kinds of devices and in particular embedded systems. Research on different ways of energy harvesting or power scavenging is being carried out extensively. A comprehensive overview of different harvesting techniques has been provided in [7]. The power provided by different techniques is mentioned below

Harvesting Method	Power Density
Solar Cells	15mW/cm3
Piezoelectric	330μW/cm3
Vibration	116μW/cm3
Thermoelectric	40μW/cm3

Table 2.1 Power density of harvesting sources [7]

In table 2.1, the comparison of the electric power density is provided for different energy harvesting methods. It shows the amount of electric power that could be generated per centimeter cube area of a panel.

Piezoelectric materials make use of vibrations to produce electrical energy. Such types of materials can sense any kind of vibrations and use inertial mass and vibrations to produce electrical energy. Vibration is also used by electrostatic methods to produce electrical energy. In this case, capacitors are used to produce the required electrical voltage. Electromagnetic waves are also being used for energy harvesting. In this case, the basic property of electromagnetic induction is applied to induce voltage on a conductor by changing the magnetic field surrounding the concerned conductor. In case of thermoelectric harvesting techniques, temperature difference is used to produce electrical energy.

2.2 Design factors for energy harvesting techniques

A number of factors need to be considered for making use of energy harvesting for an embedded system [7]. In general these can be divided in to three categories

- Environmental
- Physical
- Electrical

Environmental specifications

The environmental factors include the operating temperature and the amount of physical degradation, the system can tolerate. The physical degradation may include contact with water or any other natural substance. Operating temperature of the system is very important particularly in the case of solar cells. Solar cells usually require direct sun light and therefore the system must be able to perform under operating temperatures which may be on the higher side. Moreover, system may be capable to operate in very low temperatures. Such a scenario can easily be faced in deploying wireless sensor nodes in a country such as Finland.

Physical specifications

The physical aspects of the system deployed for energy harvesting have profound importance particularly in the case of embedded systems. The size of embedded systems is on the smaller scale and therefore the size, shape and weight of the harvesting module can dictate overall system design. In case of Solar cells, the size of the solar panels is directly proportional to the amount of electrical power produced. Hence a tradeoff is to be established when selecting the equipment for energy harvesting and the final size, shape and weight of the system.

Electrical specifications

The electrical aspects of the energy harvesting system are of utmost importance to the design circuitry. The variable include the below mentioned

- Maximum voltage to be provided to the system
- Minimum current requirements for the stable system
- Power density of the particular energy harvesting methods

Two types of mechanisms can be used to provide the harvested energy to the system. In the first case, we can supply the harvested energy directly to the system. In this scenario, the efficiency of the energy harvesting and its subsequent usage would be low [7]. The second case is in which we use the harvested energy to charge a rechargeable battery which in turn provides the voltage and current to the system. This is power efficient strategy and is mostly used in all the solar powered embedded systems. It also ensures reliability in the case of no available solar power.

2.3 Solar power and wireless sensor networks

Extensive research has been carried out in the field of solar powered wireless sensors. A number of different network topologies for sensor networks have been described in earlier research projects. There have been significant contributions in the field of solar power for such a system. In [8], an optimal approach has been described for the design of micro power solutions for solar photovoltaic cells. The word micro has been used because the power involved is in micro or milli watts. In [8], it has been shown that we may use series-parallel combination of solar cells for best performance. We need to use such a system for the solar charging of our desired system. A possible application of our research result can be the use of sensor platform in deep forest temperature monitoring. Micro-solar power sub systems in deep forest settings have been discussed in [9]. In [9], several design variables such as sizing of the solar panel, charging times, photovoltaic cell composition and voltage regulation have been discussed. Also the concept of super capacitor has been proposed in [9] for use with solar charging systems. Functional prototypes of solar powered wireless sensors have been developed as described in [10]. In [10], a system known as EverLast has been described. The 'EverLast' uses the concepts of feed-forward charging, pulse frequency modulation and converter to enable higher efficiency of solar charging. The solar charging system is used with wireless sensors in EverLast. The wireless sensor network is charged with the help of a super-capacitor in [10]. A complete system implementation for very long battery times has been provided with EverLast [10]. The radio technology used in EverLast consists of transmitters which have a range of less than 10 meters. In [11], a model for use of photovoltaic cells has been described. This model uses the concepts of maximum power point (MPP) and has shown promising results with simulations for long battery times. EverLast has been designed to work efficiently with higher duty cycles. This is very promising development as usually solar powered wireless sensor networks have small duty cycles to conserve energy. The use of batteries and charging systems for longer duration can cause the fatigue effect on the devices used for solar panels and storing the energy. In [12], a model system has been proposed with the use of super capacitors and independent solar power system for the sensor networks. In [12], the system has been made independent of the microcontroller and therefore has achieved higher efficiency. In [13], a practical design guide has been provided for the development of solar powered sensor networks. A model for monthly harvested energy has been provided. Factors such as amount of solar radiation, radiation angle, and voltage regulation and battery capacity have been discussed in [13]. Low power microcontrollers have been involved in building up wireless sensor networks. In [14], a model has been developed for wireless sensor networks which use solar power and MSP430 micro controller. The setup and existence of long life wireless sensor networks has been discussed in [15] with emphasis on operating point of the solar panel setup. We would consider the models of solar powered wireless sensor network when devising a model for our prototype. During the literature review, it has been found that most of the research work has been carried on sensor networks with radio transmitters of short range. There seems to be a need of research work on sensor platforms that are part of a cellular network. Our research is based on designing the sensor platform that has the capability to transmit and receive information in a cellular network such as GSM, UMTS or LTE.

2.4 Solar cells

In the case of solar cells, additional variables need to be checked for efficient power design. These include

- Amount of sunlight available over all the seasons
- Percentage amount of cloud cover
- Day and night times
- Amount of rain

The most used form of ambient energy is the solar cells and batteries. Solar panels have been used to energize high power equipment. However the use of ambient energy involves a number of limitations and design specifications.

A lot of work has been carried out in the field of solar electronics in the past decade or so. A photovoltaic cell is often referred as solar cell. A solar cell is a solid state electrical device which has the capability of converting energy received in direct sunlight in to electrical energy in the form of voltage and current. The conversion takes place as an implementation of the photovoltaic effect. The price and size of solar cells have reduced to a great extent and therefore, solar cells have been employed in research and industrial projects for wide variety of purposes. As explained in [16], the solar cells can be considered as a system of Markov chain with regards to energy generation process and the relative states. The solar cells are charged in the case of access to direct sun light while in the case of no sufficient sun light, the batteries being powered by solar cells provide the power to the system. A photovoltaic cell is often referred as solar cell.

As mentioned in [16], the discharging of the batteries can be carried out in accordance with the process known as 'relaxation effect'. In this process, when the solar power is turned off, the material from the electrodes of the batteries moves away and new material is deposited on the electrodes so that power can be generated. The discharging current holds a lot of importance as if it is greater than the required threshold, then the batteries won't be able to charge properly and lead to system shutdown.

2.5 Model for operating solar cells for system power

The mode of operation for the Solar cells is essential in achieving the goal of unlimited lifetime of the system without reinstallation of any charging equipment. Research work has been done on stochastic schemes for Solar charging of Wireless sensor nodes and other embedded systems. A detailed and suitable scheme has been discussed in [17] which provides a base for developing a system with infinite life time Solar cells and rechargeable batteries.

The goal of the earlier systems with battery backup was to ensure that the power consumption is optimized to give maximum life time. However, the goal of the systems based on energy harvesting is to ensure the availability of the system over extended period of time [17]. This change in the system design, results from the unpredictable nature of the energy harvesting sources. In order to devise a suitable scheme for Solar charging, we need to keep in view, the blackout periods. The blackout periods suggest the time when there is no energy available for harvesting and the battery backup for the system has already been utilized. The system must have a mechanism to get out of the blackout phase once the energy has been harvest and the batteries or super capacitors have been charged.

The model presented in [17] is particularly useful because it describes the overall functioning of the solar cells. Therefore, we can use the model with any internal circuitry as the model is not dependent on the internal design of the system.

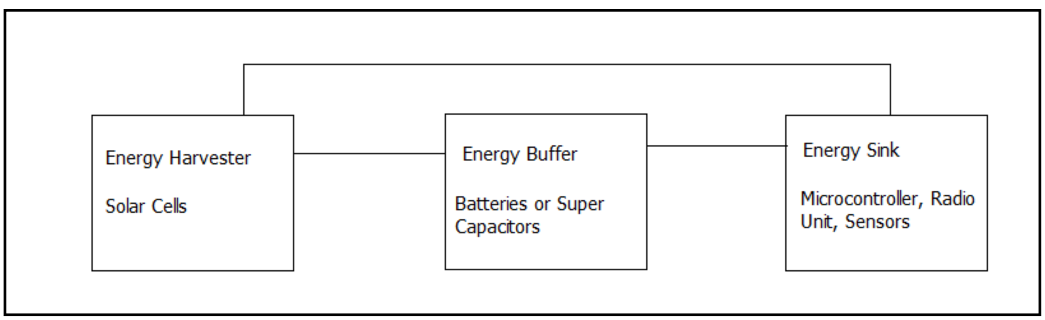

Figure 2.1 Model for system with solar charging [17]

The model described in [17] considers three components namely

- Energy harvester
- Energy buffer
- Energy sink

The model is based on stochastic models for each of these modules of the system.

Energy harvester

The energy harvester is the module which produces the electrical energy from ambient sources. Solar cell is an example of energy harvester. The stochastic model for energy harvester consists of a Markov chain with a number of transition states [17]. The greater number of transition states would lead to greater accuracy in the predicted results of the solar energy being produced and consumed by the system. In [17], it is assumed that the sampling time for the energy measurement is ten seconds. Therefore, on the time scale we have ten transition states with the last transition state indicating the energy buffer to be completely charged by the energy provided by the energy harvester. A very important consideration is the fact that the transition is done only within immediate neighbor state as the power provided by the solar cells is considered to be small.

Energy buffer

The energy buffer module is usually made up of rechargeable batteries or super capacitors. The stochastic model of energy buffer is simple as there are two states. In the first state, the buffer is being charged up by the harvester module and in the other state; it is providing electrical energy to the energy sink. The simplification of the states for energy buffer is due to the scheme used for the energy being provided to the energy sink. In case, the energy provided by the harvester is greater than the buffer, the energy sink will take energy directly from the harvester. Therefore, the only case when the energy is taken from the buffer is when its stored energy is greater than the amount of energy provided by the harvester. Such a scenario helps also in avoiding black out phases.

Energy sink

The energy sink is module for which the power or the energy is being provided. The stochastic model for such node consists of three states [17]. The first state is the activity state in which any type of pre-planned action is performed by the module. The next state is the stand by state in which the power consumption by the module is the least. The third state is the blackout state in which the power is not being provided to the energy sink module and it stops to function. A mechanism needs to be devised which enables the module to access the energy module in a loop to check for power and start to function when the required power is available.

In [17], simulation and actual testing results are provided for test cases of solar panels and the impact of capacity of energy buffer and power scaling factor of harvester on the overall system performance. These are relevant guides for any system development with solar power usage. In [18], real time measurements of current generated by a solar panel placed on a roof top have been given. These measurements are for one day and include the effect of clouds, sun light and other environmental factors on the output of solar cell.

