“Design of a Wireless Monitoring System Based on the ZigBee Protocol for Photovoltaic Systems”

A Thesis submitted for the degree of

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ABSTRACT

This work deals with the possibility of using the promising technology of wireless sensor networks (WSN) in the field of photovoltaic (PV) plant supervising and monitoring. The knowledge of the status and good working condition of each PV module separately as well as of any component of the PV system will guide in a more efficient way of power management.

This work will concentrate on monitoring and controlling as well as healthy operation control of PV panels separately. Data logging will be also available and can be used for reference or statistical purposes.

The nature of wireless sensor networks (WSN) offers several advantages on monitoring and controlling applications over other traditional technologies including self-healing, self-organization, and flexibility.

The versatility, ease of use, and reliability of a mesh network topology offered by the ZigBee technology that is based on the IEEE 802.15.4 standard, are used in this work to offer the maximum of its capabilities on the system being presented. A set of sensors attached on each PV panel are connected to a wireless ZigBee module. Each PV panel has its own ZigBee device located at its back side. All ZigBee devices forms a network with all the necessary devices of the ZigBee protocol included, such as end devises (RFD), a router (FFD), and a coordinator (COO).

An extra ZigBee device might optionally be used to serve the whole system as an Ethernet gateway for making the system able to be connected to the internet.

The factors that are being monitored are the panel’s temperature, the output voltage, and output current.

At the router device that operates as a parent for all the end devices, extra monitored factors are the air dust concentration, current irradiance and also the angle of the PV array (in the case of tracking system use).Two controlling outputs (relays) are located at the router device offering the capability of controlling the motors or the actuators of a tracking system.

Table of contents

List of figures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

.

Appendix

List of tables

Acronyms and Abbreviations

A	*Ampere*
AC	*Alternating Current*
ADC	*Analog to Digital Converter*
AES	*Advanced Encryption Standard*
ALE	*Address Latch Enable*
AMI	*Advanced Metering Infrastructure*
AODV	*Ad-hoc On Demand Vector*
AP	*Access Point*
APL	*Application Support Layer*
APS	*Application Support*
APS	*Asynchronous Power Save*
ARIB	*Association of Radio Industries and Business*
ASCII	*American Standard Code for Information Interchange*
ASK	*Amplitude Shift Keying*
BAN	*Body Area Network*
BB	*Base Band*
BER	*Bit Error Rate*
BPSK	*Binary Phase Shift Keying*
BR	*Basic Rate*
CAN	*Campus Area Network*
CAP	*Contention Access Period*
CCA	*Clear Channel Assessment*
CFP	*Contention Free Period*

CH	*Cluster Header*
CID	*Cluster ID*
CLK	*Clock*
COO	*Coordinator*
CSMA-CA	*Carrier Sense Multiple Access with Collision Avoidance*
CTA	*Channel Time Allocation*
DC	*Direct Current*
DD	*Designated Device*
DEV	*Data Device*
DPST	*Double Pole Single Through*
DQPSK	*Differential Quadrature Phase Shift Keying*
DSPS	*Device Synchronized Power Save*
ECU	*Electronic Control Circuit*
EDR	*Enhanced Data Rate*
EEPROM	*Electrically Erasable ROM*
EIRP	*Equivalent Isotropically Radiated Power*
ESD	*Electrostatic Sensitive Device*
ETS	*European Telecommunication Standard*
FCS	*Frame Check Sequence*
FER	*Frame Error Rate*
FFD	*Full Function Device*
FHSS	*Frequency Hopping Spread Spectrum*
FM	*Frequency Modulation*
GPIO	*General Purpose Input Output*
GSM	*Global System for Mobile communications*
GTS	*Guaranteed Time Slot*
GUI	*Graphic User Interface*
HCI	*Host Control Interface*
HCS	*Header Check Sequence*
I/O	*Input Output*
I^2C	*Inter-Intergraded Circuit (serial bus protocol)*
IC	*Intergraded Circuit*
IEEE	*Institute of Electrical and Electronic Engineers*
ISM	*Industrial Scientific Medical*
Kw	*Kilowatt*
KWh	*Kilowatt per Hour*
LAN	*Local Area Network*
LC	*Link Controller*
LDO	*Low Drop Out*
LDR	*Light Depended Resistor*
LED	*Light Emitting Diode*
LLC	*Logical Control Layer*
LM	*Link Manager*
LQI	*Link Quality Indicator*
mA	*miliAmpere*
MAC	*Medium Access Control*
MAN	*Metropolitan Area Network*
MCTA	*Management Channel Time Allocation*
MMPT	*Maximum Power Point Tracking*

mV	*milliVolt*
Mw	*Megawatt*
nA	*nanoAmpere*
NWK	*Network*
OEM	*Original Equipment Manufacturer*
OSI	*Open System Interconnection*
PAN	*Personal Area Network*
PC	*Personal Computer*
PCB	*Printed Circuit Board*
PHY	*Physical*
PLME	*Physical layer management entity*
PNC	*Piconet Coordinator*
PNID	*Piconet ID*
POS	*Personal Operating Space*
PR	*Precision Rectifier*
PPP	*Point to Point Protocol*
PSPS	*Piconet Synchronized Power Save*
PV	*Photovoltaic*
PVAS	*PV Area Sector*
PWM	*Pulse Width Modulation*
QAM	*Quadrature Amplitude Modulation*
QoS	*Quality of Service*
QPSK	*Quadrature Phase Shift Keying*
REMB	*Remote Board*
RF	*Radio Frequency*
RH	*Relative Humidity*
RREQ	*Request*
RSSI	*Received Signal Strength Indicator*
SAN	*Storage Area Network*
SAP	*Service Access Point*
SCADA	*Supervisory Control And Data acquisition*
Si	*Silicon*
SIF	*Serial Interface*
SMD	*Surface Mount Devices*
SMPS	*Switch Mode Power Supply*
SMT	*Surface Mount Technology*
SNR	*Signal to Noise Ratio*
SSCS	*Service Specific Convergence Sublayer*
TCM	*Trellis Coded Modulation*
TDD	*Time Division Duplex*
TTL	*Transistor-Transistor Logic*
UART	*Universal Asynchronous Receive Transmit*
UPS	*Uninterruptable Power Supply*
USB	*Universal Serial Bus*
V	*Volt*
VCO	*Voltage Controlled Oscillator*
VOC	*Open Circuit Voltage*
$V_{p\text{-}p}$	*Peak to Peak Voltage*
W	*Watt*
WAN	*Wide Area Network*

WAP	*Wireless Application protocol*
Wh	*Watthour*
WiFI	*Wireless Fidelity*
WLAN	*Wireless Local Area Network*
WPAN	*Wireless Personal Area Network*
ZDO	*ZigBee Device Object*
ZR	*ZigBee Router*

Chapter 1

Introduction

1.1 Overview

Only a small part of the electric energy production in Europe comes from photovoltaic energy systems. The aim of the European Union is to reach the threshold of 20% of the overall energy production to come from reusable energy resources.