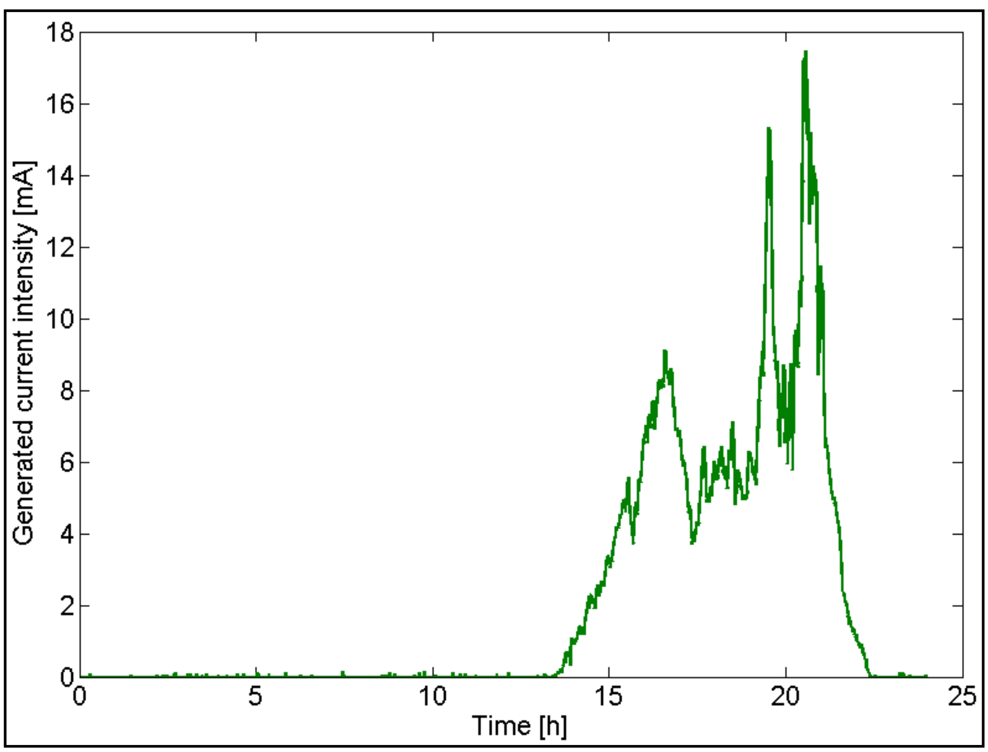

*Figure 2.2 Current produced by a 5.5*15 cm2 solar panel [18]*

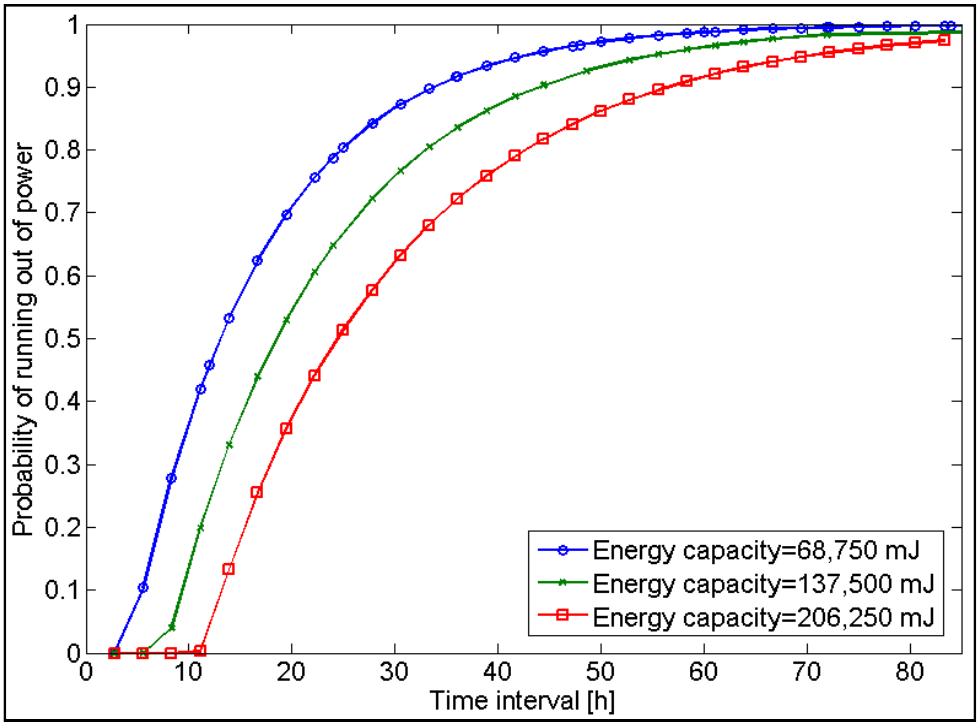

Figure 2.3 Variation of outage probability with buffer capacity [3]

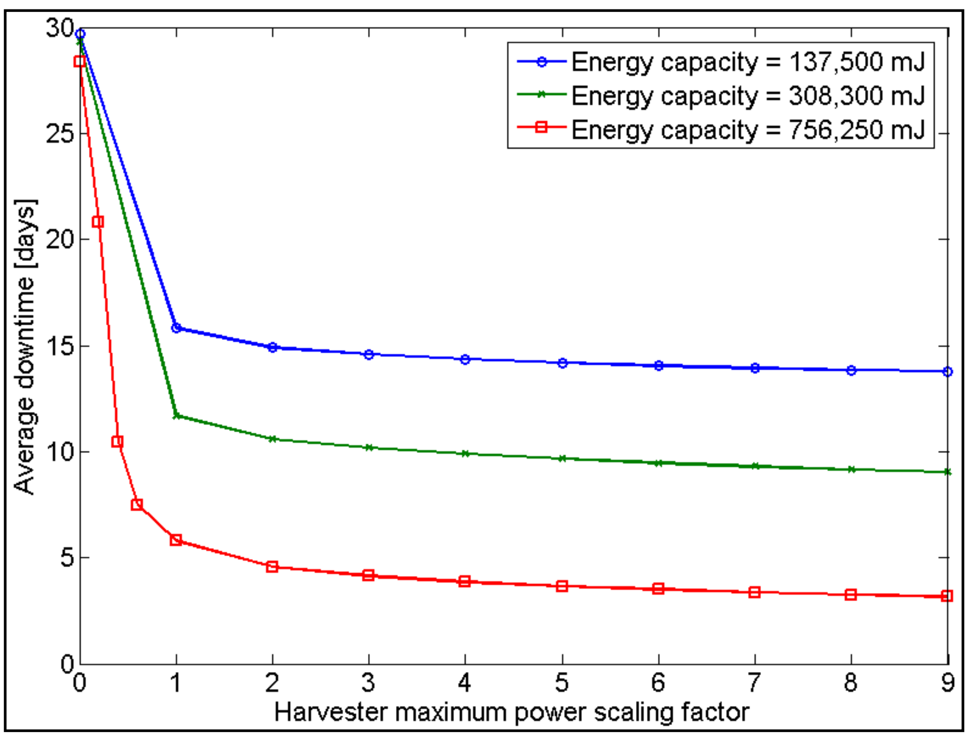

Figure 2.4 Variation of downtime with power scaling factor of energy harvester [18]

The current measurements are shown in the figure 2.2. Using the results in [18], a discrete time Markov chain model has been used in [17] to simulate the outage times of the system with variable storage capacity. These results are provided in the figure 2.3. In [17], there is a comparative analysis for the power being produced by the solar panels and the outage days expected with a certain storage capacity. The simulation results are again based on discrete time Markov chain model of the solar charging system. These results are given in the figure 2.4.

The above plots give an idea in to the design factors we need to consider for implementation prototype. We need to select the components in order to ensure we have zero down time with respect to selected duty cycle. Duty cycle is the ratio of the time the energy sink is in active state to the amount of time it is idle or in sleep state.

2.6 Solar charging of embedded systems

The current consumption of the embedded systems and microcontrollers has reduced significantly over the passage of last two decades. Many manufactures for the microcontrollers are now pushing towards attaining a battery life time of more than two decades by using a combination of energy harvesting and highly power efficient microcontrollers. The use of energy harvesting with small embedded systems is a new research area. It can pave the way for cheap and energy efficient devices which can communicate in the Machine to Machine networks and Machine to human networks. In case of microcontrollers, two factors are very important when considering the use of energy harvesting techniques. The first factor is the size of platform that is required to harvest the ambient form of energy. Second factor is the amount of energy that can be generated from the harvesting setup. For example, if we are considering Solar powered setup for the microcontroller application, the size of the solar panels should be small enough to enable a feasible size of the application. Secondly, we require a battery resource in the case of no ambient energy being available for harvesting. In case of solar energy, a situation for such a scenario is in the night or in cloudy conditions. We need to consider further details and scenarios for areas where the sunlight is not available throughout the year.

2.7 Low power microcontrollers

A lot of work has been done in the field of power efficient microcontrollers. Due to the technological developments, the current ratings during the complete shutdown mode have been reduced in the range of microamperes.

As mentioned in [19], the main factors which drive the power consumption of the microcontroller are as under

- Operation modes for power conservation
- Clock scaling
- Memory architecture
- I/O pins and current requirements
- Instruction set complexity
- Software handling

Out of all these, the modes of operation divide the current available products in to two main categories. The first group has the ability to completely shut down all the clocks and then use one subsidiary clock or external interrupt to wake up. The other category has only a power down or idle mode. We would be primarily working with the microcontrollers which have a complete shutdown mode of operation.

The clock scaling refers to the functionality where using dividers we can scale down the clock frequency to conserve power and achieve power efficient duty cycle. The effects of this on the power conservation have been provided in [19]. The memory architecture plays an important role in the interrupt handling when the processor is schedule to wake up. The amount of time required to wake up from sleep and stabilize may be very important in operations where time synchronization play an important role. The Input and output functionality of the processor also drives the current ratings and it can be controlled by software shutdown. In [19], the type and intensity of effect of software and instruction complexity has also been given with regards to power conservation of the processor and embedded system.

Comparative analysis of low power microcontrollers

A number of low power microcontrollers are being manufactured. All of them have their particular specifications with respect to clock, power down modes, idle and active mode currents. In [19], a comparison of the processing ability and the relevant current consumption of the current processor have been provided. This comparison is very useful while selecting a particular processor for a low power application. The comparison is also very useful because both processing capabilities and low power consumption are factors for selection of a particular processor

	AVR	PIC16	PIC18	MSP	8051
Bit level processing	8	8	8	16	8
Max clock frequency	8Mhz	10MHz	20MHz	6MHz	6.3MHz
Power down mode current	8µA	20µA	2.6µA	1.8µA	21µA
Idle	0.5mA	220µA	120µA	55µA	n/a
Idle	4mA	1.5mA	843µA	440µA	n/a
Active mode current 32Khz clock	88µA	n/a	35µA	19.2µA	2.78mA
Active mode current 1MHZ clock	2mA	220µA	480µA	240µA	4.05mA
Active mode current 8MHZ clock	8mA	1.5mA	2.4mA	1.9mA	13.3mA
Wakeup time	2ms	102µs	10µS	6µs	20µs

Table 2.2 Comparative analysis of low power microcontrollers [19]

Design decision for the prototype

One important observation is the fact that we would be using a wireless module which would be interfaced with the processor. Therefore, we would start our design with the commercial product which is provided in the form best suited for the interfacing with the wireless module.

Keeping in view the current requirements and the possibility to interface commercially available wireless modules, we will be working with the Arduino prototyping platforms. These platforms use the AVR microcontrollers. However, if a design prototype is developed to maintain lower current consumptions, it requires little effort to develop a similar design with a different choice of microcontroller. Another important factor would be the current consumed in running and operating the wireless module. This would be discussed in detail in the later parts when we discuss implementation of the prototype.

2.8 Sleeping nodes and power conservation

The concept of Sleeping Nodes plays a very important role in energy harvesting. Depending on the nature of the application, the sensor device can be set to long durations of sleep mode to conserve energy. The device only wakes up when a certain condition is met such as completion of sleep cycle, provision of solar power or arrival of new data. Sleep scheduling has been often used in wireless sensor networks to conserve energy and provide longer battery times. Different topologies and schemes for sleep scheduling have been developed as discussed in [20], [21] and [22]. Most of the works have been done to combine the sleep scheduling with the efficient routing protocols of the sensor networks.

The sleeping time is also very important in relation to the total power consumption. There scenarios for sleep strategy which need to be explored for the relative optimization of battery times are stated in discussed in [23]. These are as under

- Always on (This scenario refers to the normal usage of phones and other communicating devices)
- Always off (This scenario refers to very long sleep times and small wake up time)
- Partial off and on (This scenario refers to sleep intervals during normal usage)

In our scope of work, we will be looking in to the possibility of the infinite battery times in the second scenario. Our prototype is supposed to be sleeping for majority of the time. Hence the power consumed by the controller and the ability to minimize the power used by the wireless device would give us the most efficient design.