Monitoring a PV plant has a great impact on its efficiency. Even for small PV plants, regular performance checks on the functioning are necessary for a reliable use and successful integration. Monitoring for large PV systems is performed by specially designed hardware and software that might be expensive and is mainly operated by specially trained personnel. For small PV systems up to 5KW, these checks are not performed due to monitoring system costs [63]. Therefore small systems are often not checked on a regular basis. This situation can lead to partial energy losses that usual originate from partial system faults or decreasing performance that can be unnoticed for a long time. Thus, in order to achieve the maximum energy out of a PV plant, a low-cost, easy to use monitoring system is needed.

A system that monitors the state of a Photovoltaic plant in real time and simultaneously controls the energy production procedure may help to improve power management issues and thus the entire system energy production efficiency.

Monitoring and control of the status of a PV area is a matter that can be implemented with a variety of ways like SCADA and Eibus.

Developing a monitoring and control system using the ZigBee technology will be an alternative proposal to the already widely used and also reliable systems such as SCADA and Eibus. Major advantages of the ZigBee system versus the other are the low market and building cost, the systems hardware simplicity, the very low power consumption, and the advanced reliability.

Although ZigBee uses a wireless network to operate, its reliability trends to be very high. As already known the ZigBee protocol is almost invulnerable to noisy environments like industrial.

1.2 Scope of Thesis – Goal of the work

- The main goal of this Thesis is to examine the possibility of making ZigBee a suitable technology in the field of monitoring and controlling systems in the continuously growing market of PV solar energy systems.
- The aim is to study the ZigBee protocol as well as other wireless technologies and how each of them works. Routing strategies will also be discussed.
- To see the working of mess networking supported by the ZigBee protocol.
- To present the designing and development phases of the hardware-software parts of the system.
- To give some basic results and measurements.
- To provide all the vital information about system working behavior.

1.3 Related work

A lot of research has been done and a variety of applications based on the ZigBee protocol has been developed. The ease of use of the ZigBee protocol stack makes it a simple but also a reliable solution in a wide field of electronic applications such as telemetry, monitoring, wireless sensing, tracking, security, health services and many others.

1.4 Structure of the Thesis

Chapter 2 is dedicated to a general theoretical background. Herein an overview of network technologies and topologies is given.
Chapter 2 also describes different short range wireless technologies solutions like IEEE 802.15.1, IEEE 802.15.2, IEEE 802.15.3, IEEE 802.15.4, as well as ZigBee.
The ZigBee protocol will be discussed in more detail.

Chapter 3 introduces in some detail the photovoltaic system basics and gives an initial knowledge about the necessity of monitoring a photovoltaic plant.

Chapter 4 gives reader a first simple “view” of the system. Its basic function is given here with a presentation of block diagrams. Describes the hardware part of the project. Presents a general description of the ZigBee modules used in this work and it is divided it three major sectors. The first part contains a detailed description of the system’s ZigBee coordinator (COO) construction. The second part has a good description of the system’s ZigBee router (ROUT) and the third part gives a description of the ZigBee end devices (ZED). Brief reference about sensors is also included.

The total reliability, stability and functionality health are presented in **Chapter 5**. All the hardware (devices, pcb’s and peripherals) are checked for their ability to operate normally and form a wireless network that will be able to carry out all the monitored parameters. Measurements and results are also included in this chapter.

Chapter 6 draws the conclusions from the thesis and suggests possible further implementations.

Appendix A contains all the vital information concerning the GUI software as well as the firmware developed for the ZigBee devices.

Chapter 2

Theoretical background

2.1 Local networks

As known a network is a connection of computers (and/or) devices connected to each other. The need of data transferring from a computer or a device to another and the massive progress in data communication had led to the development of various network types, topologies and communication protocols.

2.2 Types of networks

One way to categorize the different types of computer network designs is by their scope or scale. The networking industry refers to nearly every type of design as some kind of area network. Some examples of area network types are:

- LAN - Local Area Network
- WLAN - Wireless Local Area Network
- WAN - Wide Area Network
- MAN - Metropolitan Area Network
- SAN - Storage Area Network, System Area Network, Server Area Network, or sometimes Small Area Network
- CAN - Campus Area Network, Controller Area Network, or sometimes Cluster Area
- PAN – Personal Area Network
- BAN – Body Area Network
- DAN – Desk Area Network

- A **LAN** (Local Area Network) is a network that connects devices at a relatively short distance. (Connection is done with the use of a media like wire or optic fibre). A networked office building, school, or home usually contains a single LAN, though sometimes one building will contain a few small LANs and occasionally a LAN will span a group of nearby buildings.

- A **WAN** (Wide Area Network) is two or more LAN that is connected together over a wide geographic area. This may be networks located across town, across a state, across a country or across the world.

- A **WLAN** (Wireless local area network) is a type of a LAN that uses high frequency radio waves (or even a laser beam) rather than wire or optic fiber to achieve communication between different nodes. WLAN is a flexible communication system, because it can be used as an expansion of a wired LAN, or even as an alternative solution, in order not to be used a wired LAN. WLANs transmit and receive data over the air, by using electromagnetic waves. Thus, WLANs combine data connectivity with user mobility and through a simplified configuration enable movable LANs. The radius of coverage for a typical WLAN system is up to 150m, but it can be increased by adding APs. Although this range can be increased when high gain directional antennas are used. APs connect wired and wireless networks together.

- A **MAN** (Metropolitan Area Network) typically covers an area of between 5 and 50 km diameter. Many MANs cover an area in the size of a city, although in some cases MANs may be as small as a group of buildings.

- A **CAN** (Campus Area Network) is generally a network spanning multiple LANs but smaller than a MAN, such as on a university or local business campus. But there is also the CAN-bus type that is a serial protocol that is also a type of network used specially in automotive applications (and must not be confused with that of computer communications) for control and monitoring of the ECUs (Electronic Control Unit) of a car or truck.