3 System architecture

The architecture design of the of the solar powered based cellular sensor consists of the following basic modules

- Power module
- Processing module
- Cellular access module
- Electronics module

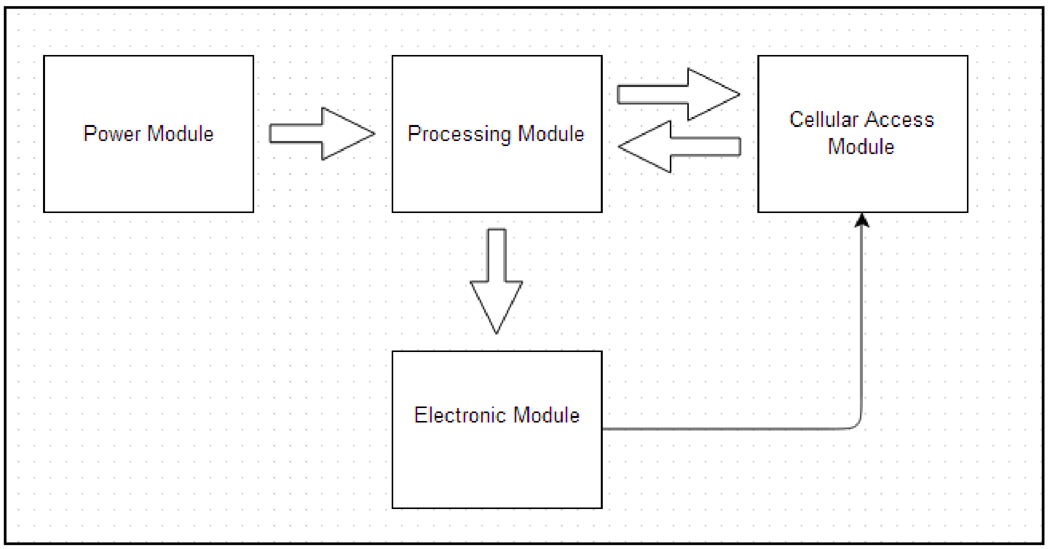

Figure 3.1 Architecture Model

3.1 Power module

This module is concerned with the power to be provided to the system. Our main goal is to use energy harvesting to provide power to the system. However, in the case of no solar power being available, there needs to be a backup power source to provide the required electrical power to the system. The amount of required power dictates the size of the solar panel to be used. In general, the microprocessor systems using the 8 or 16 bit microcontrollers usually work on

TTL logic and therefore a battery which can provide 5V with the suitable amount of current can provide the required electrical power. The power module would only power up the microprocessor system. However, the microprocessor system would then be used to power up the cellular access module.

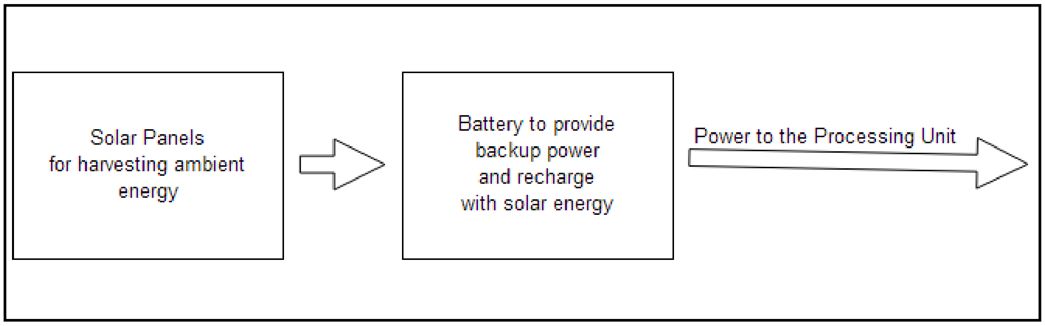

Figure 3.2 Power module

3.2 Processing module

The processing module which consists of a microcontroller/microprocessor unit is used to induce sleep on the system and then wake it up to power up the cellular access model. The internal clocks or timers of the microcontroller need to be used to wake up the microcontroller systems and later the cellular access module. During the sleep module, the processing module goes in to the power down mode which is intended to keep the power consumption to the bare minimum. Also the functionality for the sleep duration is also to be implemented in the processing module. The power on and off for the cellular access module is controlled via the processing module in combination with the electronic module. The sensing function and processing of the sensor data is also included in the processing module.

3.3 Cellular Access module

The cellular access module is used to connect to the cellular network to communicate with the other devices and also post the sensor data on the web server. The data and the commands sent to the cellular module are given by the processing module. Cellular module is used just as a connection between the processing unit and the internet or in other words the "cloud". The cellular module should have the ability to shut down completely after the transmission of the data. Moreover, there is no limitation on the technology being used as we can use GSM, 3G or 4G cellular access modules.

3.4 Electronics module

The electronics module is aimed at minimizing the power consumption. This module is used to turn off the modem functionality of the cellular access modem. Moreover, it is also used to switch power on and off to the cellular access module during the sleep and wake up of the system. This module also takes care of the current surges which appear during the switching of the current and voltages to the cellular access module.

4 Implementation

We would be exploring the possibility of a solar powered CPU platform that would work as a sensor connected with a cellular network for regular updates. The practicality of such a system sending updates from a remote area depends on the amount of power consumed in the sensor update to the network, amount of power that the solar cell can generate and the power consumption that can be reduced through sleeping nodes. The goal is to analyze and establish a system that would not require manual power recharge in the span for years if not decades. Such long periods between manual charging would enable to connect a society with thousands of devices without the need of changing batteries every other day or week.

4.1 Main implementation goals

The main goals that need to be accomplished to devise a system that can work on independent power source for years are

- Design and implementation of power efficient sleeping CPU platform
- Use of solar power cell and batteries for power of CPU platform
- A power efficient communication link between the CPU platform and cellular network
- Communication with cellular network in power optimized scheme
- Analysis of sensor updates and relative power usage

Design and implementation of power efficient sleeping CPU platform

A sleeping node is essential for operations in which continuous execution is not required. Inducing sleep in the device would save a significant amount of power and therefore, fewer loads on the power source. Considering that we are implementing solar cells and batteries as the power source, we need a sleeping node for power efficiency and giving enough time for the solar cell to charge up and provide required amount of power for the operational time.

Use of solar power cell and batteries for power of CPU platform

New sources of energy and in particular electrical power are being sought to provide power to ever increasing demands of electronic and communication devices. We are using solar power cells and connecting them with batteries to provide power to CPU platform. This would be essential in realizing a system which is self-sufficient in providing electric power for operations. The use of solar power is eco-friendly. Moreover, it is continuous and ubiquitous over the entire coverage area of the cellular networks.

A power efficient communication link between the CPU platform and cellular network

The sensor data which is to be read by the CPU platform needs to be sent over a cellular network. The link between the CPU platform and the cellular network is of significance both for the connection with the network and power consumption. We intend to use a cellular modem that can work in power efficient mode while taking power from the CPU platform. It should be noted that it is the part of the design to keep the cellular modem in off mode while the node is sleeping.

Communication with cellular network in power optimized way

The amount of sensor data updates would directly govern the amount of power being consumed by our system. Therefore, careful planning for the update frequency is required. The system is required to run at different frequency for sensor update with the cellular network to check for the optimized power consumption so that the system can be self-sufficient in power resource on the scale of years.

Analysis of sensor updates and relative power usage

The measurement of power being consumed by the system is essential in drawing meaningful conclusion about the prospect of taking the concept of cellular sensor towards commercial deployment. The implementation of design can be based on electronic circuits and software development on the CPU platform to check for the currents and voltages

4.2 Design of power efficient sleeping node

Power conservation is the key goal in implementation of the desired system. The power conservation is necessary for realizing the idea of cellular sensors which can last without a battery replacement for months if not years. The implementation of power efficient presented with the below mentioned challenges

- Selection of processor with lowest possible power consumption
- Sleeping processor node while no functions are being used

The first challenge is the use of platform which has the capability to handle sensor data and can process it and transfer it to a cellular network via any communication mode.

Power efficient CPU platform

A number of small microcontrollers are available with implementation of tiny Operating systems [19]. Microcontrollers such as PIC16F877, PIC18F4525, MSP430 and ATMEL ATMega328 are available with all the basic Input/output functionalities, processing capabilities and ability to communicate with other devices. In [19], a comparison of these CPU platforms has been provided which details the current consumption and relative processing capability. MSP430 operates at a 16 bit level while all the others use 8 bit operations. However, additional operations can be carried out using an 8 bit carry flag. However, the main interest for the application is the sleep capability and the amount of current that is drawn in a particular sleep mode.

For the implementation, the Arduino UNO platform meets all the major requirements. It is a platform used for prototyping electronics projects and makes use of the ATMEL328 Microcontroller. The Arduino platform provides all the necessary add on to make full use of the capabilities of the mentioned microcontroller.

Specification of the sleeping mode

The microcontroller is to be designed as a sleeping node which wakes up to send the sensor data to the cellular modem and then goes back to sleep. This mode will results in conservation of power and enable our system to last battery time ranging up to years.

Six sleep modes available in ATMEL328 Microcontroller [24] which are

- Idle mode
- Standby mode
- Extended standby mode
- Power down mode
- Power save mode

- ADC noise reduction Mode

Idle mode

In the idle mode, upon receiving the sleep command, the CPU and the flash memory of the microcontroller are shut down. All the other units such as SPI, USART, Analog to digital convertor, 2 wire serial interface, timers and all the interrupts are active. This is the most power inefficient sleep mode. However it can be improved by shutting down the timers, ADC and other unit before going to sleep. In order to wake up from this sleep, an interrupt generated from any of the timers, an input to the UART or external interrupt can be used. In the idle mode, only two clocks are shut down and i.e. CPU clock and clock for the flash memory.

Power down mode

The power down mode is the most power efficient mode. In this mode, all the clocks except for the asynchronous clocks are shut down. In other words, in order to wake up from this mode, we need to have an external interrupt, a time over flow of the Watch dog timer, an input on the UART interface or Watch dog timer runs on an asynchronous clock of frequency 128 KHZ. The waking up of the processor from power down mode can take considerable time when compared to the other modes. This time defined by the wake up fuses.

Stand-by mode

The standby mode is very similar to the power down mode. However the only difference is that the CPU oscillator is running and therefore consumes more power than the power down mode.

Power save mode

Power save mode is also similar to the power down mode with an addition of the timer1 which can be operated by the external clock source. Therefore, in power save mode, when the processor goes to sleep, the external clock timer keeps running and an overflow from this timer can be used to wake up the timer. The power save mode is often used to induce sleep times in the range of real time calculations. Moreover, the timer oscillator and the main clock are also active.

Extended stand-by mode

The extended standby mode is identical to power save mode. The only difference lies in the fact that in this mode the Timer oscillator is kept running.

ADC noise reduction mode

In this mode the CPU clock, the flash memory clock and Input-Output clocks are turned off. All the other clocks are operational. A summary of all the modes with operational clocks and wake up sources is given in the below mentioned table [24].

	Active Clock Domains					Oscillators		Wake-up Sources							
Sleep Mode	clk_{CPU}	clk_{FLASH}	clk_{IO}	clk_{ADC}	clk_{ASY}	Main Clock Source Enabled	Timer Oscillator Enabled	INT1, INT0 and Pin Change	TWI Address Match	Timer2	SPM/EEPROM Ready	ADC	WDT	Other I/O	Software BOD Disable
Idle			X	X	X	X	X(2)	X	X	X	X	X	X	X	
ADC Noise Reduction				X	X	X	X(2)	X(3)	X	X(2)	X	X	X		
Power-down								X(3)	X				X		X
Power-save					X		X(2)	X(3)	X	X			X		X
Standby(1)						X		X(3)	X				X		X
Extended Standby					X(2)	X	X(2)	X(3)	X	X			X		X

Figure 4.1 Comparison of different modes of operation [24]

Software and hardware design specifications

The power usage of the system requires the least possible power to be used. Therefore it is imperative to stick to internal oscillator provided by the processor board. The most optimal use of power is carried out by the Power down mode. However, the selection of the wake up procedure is of importance due to the below mentioned reasons

The wake up trigger must be supported by the microcontroller and provided at the required time of wake up. This is due to the fact that the sensor system is to be placed with no human intervention for wake up or charging procedures. However, the sleep functionality should be deep enough to conserve the most amount of energy. This gives rise to the situation where we need to send the processor to the most power efficient mode and that is the power down mode.
In case of power down modes, the options for waking up the microcontroller are limited as all the timer clocks are shut down. There is the option of an external trigger which can be in the form of UART serial data or an external interrupt. The external interrupt option can be implemented by using a real time clock circuit and powering it through the same source as that used for the microcontroller. This requires extra power consumption on the batteries and therefore we would prefer an option where an internal source can provide the require wake up signal.