- A **PAN** (Personal Area Network) consists of a dynamic group of less than 255 devices that communicate within about a 10m range. Unlike with wireless LANs, only devices within this limited area typically participate in the network, and no online connection with external devices is defined. One device is selected to assume the role of the controller during wireless PAN initialization, and this controller device mediates communication within the WPAN. The controller broadcasts a beacon that lets all devices synchronize with each other and allocates time slots for the devices. The detailed function of this type of network is going to be further discussed in this chapter.

- **BAN** (Body Area Network) is a limited range network and it is used for medical purposes like health monitoring. This network consists of various types of wireless sensors attached in the human body.

2.3 Basic Network Topologies

Network topology is the arrangement of the elements of a network. These elements are nodes or links. When two computers or devices are connected directly through a link then this topology is called peer-to-peer and is the simplest topology of all. The most wide spreading topologies are

-The BUS topology
-The RING topology
-The STAR topology
-The TREE topology
-The Mesh topology

In Bus topology (Figure 2-1) the base stations are connected to a common shared physical mean. The frames that are being sent by a base station go through the physical mean (wire, optic fiber) and then directly to the other base station or to the base stations. A necessary requirement in order to reach the right frame the right base station is to have the specific address of that specific base station.

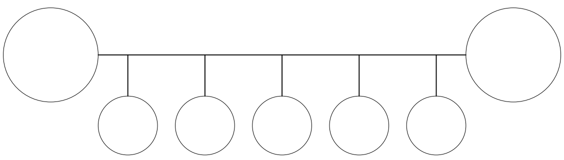

Figure 2-1: The Bus topology [6].

In Ring topology (Figure 2-2) there is a close way of the natural mean and all the base stations connected sequentially. All the frames are transmitted to every base station in proportion to their destination address. The information’s flow is only one-way.

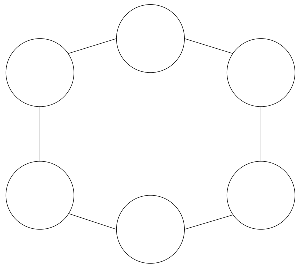

Figure 2-2: The ring topology [6].

In Star topology (Figure 2-3) all the base stations are connected to a central service unit. The network's reliability depends on this unit. The frames that this unit sends to all the other base stations must have a destination address. This topology can expand, if extra service units added.

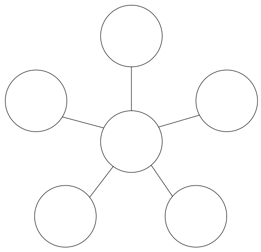

Figure 2-3: The Star topology [6].

The Tree (Figure 2-4) topology is a generalization of the Bus topology. A tree topology combines characteristics of linear bus and star topologies. It consists of groups of star-configured workstations connected to a linear bus backbone cable. Tree topologies allow for the expansion of an existing network.

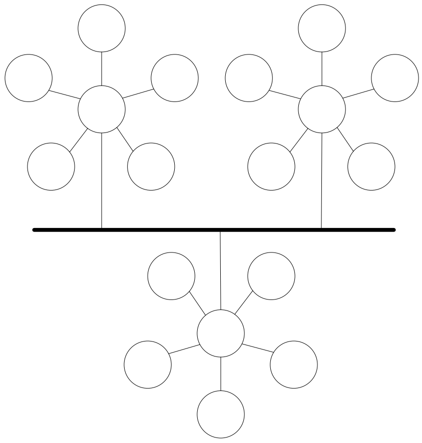

Figure 2-4: The Tree topology [6].

In a mesh topology, (Figure 2-5) in contrast to the tree topology, there are no hierarchical relationships. Any device in a mesh topology is allowed to attempt to contact any other device either directly or by taking advantage of routing-capable devices to relay the message on behalf of the message originator. In mesh topology, the route from the source device to the destination is created on demand and can be modified if the environment changes. The capability of a mesh network to create and modify routes dynamically increases the reliability of the wireless connections. If, for any reason, the source device cannot communicate with the destination device using a previously established route, the routing-capable devices in the network can cooperate to find an alternative path from the source device to the destination device [6]. This is clarified further in the route discovery and maintenance subsections.

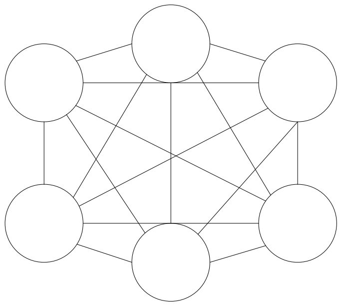

Figure 2-5: The mesh topology [6].

Finally there are some other types of topologies which are the result of the combination of the previous topologies. These are:

-The Star-Bus topology

-The Star-Ring topology

2.3.1 WLAN Topologies

The main existing topologies are two that are the independent and the infrastructure. The simplest WLAN topology is the independent, (Figure 2-6) which connects a pair of PCs with wireless adapters. There is no necessity of having AP (Access Point) here, because it's about a peer-to-peer connection but if an AP exists, it only acts as a repeater, in order to extend the range of the existing network.

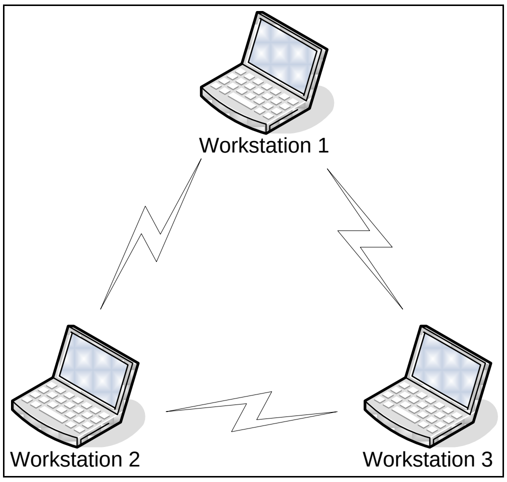

Figure 2-6: An independent WLAN.

The infrastructure WLAN topology (Figure 2-7) is more complex. Multiple APs link the WLAN to the wired network and allow users to efficiently share network resources. Through APs, all communications take place. APs apart from controlling communications with the workstations belonging to them, takes also care of communications with all the other APs in the network.