The use of watch dog timer is a design efficient choice for waking up the processor from power down sleep. Watch dog timer is a timer module which runs on a separate 128 KHZ clock. The clock can be pre-scaled to provide timer duration of up to 8 seconds. The processor can be programmed to provide a watch dog timer interrupt every 8 seconds. This interrupt is generated by the over flow flag. After every 8 seconds, the processor wakes up.

WDP3	WDP2	WDP1	WDP0	Number of WDT Oscillator Cycles	Typical Time-out at V_{CC} = 5.0V
0	0	0	0	2K (2048) cycles	16 ms
0	0	0	1	4K (4096) cycles	32 ms
0	0	1	0	8K (8192) cycles	64 ms
0	0	1	1	16K (16384) cycles	0.125 s
0	1	0	0	32K (32768) cycles	0.25 s
0	1	0	1	64K (65536) cycles	0.5 s
0	1	1	0	128K (131072) cycles	1.0 s
0	1	1	1	256K (262144) cycles	2.0 s
1	0	0	0	512K (524288) cycles	4.0 s
1	0	0	1	1024K (1048576) cycles	8.0 s

Figure 4.2 Watch dog timer settings [24]

In our design, we need to make the processor sleep for longer time. Therefore the three bits as mentioned in the table below are set to induce a total timer of 8 seconds for the timer overflow flag. When the over flow flag of the Watch Dog time is set, it takes the program execution pointer to the interrupt service routine. In the interrupt service routine, a counter has been placed which increments each time the Watch dog timer overflows. This counter is then used as a functional unit to record time and decides about the relevant sleep strategy. For example in order to induce a sleep of one hour, the program counter does not enter the wake up execution loop till the sleep counter has reached the value of 450. Therefore, the relevant sleep times can be easily changed by modifying the value of the counter in the software.

Power conservation via shutdown of units

Power consumption is further reduced by shutting down rest of units which are not to be used during the sleep mode. In case of power down modes, only the Analog to Digital Converter and BOD needs to be disabled. In case of other modes we can shut down Input/output ports and also use power reduction registers.

The Arduino platform which is being used for prototyping contains additional components which consume a significant amount of power. These components include the Voltage regulator, the Power-on LED and the USB chip which is to implement USB to serial converter. These components draw significant amount of current and therefore need to be analyzed for any further improvement in power conservation.

4.3 Cellular access module design and implementation

The ability of the system to communicate with the cellular network is essential in building a system which has the ability to stay connected with the outside world. The ability to communicate with the cellular network would enable the system to send any type of information over the cellular link. The information can be sent via short message service or posting data on the internet. The design goals for this module are as under

- The module should be able to communicate with the Arduino platform
- A mechanism should be available to switch off the cellular module during sleep intervals
- The hardware and software configuration should be flexible to allow for any mode of communication

The following design specification has been implemented by two following models

- GPRS shield for Arduino processor platform
- USB Host coupled with USB GPRS Modem

GPRS shield for Arduino platform

The GPRS shield is a combination of electronic hardware which comes with a SIM900 GPRS module. It provides all the functionalities of a GSM phone to the Arduino platform except for the phone display and other features particular to a GSM Phone [25]. We can use the shield for the below mentioned functions

- Internet via GPRS
- SMS
- Voice Calls

This shield is able to communicate with the Arduino platform via the serial interface (UART). The main component of the shield is SIM900 GSM/GPRS engine which has been developed by SIMCOM. It is capable of quad band operation in GSM 850, EGSM900, DCS1800 and PCS1900. The connections for GPRS are based on multi slot class 10 and multi-slot class 8 [25]. The particular module has been chosen because of power conservation provided in the form of sleep mode for the SIM900 GSM/GPRS engine. The SIM900 module only consumes one milliamp current in the sleep mode which can thus lead to substantial power gains in the form battery life. Moreover, the implementation of SIM900 engine on the GPRS shield provides a way to switch off the SIM900 module via the software [26].

The functionality for the switch off/On is provided in the form a transistor switch. The gate of the switch is connected to the digital pin 9 of the Arduino platform. The pin is required to be toggled between the digital high and low in order to power on or power off the GPRS/GSM engine.

In order to conserve power, another design element has been added. The power to the GPRS/GSM shield is provided by the Arduino via the VIN voltage pin. In order to cut off the power of the entire shield, a transistor based switch can be added. This transistor based switch would open and close its connections in accordance with the sleep timings of the system. Therefore, when the processor is in sleep mode, the batteries would only require to power up the processor.

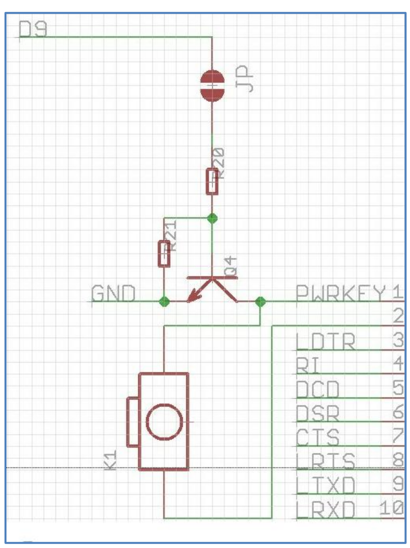

Figure 4.3 Switch-off mechanism in GPRS shield [26]

A certain delay is required in the code after the controller wakes up. This delay is required for two reasons. Firstly it is required to stabilize the connection between the GPRS shield and the Arduino platform. In the next step, time is required to power up the SIM900 GPRS/GSM engine and time is required to register with the network. Once the SIM900 is registered with the network, normal operations without any delays can proceed.

After the power on procedure of the GPRS shield or the USB Modem, the Arduino needs to communicate with the GPRS modem to establish a communication with the cellular network. This cellular link is established by the following communication architecture

- Arduino platform sends the required commands and communication to the GPRS Modem
- GPRS Modem sends the commands to the wireless network to establish the cellular communication

In the first phase, the Arduino uses the serial interface to communicate with the GPRS shield. In case of the prototype implementation, we only need one serial connection between the Atmel microcontroller and the GPRS modem. However, in case we need to communicate with the GPRS shield and also show the required messages from the cellular network, we will have to use two serial interfaces. In the case of our platform i.e. the Arduino UNO, we will be using one Hardware serial interface and one software serial interface. The software serial interface can also be termed as virtual serial interface. The virtual interface would be used to communicate over digital pins with the GPRS shield. These digital pins would take the form of serial Rx and Tx by using software functionality. The hardware UART will be used to send all the data over the virtual serial interface to the computer in order view the communication between our system and the cellular network. During the debugging process, the implementation of two UARTs proved to be very helpful.

Once the serial communication between the Arduino and GPRS modem is functioning properly, we need to setup a cellular link with the Wireless network. In our case, we will be communicating with a GSM network which would later be used to establish a GPRS connection for data transfer. In order to communicate with the GPRS modem, we use equipment specific commands called the AT commands. We would be using the set of AT commands as mentioned in [27]. There are a number of commands which are used in our software to check for network registration. The network response received is of a certain format which can be decoded as per the descriptions provided in [27].

We need to send some additional commands to setup the GPRS connection as by default, the GPRS modem would be detached from the Internet. All of these commands and their sequence of use can be found in [27]. As we have carried our research and prototype implementation in Finland, we have been careful in assigning the correct APN, username and passwords for the SIM card that we are using. The AT commands are sent from the Arduino to the GPRS modem as strings where they are in turn sent to the network. We open up a TCP/IP connection using the AT commands.

Once the TCP\IP connection is open, we can then send our data in normal HTTP format to the web server. All the GPRS connections are closed once the data has been sent over the GPRS link and confirmation has been received.

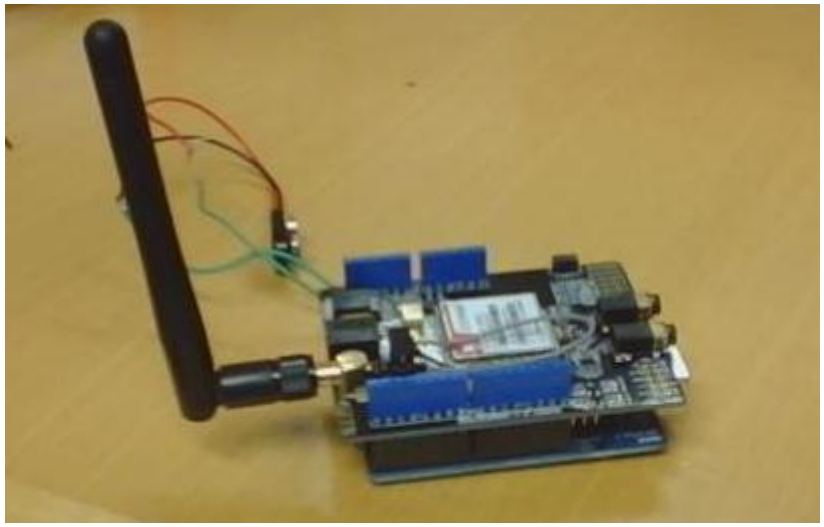

Figure 4.4 Prototype with GPRS shield and Arduino UNO

USB modem with Arduino platform

In case of a USB modem, we have a slightly different implementation scenario. We use the functionality of the USB host shield to connect with the PL2303 chip of the USB Modem. Therefore, in this case, all the communication is performed between the Arduino and the GPRS modem is performed over a USB link. As we are using the PL2303 chip in the GPRS module and the SPI in Arduino for the communication, the hardware UART can be used to show the communication messages on the computer. Therefore in this case we avoid the use of two serial interfaces.

The design of the system requires the CPU platform to provide power to the USB Modem. In order to achieve this, the processor platform is required to act as USB host with a VBUS connection of 5 volts and 3.3 volts. However, the Arduino platform does not come with an on board implementation of a USB host.

A USB host implementation would enable the processor platform to communicate with the USB modem and provide power to the USB modem as well. The circuit required for a USB host has already been implemented by a number of vendors. The plug and play module for the USB host enables the

Arduino platform to communicate and provide the power. The details for the USB host are given as under

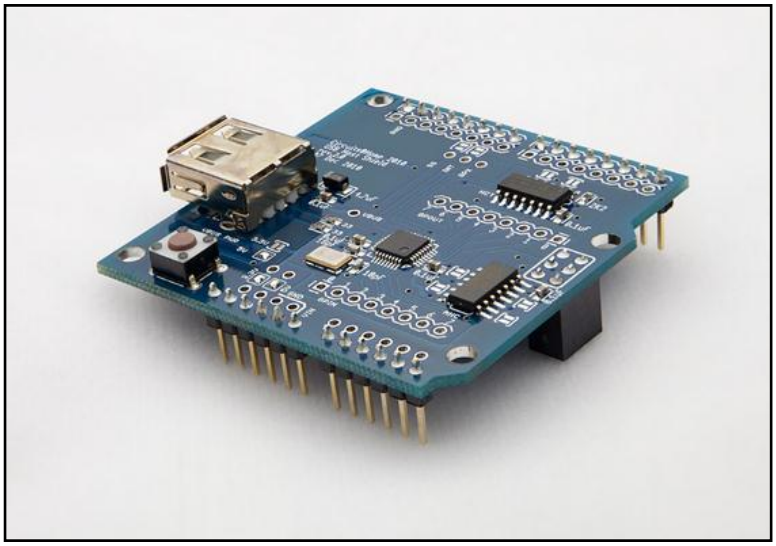

Figure 4.5 USB host shield [28]

The USB Host shield provides the functions of USB host to the Arduino platform. Using the internal circuitry of this module, the Arduino platform can communicate with USB devices such as Keyboards, mouse, digital camera and USB Modem.

The main component of this circuit boards is the integrated circuit named MAX3421E. This IC is the component which provides USB host functionality. Arduino can communicate with MAX3421E using its SPI which enables it to update and retrieve data from the registers of MAX3421E. In addition to this, a number of features are available on the board which include the below mentioned

- Power select jumpers
- Power pins
- Analog pins
- GPIN pins

- ICSP connector
- GPOUT pins
- Digital I/O pins
- MAX3421E interface pads

The details of the USB host circuit board can be found in [28]. The board enables the Arduino platform to communicate with the USB device over the SPI interface. In order to communicate with the cellular network, we require a setup in which the cellular USB modem can communicate with the Arduino platform using the USB host functionality of the USB Host shield.