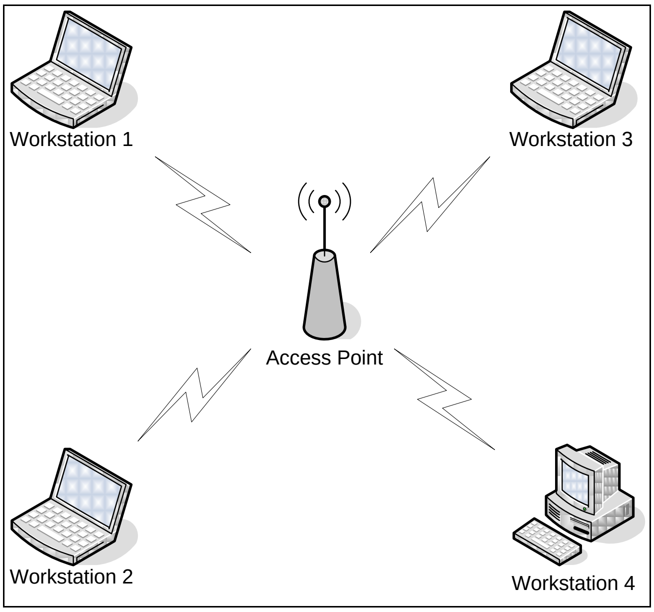

Figure 2-7: An infrastructure WLAN.

2.4 Sort range wireless technologies

Among others, there are four commonly used sort range wireless technologies. a) The IEEE 802.15.1 (Bluetooth), b) The IEEE 802.15.3 designed for High Rate WPANs, c) The IEEE 802.15.4 designed for Low Rate WPANs, and d) The ZigBee. Each one has advantages and disadvantages over the others in regard of power consuming, and data rate and also each of them has its own field of applications. The next chapters are dedicated in a brief description.

2.5 The IEEE 802 working groups

There are many major working groups of the IEEE part that exists. As for example: a) The IEEE 802.1.xx that is a higher layer LAN protocols working group, b) The 802.11.xx that is a WLAN working group, c) The 802.15.xx, that is a group for WPANs and d) The 802.20.x MWBA (Mobile Wireless Broadband Access) working group and others. Each working group is divided into groups called task groups. In the 802.15.x working group, four task groups are available [11], [12]. These are:

a) TG1, 802.15.1/Bluetooth
b) TG2, 802.15.2 Coexistence
c) TG3, 802.15.3 WPAN High Rate
d) TG4, 802.15.4 WPAN Low Rate

2.6 IEEE 802.15.1 (Bluetooth)

2.6.1 Overview of the 802.15.1 protocol

This standard defines services and protocol elements that permit the exchange of management information between stations associated in a wireless personal area network (WPAN) [1]. As mentioned above, WPANs are used to transfer data over short distances through an RF (Radio frequency) link (see chapter 2.2).

Unlike WLANs, a connection through a WPAN needs no or little infrastructure, a fact that allows the implementation of small inexpensive low powered applications [1].

2.6.2 General description

Physical and also MAC (Medium Access Control) layers are defined in this subsection for portable and moving devices (within an area of 10m) [1].

The IEEE 802.15.1 uses an RF link that is optimised for battery operated, lightweight, small size devices. The RF link operates in the unlicensed ISM (Industrial Scientific Medical) band at 2400MHz (from 2400MHz to 2483.5MHz). Interference, noise and fading are avoided using frequency hopped transceivers operating in the same band using the spread spectrum technique (FHSS). The modulation is binary FM (Frequency modulation) for reduced transceiver circuitry complexity. The transmitting/receiving frequency changes 1600 times/sec across 79 frequencies in the ISM band. Frequency hopping follows a pseudo-random order as each data packet is transmitted, thus each packet is transmitted on a different frequency [1].

Full duplex transmission is achieved with the use of TDD (Time Division Duplex) technique. Data as well as voice can be supported by the IEEE 802.15.1. The data rates supported are 1Mb/sec in the BR mode (Basic Rate) and also 2Mb/sec or even 3Mb/sec in the EDR (Enhanced Data Rate) mode. Voice can be broadcasted at a rate of 64Kbps [1].

2.6.3 The IEEE802.15.1 protocol stack

As shown in figure 2-8, the hierarchy of the stack layers beginning from the lower layer is:

-The physical channel

-The physical link

-The logical link

-The L2CAP channel

Non Bluetooth specific protocols are also included like the PPP (Point-to-Point Protocol) and WAP (Wireless Application Protocol). A brief description of the protocol stack follows.

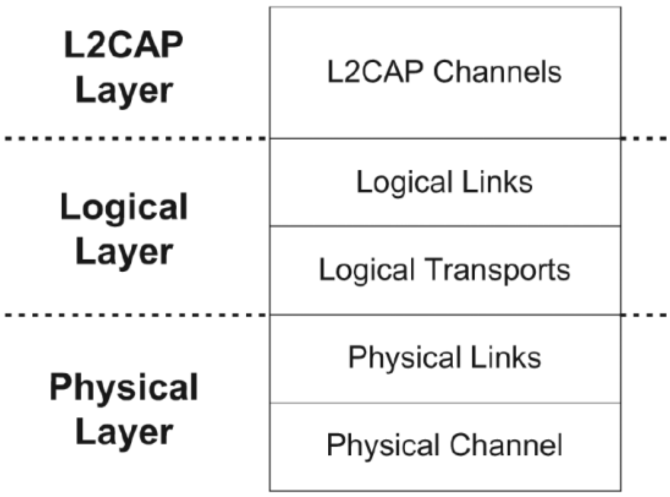

Figure 2-8: IEEE802.15.1 protocol stack layer [1].

In figure 2-9 the four lowest segments of the stack are shown. These segments part the core system architecture. The lowest three segments parts a subsystem called the controller.

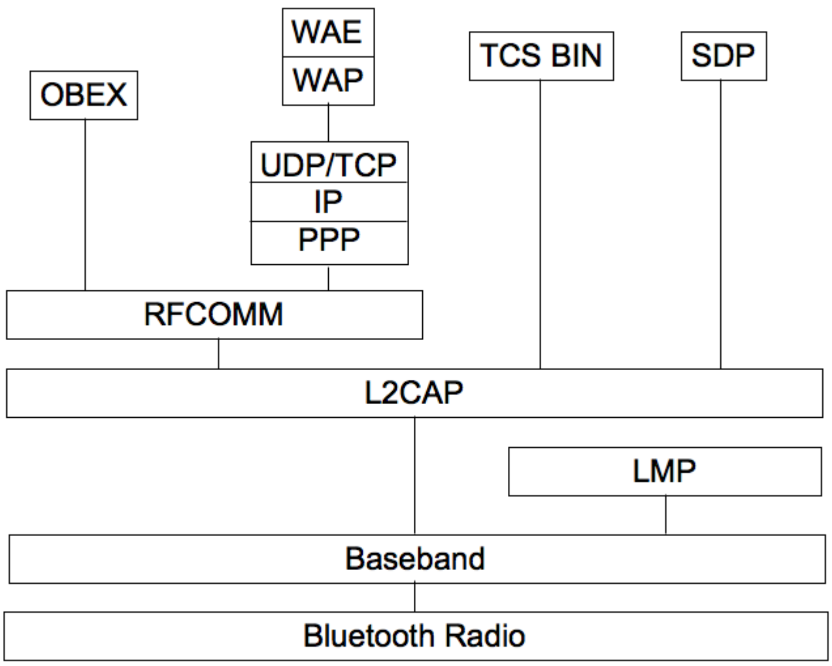

Figure 2-9: The IEEE.802.15.1 protocol stack [1].

Above of the Bluetooth radio layer the BB (Baseband) layer is located. The baseband protocol acts as a link controller (LC). The link controller is connected with the Link Manager to provide link level routing like link connection and power control.

The LCP (Link Control Protocol) is managed directly from the link controller (LC). LC also encodes and decodes the Bluetooth packets.
The LM (Link Manager) creates and modifies the logical link. Other protocols are carried out by the LM like link setup and link configuration.
The L2CAP layer is located over the BB protocol. It provides data services to the upper layers protocols, with protocol multiplexing capabilities.
The HCI (Host Controller Interface) provides a command interface between the BB and the LM as well as access to control registers and hardware status [1].

2.6.4 Newer versions of the Bluetooth

A newer version of Bluetooth is now available. This is the Bluetooth V2.0. It is also compatible with older Bluetooth devices (Bluetooth V.1.1) and it can support data rates up to 10Mbps. Even lower power consumption has been achieved in this new version as well as an even better BER (Bit Error Rate).

2.6.5 Network topology

The simplest topology for Bluetooth devices is the piconet. This topology supports point-to-point or a point-to-multipoint connection (figure 2-10).

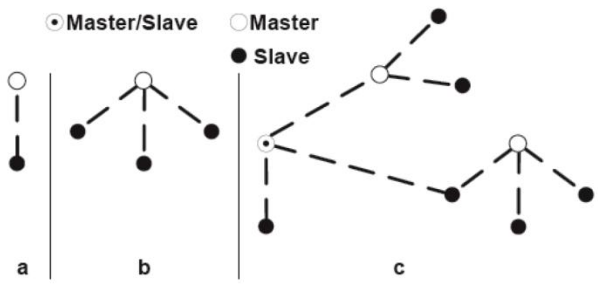

Figure 2-10: The piconet network topologies. a) Point-to-point connection (single slave operation), b) point-to-multipoint connection (multislave operation), c) scatter net operation [1].

Two or more devices sharing the same physical channel can form a piconet. Each device can be (depend on the application) a master or a slave. Only one master device can exist on a piconet while all the other devices are the slaves. However a slave can be a part of a different piconet, as well as a master may be a slave for other piconets. Up to seven slaves are permitted to be active in the piconet. Each piconet has its own hoping sequence (see chapter 2.6.2). A piconet is synchronized by the clock of the master device. The slave devices adjust their clocks with a timing offset in order to match the master's clock.

2.6.6 Power classification

A three level power classification classifies each device.

Power class	Maximum output power (P_{max})	Nominal output power	Minimum output power (P_{min})	Power control
1	100 mW (20 dBm)	N/A	1 mW (0 dBm)	P_{min}<+4 dBm to P_{max} Optional: P_{min}[a] to P_{max}
2	2.5 mW (4 dBm)	1 mW (0 dBm)	0.25 mW (–6 dBm)	Optional: P_{min}[a] to P_{max}
3	1 mW (0 dBm)	N/A	N/A	Optional: P_{min}[a] to P_{max}

[a]The lower power limit P_{min}<–30dBm is suggested, but is not mandatory, and may be chosen according to application needs.

Table 2-1: The available power classes as given by the IEEE [1].

As shown in table 2-1, there are three power classes. Power class 1 is used where larger connection distances between Bluetooth devices are needed. A Bluetooth 'hands free' device uses power class 3. Although these three power classes there is an optional capability of variation of the transmitted power level for a device.

2.6.7 About security

The transmission technique of Bluetooth (FHSS), (see chapter 2.6.2) provides a good level of security. This is because the Bluetooth radio system uses the fast frequency hopping technique and it does not operates in a fixed frequency in the 2.4GHz band but the frequency is changing 1600times/sec with a pseudo-random sequence.

Four entities are used for security at the link level. These are:

a) A unique 48-bit address for each Bluetooth device.

b) A private encryption key that is 8-128bits in length used for encryption.

c) A private authentication key that is 128bits in length

d) A 128 bit random or pseudo-random number that is produced by the Bluetooth device.

2.7 The IEEE 802.15.3

2.7.1 Overview

The IEEE802.15.3 is a standard designed for real time distribution of multimedia contents like music, video and still imaging through a WPAN, providing QoS (Quality of Service). The main goals of this standard is too provide low complexity, low cost, low power consumption and high data rates connectivity among devices within a WPAN [2]. The data rates supported are high enough (>20Mb/sec).

The standard is intended for home multimedia wireless networks.

2.7.2 General description

As mentioned in chapter 2.6.3, a piconet is the simplest form of a WPAN. As defined previously, a piconet is a wireless ad-hoc data communication system which allows a number of data devices (DEVs) to communicate with each other. A piconet is distinguished from other types of data networks in that communications are normally confined to a small area around person or object that typically covers at least 10m in all directions and envelops the person or a thing whether stationary or in motion [2].

As already defined in chapter 2.2 about other types of networks like LAN, MAN, WAN, each of which covers a large geographic area, a piconet is always operating in a small area around a person or object that covers typically 10m in all directions [1].