We have selected a GPRS modem which uses a PL2303 chip for converting the USB communication in to normal Serial communication. The selection of such a GPRS modem has been greatly influenced by the availability of software library for Arduino platform which enables the communication to take place between the USB host and the PL2303 IC. The details and the software for the software library can be found in [29]. The software library provides all the required functions to send the data towards the USB modem and retrieve the subsequent response.

We use the SPI in built library for the Arduino platform to send the required AT commands to the USB modem. In this scenario of implementation, the AT commands are sent to the USB modem to send an SMS. The value received from the sensor is added in to the text of the SMS. The SMS can be sent to any desired number. The implementation of the sleep strategy is similar to one use with the GPRS shield. However, there is a different scheme used to implement the power of the GPRS unit. Since the USB modem is connected to the USB Shield, it is taking its power from the USB host controller which in turn takes it power from the main VCC of the Arduino platform.

Power off scheme for USB modem

The power to the USB modem needs to be switched off in order to conserve battery resources while the processor is in deep sleep. However, in order to switch off the power, the current flowing towards the USB host shield needs to be cut off.

A variant of this scheme has been implemented in [30]. A P-MOSFET is used to control the current flowing towards the USB modem. The configuration is such that during the sleep, a 5V voltage is supplied to the “gate” terminal of the P-MOSFET. Such a voltage can be provided by setting any of the digital pins of the processor. We have used pin 9 to switch off current flowing to the USB Modem. It is to be noted that during the switch off the USB Modem, the current would be flowing in the USB host shield and the current cut off is only meant for the USB modem.

Figure 4.6 Prototype with Arduino UNO and USB modem

4.4 Solar powered batteries

The power source of the sensor module would be solar power and we would use the ambient power source to charge the batteries. The choice of suitable scheme for the solar power and the battery configuration is of utmost importance for the eventual functioning and reliability of the prototype.

The following aspects need to be considered for the scheme used for Solar charging of the system

- The power consumption of the system in sleep mode
- The peak power and current consumption in wake up mode
- The amount of solar power available to the embedded system
- The sleep and wake up strategy
- Measurement of the battery power

The power consumption in the sleep mode is very important as far as the charging and discharging intervals of the batteries is concerned. Any amount of current being consumed by the system in the sleep mode would be directly drawing current from the battery in all time intervals. Therefore, the battery should have enough power to provide to the system to keep it in sleep while there is no solar power available for the charging of the batteries.

The peak power and current drawn from the battery during the wake up and communication with the cellular network is to be considered for choosing the batteries with high enough voltage and current. In the case of very low power batteries, the system may be stable in sleep but on wake up, may become unstable and eventually be powered off.

The amount of solar power available to the system is one of the most critical design factors. As we are designing our system in Finland, the weather conditions would allow direct sun light in almost one third part of the year. During the winters, it is highly likely that there is no solar power available for intervals as long as two months. Therefore, the design of the solar batteries and the overall system needs to ensure that the system can run without any solar recharging for at most three months. Finland is one of the worst case scenarios for the amount of sun light in winters. Therefore, any system which is capable to have round the clock operation in Finland, it is expected to run in any other environment.

The sleep strategy used in the system is also an important factor in designing the solar power module. The system is designed to have a software implementation of sleep strategy which is invoked from the ATMEL processor. The design incorporates the battery power and adjusts the sleep strategy and sleep time according to the battery power remaining. Another iteration of the design can include updating the sleep strategy via web interface. In such a case, the sleep time would be communicated via HTTP transfer from the web to the ATMEL processor.

4.5 Optimization of power consumption for the prototype

The prototype developed with GPRS shield and the Arduino platform (including an 8 bit microcontroller) consumes current in the range of 40 to 50 milli Amperes without even using the cellular functionality. Therefore, the very low current of the microcontroller in the power down mode proves to be totally insignificant when considering the battery times for the prototype. In order to optimize the power consumption and make full use of the low power consumption of the microcontroller, we need to optimize the design of our prototype and remove all the redundant current consumption components.

Breadboard design of prototype

In order to optimize the current consumption, the circuit for running the microcontroller unit has been designed using a breadboard. By virtue of this design we have been able to remove the following current consuming components which are included in the Arduino platform

- Voltage regulators
- USB slots
- Input and output ports circuitry
- Additional resistances added in the Arduino circuit lay out

The circuits designed to run the microcontroller consists of the following basic functionalities

- Reset circuitry (This is important to enable testing and eventual installation of the prototype)
- Clock circuitry
- Power circuit (This includes a voltage regulator with lower current and voltage ratings)

A one ohm power resistor is added to power circuit in order to measure the voltage. This voltage is then used to measure the current being consumed by the circuit. We will be using different power strategies i.e. with power adapter, without voltage regulator to check for the possibility of lowest possible current and voltage consumption

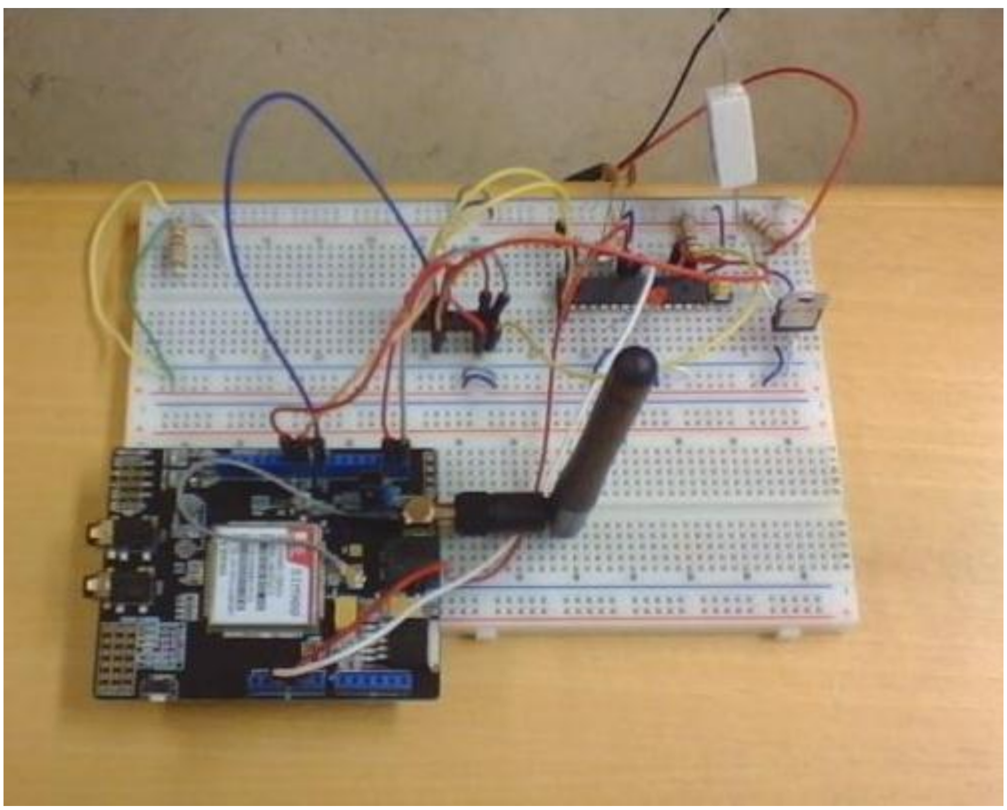

Figure 4.7 Final prototype with complete switch off capability

In the initial design of this prototype, the GPRS shield is being fed power from the VCC of the microcontroller. This results in the GPRS to be having a voltage on its input all the time during the operation of the prototype. Since we have not implemented a circuit board design for the GPRS shield, therefore the GPRS shield consumes current due to an LED on its circuit board. This situation has been easily be avoided with the help of a MOSFRT and FET switch combination. We can use a MOSFET to switch off and on the voltage being provided on the input of the GPRS shield. In this case, the control of the switch will b executed by a giving a high or low voltage on the gate of MOSFET using a digital pin of the Arduino. The design would be such that when the device has to wake up and perform an update on the web server, the 8 bit microcontroller will provide a high voltage on one of its digital pins. This pin will be connected to the gate of the MOSFET running the switch circuit. This will turn on the switch circuit and correspondingly provide the voltage and current to the GPRS shield. Hence the GPRS shield can be totally cut off during its operation. In such a scenario, we can only take the current and voltage consumed by the microcontroller for our calculations of battery life during the sleep mode.

5 Results and observations

The development of an M2M device with optimized power consumption mainly depends on two aspects

- Optimization of power consumption during the sleep mode
- Optimization of power consumption during the active/Wake up mode

Our goal has been mainly to optimize the power consumption during the sleep mode. This factor largely deals with the sleep strategy and the system design of the sensor platform. The power consumption during the wake up mode is largely related with optimization techniques and procedures involved in the cellular access. We developed our power optimized prototype from initial stages of using an Arduino platform to a breadboard design. We shall provide the results for all the intermediate stages of the prototype to provide a clear understanding of improvements in battery times that can be achieved with system design and sleep strategy optimization

The following different operating models of prototype have been developed and we shall analyze the results for each of them. The different types of prototype are as under

1. Arduino+GPRS shield
2. Arduino+GPRS modem
3. Breadboard Processor unit+GPRS shield
4. Regulated complete turn off model
5. Non-regulated complete turn off

In order to keep our calculations simple, the results are calculated using the current consumption as commercially the battery life is estimated in terms of milli Ampere hour. For actual energy consumptions, we need to take the voltage aspect in to consideration. However, since we would be working with a constant voltage supply of 9V or 5V, we shall ignore the discharging curves and voltage variations for our calculations. It is to be noted that minimum time of zero minutes in active mode refers to 0.0027 minutes of active time per hour.

5.1 Arduino+GPRS shield

In this prototype model, we have used the Arduino UNO platform to run the microcontroller. The microcontroller is used to run the GPRS shield. The power setup consists of a solar cell and an additional external alkaline battery. The digital pins of the Arduino UNO used to turn-off and off the GPRS shield. The GPRS shield is used to have cellular access and post data on the internet.

Time in Active Mode (min)	60	55	50	45	40	35	30	25	20	15
Total Current in Sleep Mode(mAmp)	42	42	42	42	42	42	42	42	42	42
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode(min)	0	5	10	15	20	25	30	35	40	45
Average milli Amp hour consumption	78	75	72	69	66	63	60	57	54	51
6000 MAH Battery Life (days)	3,21	3,33	3,47	3,62	3,79	3,97	4,17	4,39	4,63	4,9
5000 MAH Battery Life (days)	2,67	2,78	2,89	3,02	3,16	3,31	3,47	3,65	3,86	4,08
4000 MAH Battery Life (days)	2,14	2,22	2,31	2,42	2,53	2,65	2,78	2,92	3,09	3,27
3000 MAH Battery Life (days)	1,6	1,67	1,74	1,81	1,89	1,98	2,08	2,19	2,31	2,45
2000 MAH Battery Life (days)	1,07	1,11	1,16	1,21	1,26	1,32	1,39	1,46	1,54	1,63

Table 5.1 Results for Arduino and GPRS shield prototype (1)

Time in Active Mode (min)	10	5	4	3	2	1	0,5	0,25	0,05	0
Total Current in Sleep Mode(mAmp)	42	42	42	42	42	42	42	42	42	42
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode(min)	50	55	56	57	58	59	59,5	59,8	60	60
Average milli Amp hour consumption	48	45	44,4	43,8	43,2	42,6	42,3	42,2	42	42
6000 MAH Battery Life (days)	5,21	5,56	5,63	5,71	5,79	5,87	5,91	5,93	5,95	5,95
5000 MAH Battery Life (days)	4,34	4,63	4,69	4,76	4,82	4,89	4,93	4,94	4,96	4,96
4000 MAH Battery Life (days)	3,47	3,7	3,75	3,81	3,86	3,91	3,94	3,95	3,97	3,97
3000 MAH Battery Life (days)	2,6	2,78	2,82	2,85	2,89	2,93	2,96	2,97	2,97	2,98
2000 MAH Battery Life (days)	1,74	1,85	1,88	1,9	1,93	1,96	1,97	1,98	1,98	1,98

Table 5.2 Results for Arduino and GPRS shield prototype (2)

The results indicate that with this prototype the power consumption is not optimized. Majority of the electrical power is being used by the arduino platform itself and has no contribution in running of the processor or the cellular access module. The extra power being consumed by the Arduino platform is too large when compared to the power being consumed by the processor in active and sleep mode. Hence, with a battery capacity of 6000 mAH and active time of close to negligible, the system can last only for six days. With such a setup, the low currents of the processor during the sleep mode are rendered inconsequential because of the very large current being consumed by the Arduino platform.