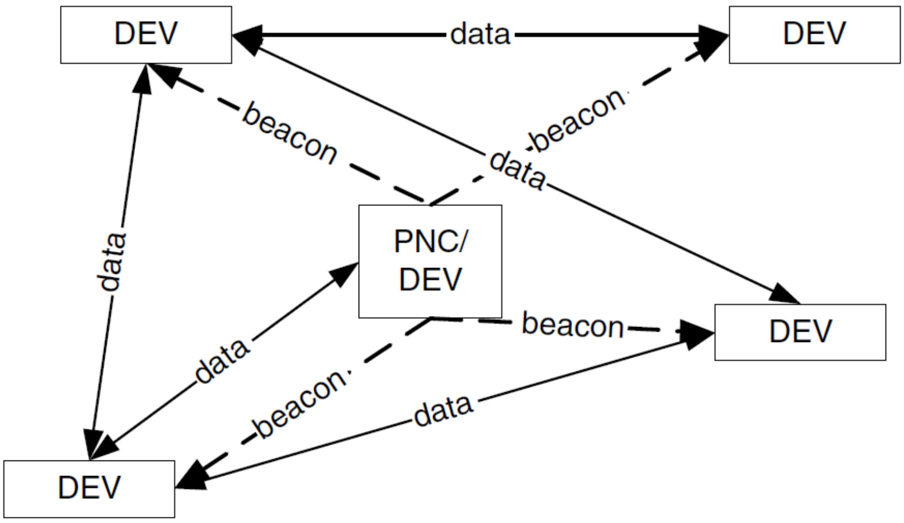

Figure 2-11: Some DEVs in a piconet [2].

The basic component of a piconet is the DEV (Figure 2-11). A DEV is a device equipped with all necessary circuitry e.g. radio, some kind of microcontroller and firmware. One DEV can become the piconet coordinator (PNC). This device forms and starts the network, provides timing for it, manages the (QoS), manages the power save modes and access to the piconet. A DEV can be able to form a subsidiary piconet. The original piconet is called then (the parent piconet) and the subsidiary called a child or a neighbor piconet.

2.7.3 Child piconet

A child piconet is one that is formed under an established piconet. The functionality of a child piconet is useful for coverage area extension or shifting of some computation or memory requirements to another PNC. The child piconet has its own ID (PNID). As the child piconet is a part of the parent piconet, it is capable to exchange data with any DEV in the parent piconet [2].

2.7.4 Neighbor piconet

A neighbor piconet is also formed under an established piconet. This functionality of a piconet is used when there are no available channels. This is done by sharing the frequency spectrum between different piconets. As with the child piconet, a neighbor piconet has its own ID (PNID) but unlike the child piconet, the neighbor piconet PNC is not a member of the parent piconet and thus does not exchange data with any DEV in the piconet [2].

2.7.5 PHY layer

The PHY layer operates in the 2.4GHz band (2400MHz-2483.5MHz) and there are is a total of 5 channels available. The Physical layer of the IEEE.802.15.3 supports up to five modulation formats (Table 2-3) with coding at 11Mbaud.

CHNL_ID	Center frequency	High-density	802.11b coexistence
1	2.412 GHz	X	X
2	2.428 GHz	X	
3	2.437 GHz		X
4	2.445 GHz	X	
5	2.462 GHz	X	X

Table 2-2: 2.4GHz PHY channel map [2].

The first set of channels is the high-density mode which allocates 4 channels while the second is an IEEE802.11b co-existence mode which allocates 3 channels.

2.7.6 Network establishment

In order for a piconet to be established, a DEV that is capable to operate as a PNC begins to transmit beacons. The first action is to scan all available channels to find one that is not in noise. When the appropriate channel found then the PNC starts the piconet by sending the beacons.

2.7.7 Modulation compliance

An 802.15.3-compliant DEV shall, at a minimum, support DQPSK modulation. In addition, if an 802.15.3 DEV supports a given modulation format other than DQPSK, it shall also support all of the lower modulation formats. For example, if an 802.15.3 implementation supports 32-QAM, it shall also support 16-QAM and QPSK-TCM as well as the DQPSK modulation formats [2].

Modulation type	Coding	Data rate
QPSK	8-state TCM	11 Mb/s
DQPSK	none	22 Mb/s
16-QAM	8-state TCM	33 Mb/s
32-QAM	8-state TCM	44 Mb/s
64-QAM	8-state TCM	55 Mb/s

Table 2-3: Modulation, coding and data rates for the IEEE802.15.3 PHY layer [2].

2.7.8 Transmitting power

Table 2-4 shows the maximum output power of a DEV. A compliant transmitter that is capable of transmitting more than 0dBm must be capable to reduce its power to less than 0dBm in monotonic steps no smaller than 3db and no higher than 5dB. The minimum power level required to support TPC (Transmit Power Control) is 0dBm [2].

Geographical Region	Power limit	Regulatory document
Japan	10 mW	ARIB STD-T66
Europe (except Spain and France)	100 mW EIRP 10 mW/MHz peak power density	ETS 300-328 [B1]
USA	50 mV/m at 3 m in at least a 1 MHz resolution bandwidth*	47 CFR 15.249

*Electric field strength measurement rather than conducted power measurement.

Table 2-4: Maximum transmit power levels [2].

A compliant DEV may use any transmit power level up to the applicable limits in the geographical region.

2.7.9 Basic receiver specifications

As for any transceiver system, some basic receiver specifications like the receiver's sensitivity, the maximum input level, the RSSI (Receiving Signal Strength Indicator) and LQI (Link Quality Indicator) are presented here.

2.7.10 Receiver sensitivity

The receiver sensitivity is the minimum power level of the incoming signal, in dBm, present at the input of the receiver for which the error rate criterion is met. The error ratio shall be determined after any error correction has been applied. Compliant systems may have a lower actual sensitivity than the reference sensitivity.

Modulation	Reference sensitivity
QPSK-TCM	–82 dBm
DQPSK	–75 dBm
16-QAM-TCM	–74 dBm
32-QAM-TCM	–71 dBm
64-QAM-TCM	–68 dBm

Table 2-5: Sensitivity levels for different type of modulation [2].

A compliant DEV shall achieve at least the reference sensitivity listed in table above for each of the modulation formats that the DEV supports.

2.7.11 Maximum input level

The receiver maximum input level is the maximum power level of the incoming signal, in dBm, present at the input of the receiver for which the error rate criterion* is met. A compliant receiver shall have a receiver maximum input level of at least –10 dBm for each of the modulation formats that the DEV supports [2].

(* The error rate criterion shall be a frame error rate (FER) of less than 8% with a frame payload length of 1024 octets of pseudo-random data generated with a PN23 sequence as defined by xn+1= xn23 + xn5 + 1).

(PN is Pseudo-random noise sequence of binary numbers which appears to be random but is in fact deterministic).

2.7.12 Receiver RSSI

RSSI is defined as the power relative to the maximum receiver input power level, (as described in 11.6.3 of the of IEEE802.15.3 standard), in 8 steps of 8 dB with +/– 4 dB step size accuracy. The range covered shall be a minimum of 40 dB. The steps shall be monotonic [2].

2.7.13 LQI (Link Quality Indicator)

The link quality indication (LQI) shall be reported for the TCM (Trellis coded modulation) coded QAM modes using an SNR estimation.