5.2 Arduino+GPRS modem

In this version of the prototype, we have used the USB host shield, a USB modem and Arduino UNO platform. The Arduino UNO platform is used run the microcontroller and the USB model is used to provide cellular access. In this model, we use SMS as the way to provide information to the external system. There is no provision of switching off the USB modem as the size of electronic circuitry on the USB host is too small for manual addition of a mosfet switch for complete turn off of USB modem. However, in our results, we will assume that the USB modem is turned off.

Time in Active Mode (min)	60	55	50	45	40	35	30	25	20	15
Total Current in Sleep Mode(mAmp)	38	38	38	38	38	38	38	38	38	38
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	40	40	40	40	40	40	40	40	40	40
Total Current in Active Mode	48	48	48	48	48	48	48	48	48	48
Time in Sleep Mode	0	5	10	15	20	25	30	35	40	45
MAH	48	47,2	46,3	45,5	44,7	43,8	43	42,2	41,3	40,5
6000 MAH Battery Life (days)	5,21	5,3	5,4	5,49	5,6	5,7	5,81	5,93	6,05	6,17
5000 MAH Battery Life (days)	4,34	4,42	4,5	4,58	4,66	4,75	4,84	4,94	5,04	5,14
4000 MAH Battery Life (days)	3,47	3,53	3,6	3,66	3,73	3,8	3,88	3,95	4,03	4,12
3000 MAH Battery Life (days)	2,6	2,65	2,7	2,75	2,8	2,85	2,91	2,96	3,02	3,09
2000 MAH Battery Life (days)	1,74	1,77	1,8	1,83	1,87	1,9	1,94	1,98	2,02	2,06

Table 5.3 Results for Arduino and GPRS modem prototype (1)

Time in Active Mode (min)	10	5	4	3	2	1	0,5	0,25	0,05	0
Total Current in Sleep Mode(mAmp)	38	38	38	38	38	38	38	38	38	38
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	40	40	40	40	40	40	40	40	40	40
Total Current in Active Mode	48	48	48	48	48	48	48	48	48	48
Time in Sleep Mode	50	55	56	57	58	59	59,5	59,8	60	60
MAH	39,7	38,8	38,7	38,5	38,3	38,2	38,1	38	38	38
6000 MAH Battery Life (days)	6,3	6,44	6,47	6,49	6,52	6,55	6,56	6,57	6,58	6,58
5000 MAH Battery Life (days)	5,25	5,36	5,39	5,41	5,43	5,46	5,47	5,48	5,48	5,48
4000 MAH Battery Life (days)	4,2	4,29	4,31	4,33	4,35	4,37	4,38	4,38	4,39	4,39
3000 MAH Battery Life (days)	3,15	3,22	3,23	3,25	3,26	3,28	3,28	3,29	3,29	3,29
2000 MAH Battery Life (days)	2,1	2,15	2,16	2,16	2,17	2,18	2,19	2,19	2,19	2,19

Table 5.4 Results for Arduino and GPRS Modem prototype (2)

The results of this prototype are very similar to the previous one. The inability of the Arduino platform to turn its components off during the sleep mode of the processor causes the battery to discharge at a fast rate. The current consumed by the Arduino platform is large in the sleep mode. Therefore, the maximum amount of battery life that can be achieved is around seven days. This amount of battery life is inconsequential when compared to the targets of the research work.

5.3 Breadboard processor unit+GPRS shield

In this prototype, the microcontroller setup is built on a breadboard. All the current consuming components of the Arduino UNO platform which are not required for the overall operation of the prototype are taken out. The GPRS shield is turned off and on using the digital pins of the microcontroller. The GPRS shield is used for cellular access to post data on the internet.

Time in Active Mode (min)	60	55	50	45	40	35	30	25	20	15
Total Current in Sleep Mode(mAmp)	11	11	11	11	11	11	11	11	11	11
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode	0	5	10	15	20	25	30	35	40	45
MAH	78	72,4	66,8	61,3	55,7	50,1	44,5	38,9	33,3	27,8
6000 MAH Battery Life (days)	3,21	3,45	3,74	4,08	4,49	4,99	5,62	6,42	7,5	9,01

5000 MAH Battery Life (days)	2,67	2,88	3,12	3,4	3,74	4,16	4,68	5,35	6,25	7,51
4000 MAH Battery Life (days)	2,14	2,3	2,49	2,72	2,99	3,33	3,75	4,28	5	6,01
3000 MAH Battery Life (days)	1,6	1,73	1,87	2,04	2,25	2,5	2,81	3,21	3,75	4,5
2000 MAH Battery Life (days)	1,07	1,15	1,25	1,36	1,5	1,66	1,87	2,14	2,5	3

Table 5.5 Results for breadboard processor unit and GPRS shield prototype (1)

Time in Active Mode (min)	10	5	4	3	2	1	0,5	0,25	0,05	0
Total Current in Sleep Mode(mAmp)	11	11	11	11	11	11	11	11	11	11
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode	50	55	56	57	58	59	59,5	59,8	60	60
MAH	22,2	16,6	15,5	14,4	13,2	12,1	11,6	11,3	11,1	11
6000 MAH Battery Life (days)	11,3	15,1	16,2	17,4	18,9	20,6	21,6	22,2	22,6	22,7
5000 MAH Battery Life (days)	9,4	12,6	13,5	14,5	15,7	17,2	18	18,5	18,8	18,9
4000 MAH Battery Life (days)	7,52	10,1	10,8	11,6	12,6	13,8	14,4	14,8	15,1	15,1
3000 MAH Battery Life (days)	5,64	7,54	8,08	8,71	9,45	10,3	10,8	11,1	11,3	11,4
2000 MAH Battery Life (days)	3,76	5,03	5,39	5,81	6,3	6,88	7,21	7,39	7,54	7,57

Table 5.6 Results for breadboard processor unit and GPRS shield prototype (2)

This prototype has significantly improved results when compared to the previous two versions. The improvements have been due to the inclusion of breadboard design instead of the Arduino platform. The breadboard model consumes lower current in sleep and active modes. However, still the current is relatively large when compared the current of the processor itself in the sleep mode. With this configuration, the maximum battery life of almost 23 days can be achieved.

5.4 Regulated complete turn off model

This prototype is very similar to the breadboard processor unit and GPRS shield. However, it has the additional ability to completely switch off the cellular access module. Therefore, in the sleep mode, the electronics module is able to cut off voltage to the cellular access module. This provides further improvements in current consumption scenario. The voltage being fed by the power module is regulated with the use of voltage regulator.

Time in Active Mode (min)	60	55	50	45	40	35	30	25	20	15
Total Current in Sleep Mode(mAmp)	3	3	3	3	3	3	3	3	3	3
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode	0	5	10	15	20	25	30	35	40	45
MAH	78	71,8	65,5	59,3	53	46,8	40,5	34,3	28	21,8
6000 MAH Battery Life (days)	3,21	3,48	3,82	4,22	4,72	5,35	6,17	7,3	8,93	11,5
5000 MAH Battery Life (days)	2,67	2,9	3,18	3,52	3,93	4,46	5,14	6,08	7,44	9,58
4000 MAH Battery Life (days)	2,14	2,32	2,54	2,81	3,14	3,57	4,12	4,87	5,95	7,66
3000 MAH Battery Life (days)	1,6	1,74	1,91	2,11	2,36	2,67	3,09	3,65	4,46	5,75
2000 MAH Battery Life (days)	1,07	1,16	1,27	1,41	1,57	1,78	2,06	2,43	2,98	3,83

Table 5.7 Results for Regulated complete turn off model (1)

Time in Active Mode (min)	10	5	4	3	2	1	0,5	0,25	0,05	0
Total Current in Sleep Mode(mAmp)	3	3	3	3	3	3	3	3	3	3
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode	50	55	56	57	58	59	59,5	59,8	60	60
MAH	15,5	9,25	8	6,75	5,5	4,25	3,63	3,31	3,06	3
6000 MAH Battery Life (days)	16,1	27	31,3	37	45,5	58,8	69	75,5	81,6	83,2
5000 MAH Battery Life (days)	13,4	22,5	26	30,9	37,9	49	57,5	62,9	68	69,4
4000 MAH Battery Life (days)	10,8	18	20,8	24,7	30,3	39,2	46	50,3	54,4	55,5
3000 MAH Battery Life (days)	8,06	13,5	15,6	18,5	22,7	29,4	34,5	37,7	40,8	41,6
2000 MAH Battery Life (days)	5,38	9,01	10,4	12,3	15,2	19,6	23	25,2	27,2	27,7

Table 5.8 Results for Regulated complete turn off model (1)

This prototype shows considerable improvements form the previous breadboard based version. The main improvements are from the reduction of current consumption due to complete switch off for the cellular access module. In this module, the maximum amount of battery life has been increased to eighty three days. This shows the multiplicative effect on the battery times when the current consumption of the overall system is brought closer to the current consumption of processor in the sleep mode.

5.5 Non-regulated complete turn off model

This is the prototype with the minimum current consumption. The voltage regulator is removed and the power module provides the voltage and current directly to the microcontroller module. In all other ways, this prototype is similar to the regulated complete turn off model.

Time in Active Mode	60	55	50	45	40	35	30	25	20	15
Total Current in Sleep Mode	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode	0	5	10	15	20	25	30	35	40	45
MAH	78	71,5	65,1	58,6	52,2	45,7	39,3	32,8	26,3	19,9
6000 MAH Battery Life in days	3,21	3,49	3,84	4,26	4,79	5,47	6,37	7,62	9,49	12,6
5000 MAH Battery Life	2,67	2,91	3,2	3,55	3,99	4,56	5,31	6,35	7,91	10,5
4000 MAH Battery Life	2,14	2,33	2,56	2,84	3,19	3,65	4,25	5,08	6,33	8,39
3000 MAH Battery Life	1,6	1,75	1,92	2,13	2,4	2,73	3,18	3,81	4,75	6,29
2000 MAH Battery Life	1,07	1,16	1,28	1,42	1,6	1,82	2,12	2,54	3,16	4,19

Table 5.9 Results for Non regulated complete turn off model (1)

Time in Active Mode	10	5	4	3	2	1	0,5	0,25	0,05	0
Total Current in Sleep Mode	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
Current in Active Mode(Processor)	8	8	8	8	8	8	8	8	8	8
Current in Active Mode (Cellular Module)	70	70	70	70	70	70	70	70	70	70
Total Current in Active Mode	78	78	78	78	78	78	78	78	78	78
Time in Sleep Mode	50	55	56	57	58	59	59,5	59,8	60	60
MAH	13,4	6,96	5,67	4,38	3,08	1,79	1,15	0,82	0,56	0,5
6000 MAH Battery Life in days	18,6	35,9	44,1	57,1	81,1	140	218	304	443	496
5000 MAH Battery Life	15,5	29,9	36,8	47,6	67,6	116	182	253	369	414
4000 MAH Battery Life	12,4	24	29,4	38,1	54,1	93	145	203	295	331
3000 MAH Battery Life	9,32	18	22,1	28,6	40,5	69,8	109	152	221	248
2000 MAH Battery Life	6,21	12	14,7	19	27	46,5	72,7	101	148	165

Table 5.10 Results for Non regulated complete turn off model (2)

In this module, the further enhancement of non-regulated power supply yields improvements. The current consumption in the sleep mode goes below one milli-Ampere and that provides a multiplicative effect on the battery life. The removal of voltage regulator provides a current improvement of more than three milli-Amperes. However, it may not be recommended to use the system without a voltage regulator. The maximum amount of battery life achieved from this system can be 496 days.

5.6 Comparative analysis

Current consumption

The current consumption analysis shows similar results when compared with the battery life. The two graphs below show the sharp reduction in current consumption for all the bread board versions of the prototypes. The reduction of current is also relatively sharp for the prototype of Arduino+GPRS shield. This is due to the fact that GPRS shield can turn itself off during the sleep mode.

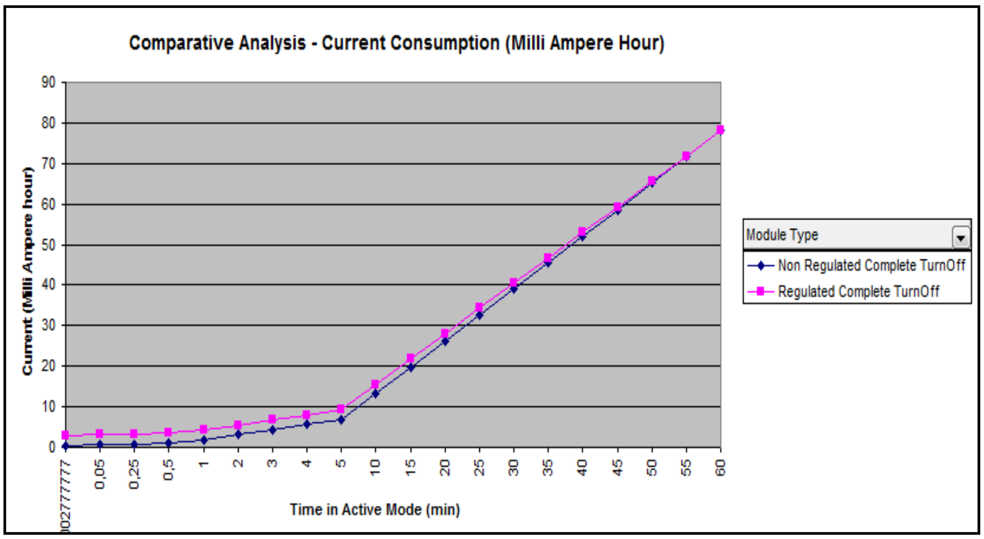

Figure 5.1 Current consumption Analysis (1)

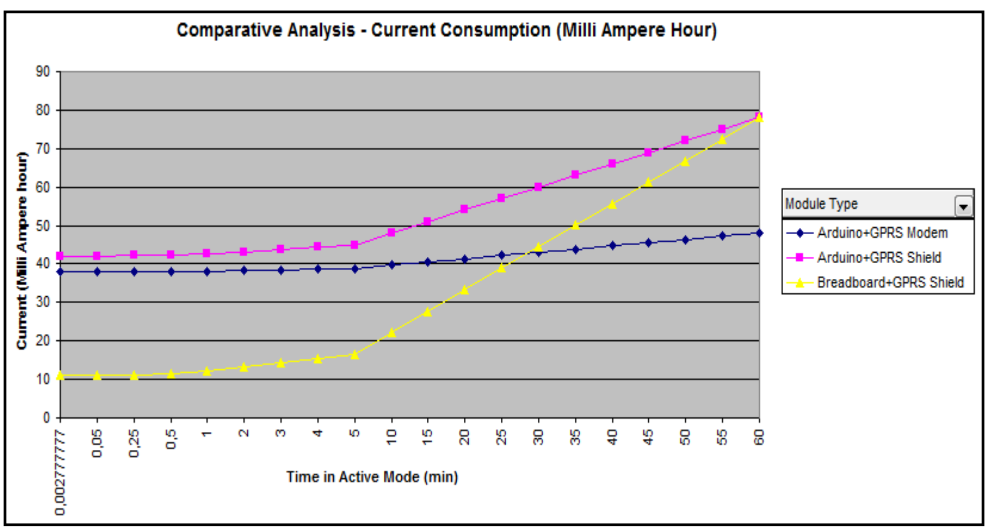

Figure 5.2 Current consumption Analysis (2)

Battery life

The curves for battery life are very similar to the current consumptions. The multiplicative effect of reduced current consumption on the battery life can clearly be observed. The effect is more evident in the prototypes which use breadboard as the system bases. The battery life is significantly improved in the latter two prototype versions which include complete turn off capabilities.

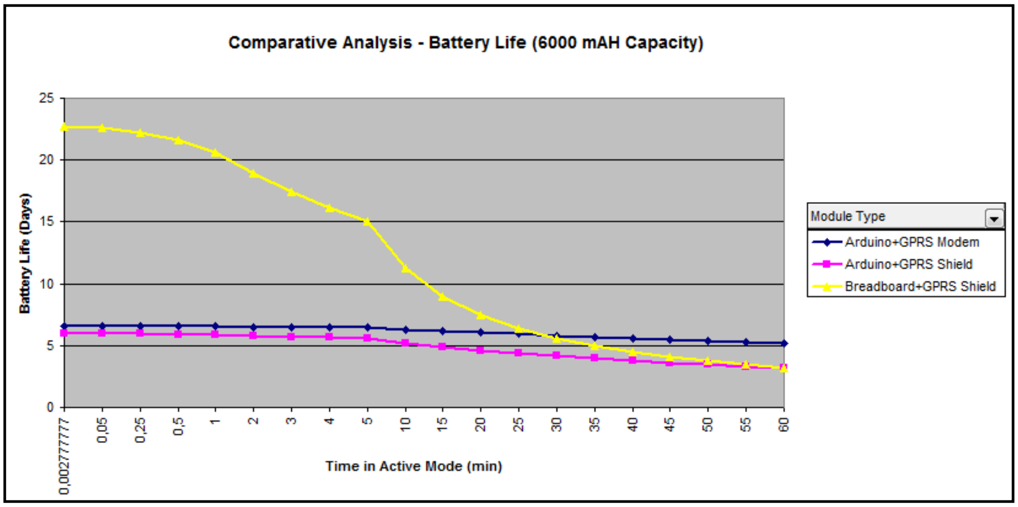

Figure 5.3 Battery life comparison (1)

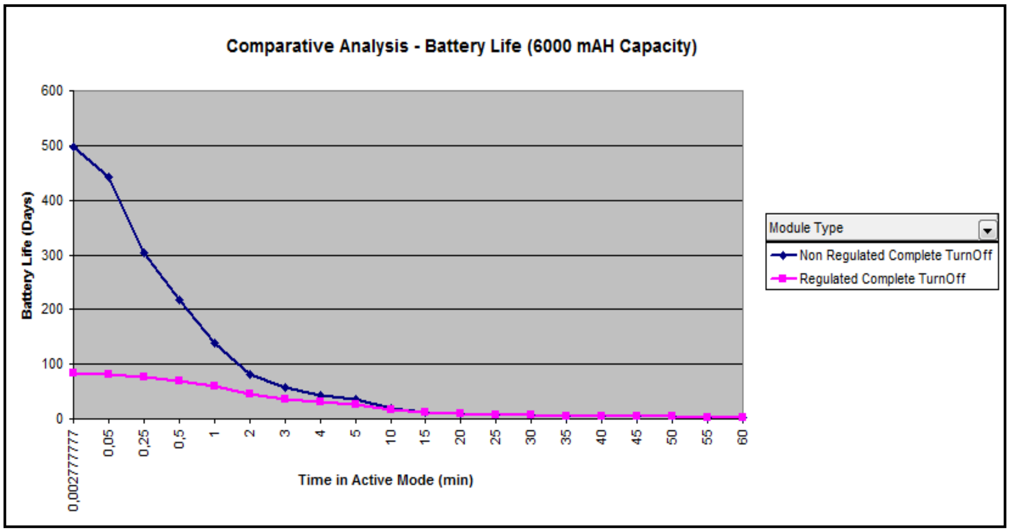

Figure 5.4 Battery life comparisons (2)

5.7 Analysis using electrical energy measurements

The results with electrical energy measurements include the impact of operating voltage for the system. Our system has an operational voltage of five volts. However, in order to ensure system stability, all the models except for non-regulated version use a nine volt battery with specific milli ampere hour capacity. The results for the consumption of electrical energy are very similar to the previous results with a difference for the case of non-regulated prototype. In the case of non-regulated voltage, we can use a battery of voltage between 5-5.5 volts and hence the electrical energy consumption goes significantly down. The below mentioned result are calculated by using 5.5 input voltage for the non-regulated prototype. The use of lower voltage clearly shows improved results and the expected amount of battery time is around three years. This is a significant improvement from the earlier considered models.

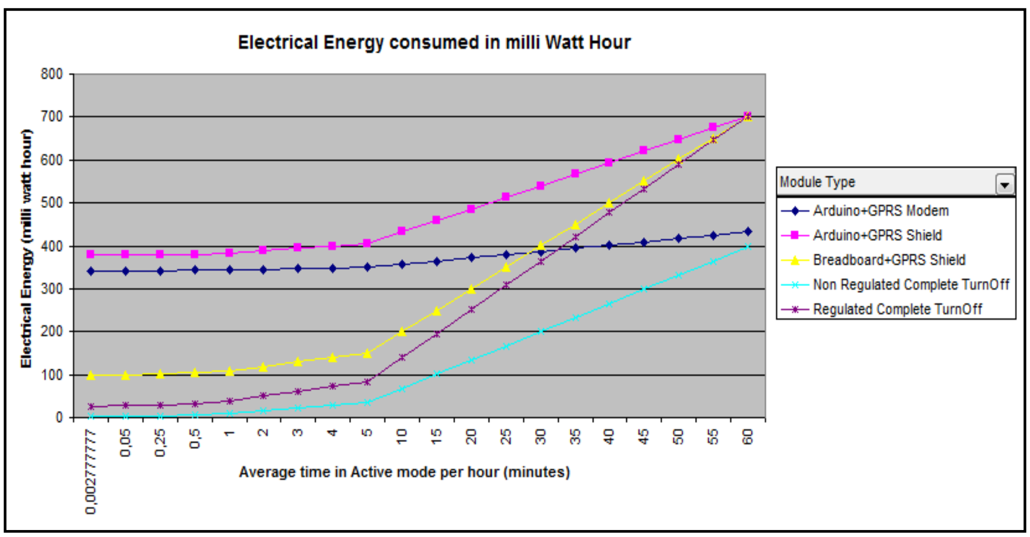

Figure 5.5 Electrical Energy Comparison

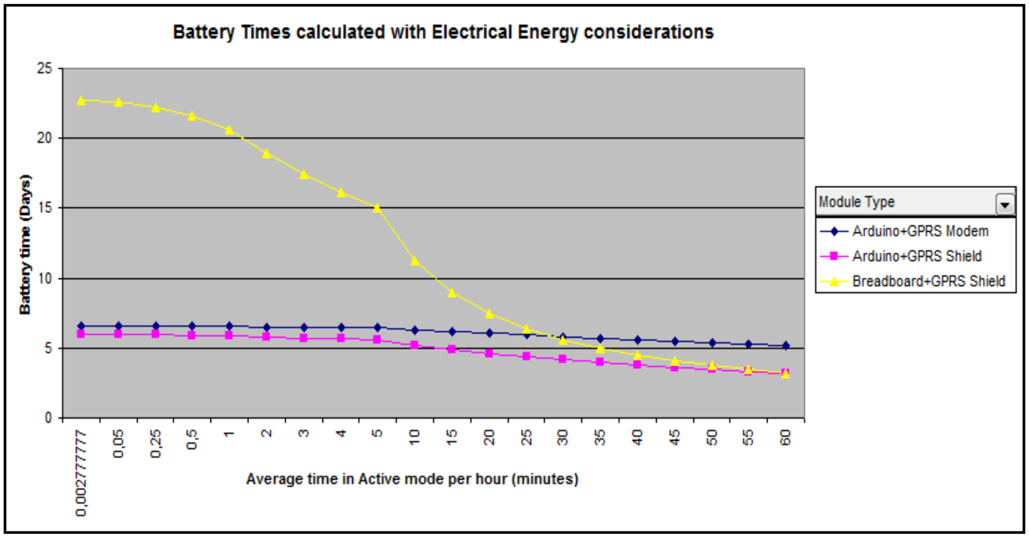

Figure 5.6 Electrical energy and battery life (1)