The SNR shall be measured at the decision point in the receiver. The SNR includes the thermal noise, distortion, uncorrected interference and other signal impairments at the decision point in the receiver. The receiver shall report the SNR as a 5-bit number that covers a range from 6 dB to 21.5 dB of SNR.

2.7.14 Power management

As defined previously, one of the main goals of the IEEE802.15.3 standard is to achieve long operation time for battery powered DEVs. The best method seems to be turning off the DEVs completely or reducing power for long periods of time where a long period is relative to the superframe duration. The 802.15.3 provides three techniques to enable DEVs to turn off for one or more superframes. These are:

a) PSPS (Piconet-Synchronized Power Save) mode.
b) DSPS (Device Synchronized Power Save) mode.
c) APS (Asynchronous Power Save) mode.

A DEV can be operated in one of these three modes plus the active mode where the DEV is always awake.

- In PSPS mode a DEV is allowed to sleep at intervals defined by the PNC. A request can be sent from the DEV to the PNC when the first wants to enter the PSPS mode. All DEVs operating in the PSPS mode are required to listen to the system wake beacons.
- DSPS mode is designed to enable groups of DEVs to sleep for multiple superframes but still be able to wake up during the same superframe.
- APS mode allows a DEV to conserve power for extended periods until the DEV chooses to listen for a beacon. The only responsibility of a DEV in APS mode is to communicate with the PNC before the end of its ATP (Association Time Period) in order to preserve its membership in the piconet.

Transmitted power in a piconet is possible to be controlled. This fact enables a Dev to minimize interference with other wireless networks that share the same channel. Two methods are allowed for controlling the transmitted power:

- The first method allows the PNC to set a maximum transmit power for the CAP (Contention Access Period), beacons and MCTAs (Minimum Contour Tracking Algorithm).
- The second method allows DEVs using a CTA (Channel Time Allocation) to request increasing or decreasing of the transmit power of the DEV.

2.7.15 Security

The IEEE802.15.3 standard provides a symmetric cryptography mechanism to assist in providing security services. Additional security services need to be provided by the higher layers to ensure proper management and establishment of the symmetric keys used in this standard. Two different modes of security are available: Security mode 0 and security mode 1 [2].

When operating in security mode 0, a DEV shall not perform any cryptographic operation on MAC frames.

When operating in security mode 1, a mechanism is provided to perform cryptographic security on frames transmitted in the piconet. This standard supports the protection of beacon and data frames using a 128-bit AES (Advanced Encryption Standard) security [2].

2.8 The IEEE802.15.4 Low-Rate

2.8.1 Overview

The IEEE802.15.4 LR is a standard defined by the IEEE, for interconnection of devices through an RF (Radio Frequency) link, in a low rate WPAN.

An LR-WPAN is a low rate wireless PAN with a minimum data rate of 250Kbps (depending on the operating frequency and modulation mode used), low cost, limited power and relaxed throughput requirements.

The main goals of this standard are a reasonable battery life, ease of installation, reliable data transfer and short range operation. The standard discussed here concern the newest version of the IEEE802.15.4 (2006) edition. This version is backward-compatible to the first (2003) edition. Thus, devices conforming to this standard are capable of joining and functioning in a PAN composed of devices conforming to the IEEE802.15.4-2003. As for the available frequencies and data rates there are 16 defined channels in the 2.4GHz ISM (Industrial Scientific Medical) band rated at 250 Kbps (Figure 2-12), 10 channels in the 915MHz band for data rates up to 40Kbps (Figure 2-13b), and 1 channel in the 868MHz band with a data rate of 20Kbps (Figure 2-13a). The use of these channels depends on each country regulations [4].

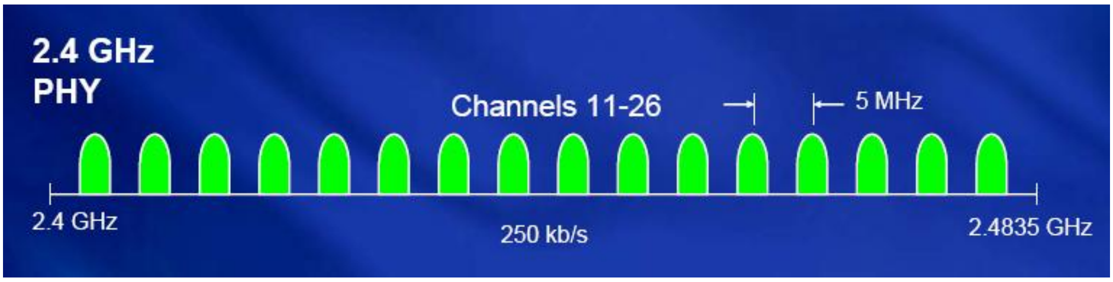

Figure 2-12: Available channels and data rate in the 2.4GHz ISM band [11].

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(a) (b)

Figure 2-13: Available channels and data rates for the 868MHz (a) and 915MHz (b) bands [11]

As shown in figures 2-12 and 2-13, there is a channel spacing of 5MHz and 2MHz (between the center frequencies) for the 2.4GHz and 915 MHz PHY respectively. The bandwidth (not shown) is 2MHz and 1MHz. For the 868MHz PHY the bandwidth is 600KHz.

2.8.2 Architecture

The IEEE802.15.4 LR (Low rate) WPAN is defined in terms of blocks (layers). This block layout is based on the OSI (Open System Interconnection) seven layer model.

As shown in figure 2-14 the main layers are the PHY (Physical) and MAC (Medium Access Controller) layer. The PHY layer contains the RF (Radio Frequency) transceiver along with its low level control mechanism. The MAC sublayer provides access to the physical channel for all types of transfer. The upper layers consist of a network layer which provides network configuration, manipulation and message routing, and an application layer which provides the intended functions of the device. The IEEE802.15.4 MAC layer provides to an 802.2 type1 LLC (Logical Control Layer) through the SSCS (Service-Specific Convergence Sublayer). The SSCS offers compatibility between different LLC sublayers and makes the MAC to be accessed through a set of access points.