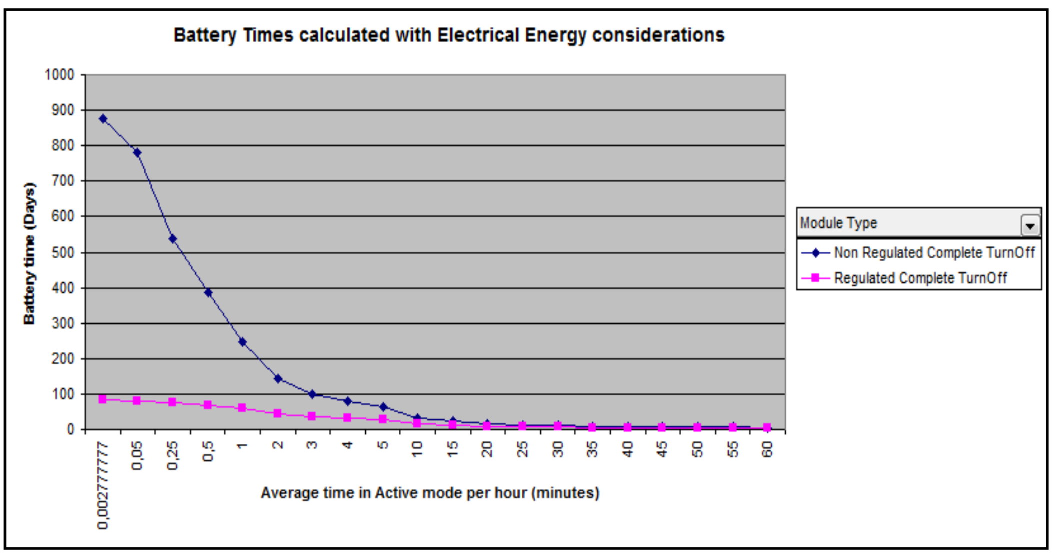

Figure 5.7 Electrical energy and battery life (2)

6 Discussion and conclusions

The results clearly show that two of the prototypes with complete turn off capability can provide battery times of more than three months. If we use a voltage regulator with the power unit, then we can achieve a battery life time of up to three months. However, by removing the voltage regulator, our prototype runs at minimal current and has a battery life of around 500 days. Therefore, with a suitable sized solar panel, we can provide the required amount of harvested energy. Without considering the natural degradation of components, we can safely say that the developed prototype can be self-sufficient for its energy supplies for even a decade.

The M2M prototype that we have developed is a sensor platform that can be used for any type of sensor to update data on the web platform. Based on a wake up strategy, this platform can last for a decade using energy conservation techniques as described above and solution of energy harvesting for recharging the battery.

There is however, the need to understand the impact of duty cycle on the achievable battery times. The results are based on a very small duty cycle i.e. the system goes in to the active mode only twice on a daily level. However, in order to improve the system performance in scenarios, where we need larger duty cycles, can be significantly affected. The time spent in communication with the cellular network has the largest part of consumed electrical energy. To improve system performance with larger duty cycles, the access network needs to be optimized to reduce the time required for the actions done during active mode.

In counties like Finland, where the direct sun light is minimum when compared to some other areas of the world, the prototype faces the biggest challenge of energy harvesting. However, since we have battery life of almost three months with the power regulated system, it is expected that the average sun light available would enable the system to recharge and last for the desired time before component replacement is necessary. Of course with countries having sun light for a major part of the year, there shall be no significant challenge for the prototype to recharge the batteries.

The idea of a sensor platform with battery life time in terms of years is hence proved feasible and practical. Taking the data of direct sunlight observed in Finland given in [31] and solar panel calculations of [32] , the approximation of available battery power proves that the our prototype can last for years. The current technology of microelectronics and wireless access modules are sufficient to develop M2M devices which can have battery times in the range of years. This in turn can pave for the deployment of M2M devices on a large scale. The future communication ecosystem is also being based on the explosion of data traffic and the large part of this traffic would be coming from the M2M devices. By reducing the amount of times we need to replace batteries, the fact of tens or hundreds of connected devices for each person can well and truly become a reality in the future.

For the large scale deployment of such platforms of sensor based systems; we need to consider the scenarios in which these M2M devices can be integrated in to the system. One such scenario which comes automatically in consideration is deployment of such devices in GSM networks. With the current trend of modernization of networks from 2G to 3G and LTE, it would be a better idea to propose a scenario in which our power saving prototype is deployed in a heterogeneous network.

6.1 Integration of M2M devices in heterogeneous networks

Heterogeneous networks consist of different Radio Access technologies to provide coverage and capacity in a cellular access network. The modern topology of heterogeneous network uses GSM as the coverage layers and WCDMA, HSPA and LTE are used to provide capacity and broadband access. Considering the low power requirements of the prototype, we will explore the scenarios where the prototype is deployed in the GSM layer or in the high capacity broad band access layer of WCDMA, HSPA or LTE.

The introduction of M2M devices in to the cellular network requires modifications on the packet core and also for the radio access end [33]. In [33], several ideas have been mentioned about the changes that can be made according to 3GPP standards. Considering these aspects and the overall functionality of radio access networks, we can look in to the scenario of integrating the M2M prototype. It is to be mentioned that we are considering only stationary M2M device and therefore some of the mobility management functions won't be considered.

Integrating in under laid GSM network layer

The devices such as the prototype in consideration are sleeping devices which wake up for a very short time during the whole day. However, the peak power and current being used during the active period can prove to be crucial in becoming a limiting factor in the overall battery life. The deployment of the M2M devices in GSM network can prove to be beneficial when we are considering large scale deployment. GSM or 2G networks have larger coverage areas and therefore, provide a way to cover remote areas with sensor networks and M2M devices. Moreover, the wireless access modules for 2G are cheap and available easily in the market. There have been products being introduced for 3G cellular access but the 2G products are readily available to be used with

M2M devices. In addition to the coverage benefits with 2G, also the bandwidth requirements for such sleep M2M devices go well with GPRS and edge which are provided by enhanced GSM networks.

The use of GPRS for the interaction with web server and the internet cloud is an essential aspect of power consumption by the M2M prototype in active mode. The procedures used for the data transfer using GPRS are as follows

- Attach
- PDP context Activation
- Data Transfer using respective protocol
- PDP context Deactivation

With our prototype, we de-attach the device from the network and then the complete shutdown is followed. The attach procedure includes the exchange of the user identity and the location of the device is then known by the network in the form of Routing area code and cell ID. This information is then used to assign the user to a particular SSGN which is used to transfer data to and from the M2M device. Once the attach procedure has been completed, then the PDP context is activated to begin the data service. In this phase, the QoS profile, peak data rates and other information is fetched by the network node and the next procedure is to start the data transfer. Once the data transfer has been completed, the device proceeds to deactivation of PDP context and de attaching and then goes to sleep.

The possible optimization which can result in further reduction of power consumption and increased battery times is reducing the time the M2M device takes to start data transfer. The process of attaching and activating PDP context takes place every time the device wakes up to update the data. A modification in the network functionality can be proposed to reduce this time for GPRS connections of the M2M device. In order reduce our scope, we can consider the stationary devices which more or less remain in the coverage area of a particular cell. A separate type of RACH channel or modification can be proposed so that the process of Attach and PDP context activation can take place quickly. An idea of stored BA list for the quick or forced cell selection can also lead to quicker attach to the network as we will have reduced time bypassing the basic cell reselection procedure. In short, research work is to be carried out for integration of M2M devices in to the cellular network and providing additional features to enhance power conservation of such devices. The main idea should be the reduction of signaling steps in connecting to the SSGN and activating the data connection.

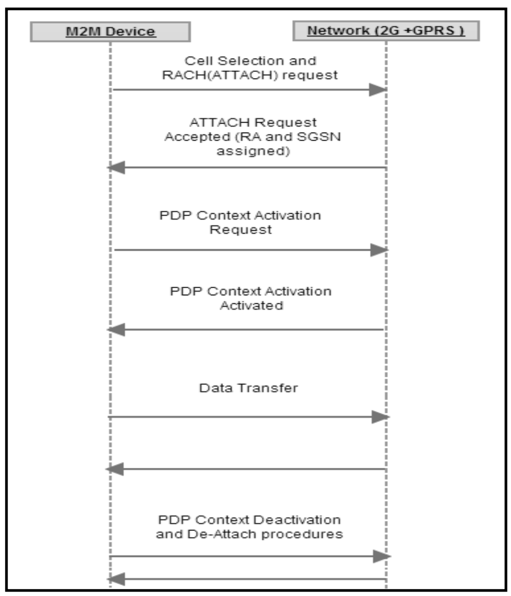

Figure 6.1 GPRS procedures

One drawback which can result from integrating or using 2G cellular access for M2M prototype is the large cell radius of 2G cells. Therefore, the power control mechanism and the selection of the power level of the modem during cell selection would lead to high power for the M2M device if it is located a further distance from the base station. The normal cell radius for 900 MHZ GSM can be in the range of kilometers and therefore high power from the

M2M device may be required to perform the required cellular access procedures.

In [33], a detailed analysis has been provided for the comparison of link and reliability performance. According to this analysis, Unstructured Supplementary Service Data (USSD) provides the best performance. However, GPRS also shows better performance when used with coding scheme 2 and other improved features. This link performance can then later dictate the power being used by the M2M device to communicate with cellular network.

Integrating in overlaid LTE network layer

LTE networks are mostly suited for the M2M devices which require higher data rate and require broad band access. However, with the small cell radius for this layer of the radio network, the power required for the M2M device would be lower as compared with GSM M2M devices.

The integration of M2M devices in LTE network poses a significant challenge on the uplink scheduling mechanism of LTE [34]. In order to send uplink data, the user has to first send scheduling requests on the uplink. Once the schedule grant has been received from the Radio base station, only then the uplink data can be mapped on to the radio bearer. The time taken to get the uplink scheduling grants becomes important for the application which use mostly uplink for data transfer and have no significant traffic for download data [34]. In [35], a number of new proposed models have been discussed which can used to cope with large scale deployment of M2M devices in LTE.

With the expected growth of M2M devices and communication, research work is being conducted to develop optimized scenarios for conserving power. LTE uses OFDMA on the physical layer. A power efficient MAC scheme for OFDMA with M2M devices has been discussed in [35]. Grouping of M2M devices and then using a single relay M2M device for communication with the network can provide energy efficiency. Such a scheme requires careful selection of the M2M device groups and the relay node or device [35]. The use of LTE for M2M is also faced with challenges such as terminal cost, interoperability with legacy devices, power consumption and mobility [36]. Enhancement of DRX cycle for the LTE networks can also provide substantial gains in terms of power efficiency [37]. The results in [37] are very encouraging and provide an insight in to the importance of power efficient modes. The results can be related with sleepy sensor platforms as it also uses deterministic intervals for active and idle mode activity.

The developed prototype with minimal power consumption is easily integrated in to the GSM network. With the addition of LTE cellular access device, the prototype can be incorporated in to a LTE network.

7 Future work

The successful implementation and development of power efficient M2M device provide an insight in the extent of battery life that can made possible with current technology. However, there can be improvements in many aspects for which future work would be required

The power consumption of M2M devices is directly dependent on the type of usage. There are two major categories for that

- Devices with very high duty cycle
- All time sleepy devices with small active period

Active devices refer to the devices which do not perform a complete shutdown of the system. In fact, they perform data transfers and then go in to idle mode. For the devices with all active modes, we need to optimize the radio access and also the protocols being used to send to and received data from the network. For the radio network procedures, work is required in optimizing and proposing a modified solution which deals with the increased amount of M2M traffic and ensures that the devices are using minimal power. The possible research fields can be optimizing the performance in heterogeneous networks, use of adaptive discontinuous transmission cycles, network planning for M2M devices and power control mechanism to reduce device power. Radio resource management techniques should also be studied in detail to adapt them for M2M asymmetric and symmetric traffic. Reduction of time in attaching and using the network to send data can also lead to better performance. Moreover, research can be conducted for the data transmission protocols and to reduce transmission power. The idea of using constrained application protocol (COAP) can be implemented in the cellular domain to reduce the time required to send and receive the data.

For the M2M devices which are mostly sleeping such as the prototype, the techniques of reducing the transmit power, total time of setting up the communication can lead towards better performance. Therefore, research and work can be done for constrained application protocol, reduction of time in attached and activation procedures with radio access network. Any work towards improvement of electronics, battery performance and solar panels would also yield a better and stable system.

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