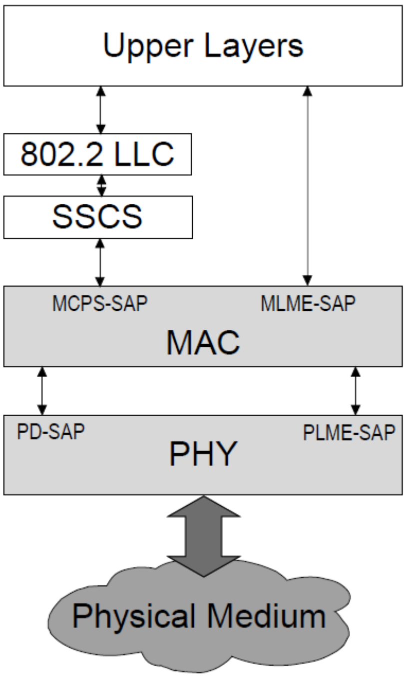


Figure 2-14: The IEEE802.15.4 LR-WPAN protocol stack [3].

2.8.3 The PHY (physical) layer

Two services provided by the PHY layer. The PHY data service and the PHY management service interfacing to the physical layer management entity (PLME) service access point (SAP) (known as the PLME-SAP). The PHY data service enables the transmission and reception of PHY protocol data units (PPDUs) across the physical radio channel [3].

The PHY is responsible for the following tasks:

- Activation and deactivation of the radio transceiver
- Energy detection (ED) within the current channel
- Link quality indicator (LQI) for received packets

- Clear channel assessment (CCA) for carrier sense multiple access with collision avoidance (CSMA-CA)
- Channel frequency selection
- Data transmission and reception

2.8.4 The MAC (Medium Access Layer)

As with PHY layer services, the MAC layer provides also the MAC data service and the MAC management service interfacing to the MAC sublayer management entity (MLNE) service access point (SAP). The MAC layer data service enables the transmission and reception of MAC protocol data units across the PHY data service [3]. The MAC sublayer handles all access to the physical radio channel and is responsible for the following tasks:

- Network beacons if the device is a coordinator
- Synchronizing to network beacons
- Supporting PAN association and disassociation
- Supporting device security
- Employing the CSMA-CA mechanism for channel access
- Handling and maintaining the GTS (Guaranteed Time Slots) mechanism
- Providing a reliable link between two peer MAC entities

2.8.5 Modulation modes supported

In addition to the 868/915MHz BPSK (Binary Phase Shift Keying) which is specified in the 2003 edition of the IEEE802.15.4 protocol, two optional high data rate PHY (physical layer) are specified.

- ASK (Amplitude Shift Keying) PHY supports data rates of 250Kbps in 868MHz and 914MHz bands which is equal to the 2.4GHz band PHY.
- The Q-PSK (Offset-Quadrature Phase Shift Keying) PHY offers a signaling scheme identical to that of the 2.4GHz band PHY for the 915MHz band and a data rate of 100Kbps for the 868MHz band.

Table 2-6 shows the supported data rates for different frequencies and modulation modes.

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
868/915 (optional)	868–868.6	400	ASK	250	12.5	20-bit PSSS
	902–928	1600	ASK	250	50	5-bit PSSS
868/915 (optional)	868–868.6	400	O-QPSK	100	25	16-ary Orthogonal
	902–928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

Table 2-6: Frequency bands and data rates [3].

In table 2-6, can be noticed that the IEEE.802.15.4 (868/915 MHz) can achieve the same bit rate with that of 2.4GHZ. In this thesis only the 2.4GHz band PHY is going to be discussed.

2.8.6 About modulation in the 2.4GHz band

The 2.4GHz band supports 250Kbps and uses the O-QPSK (Offset-Quadrature Phase Shift Keying) modulation technique. The data is first mapped into symbols (4 bits by 4 bits). The symbols are mapped into 32-bit long chips and then are modulated.

2.8.7 IEEE802.15.4 Network topologies

Two different topologies are available for an IEEE802.15.4 LR-WPAN to operate, the star topology and the peer-to-peer topology.

2.8.8 Star topology

In star topology, (Figure 2-15) communication is established between devices and a single central controller, the PAN coordinator (COO).
The coordinator is used to initiate, terminate, or route communication around the network. The pan COO serves the PAN as the primary controller. All devices that participate in the network must have a unique 64-bit address. The PAN COO is usually a mains powered device while all the rest devices are mostly battery powered.

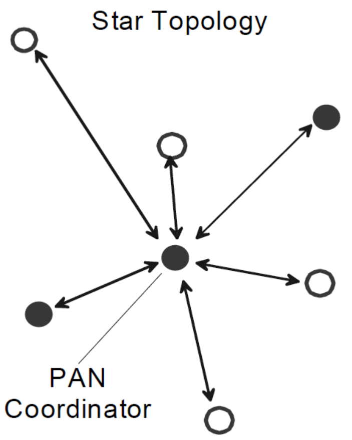


Figure 2-15: The star topology for the IEEE802.15.4 LR-WPAN [3].

While an FFD (Full Function Device) is activated it can form its own network and become the PANs coordinator. The COO names then this network with the PAN id number (PAN Identification Number). When this happens then the COO allows other devices to join the PAN.

2.8.9 Peer-to-Peer topology

In Peer-to-Peer topology (Figure 2-16) a PAN coordinator exists too. The main difference between Star and Peer-to-Peer topology is that here all devices can communicate with each other as long as they are in range of one another. More complex formations are allowed to be implemented in the Peer-to-Peer topology. A more complex topology is the mesh topology. This topology is going to be discussed in next chapter.

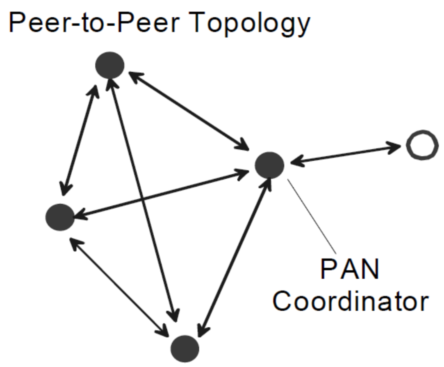


Figure 2-16: The Peer-to-Peer topology for the IEEE802.15.4 LR-WPAN [3].

Here too as with star topology, the first device that forms for the first time a PAN becomes the PAN coordinator. The main advantage of Peer-to-Peer networking against star is its self-organizing, self-healing capability.

2.8.10 Components of the IEEE802.15.4 LR-WPAN

The most basic components of this standard are the network devices. There are two types of devices in an IEEE802.15.4 LR-WPAN network. These are the RFD (Reduced Function Device) and the FFD (Full Function Device) see (Figure 2-17).

An FFD is almost taking the rule of the PAN coordinator. An FFD can be a coordinator and communicate with other FFDs or RFDs.

An RFD is the simplest device on the network as it is not necessary to receive or transmit large amounts of data. Thus an RFD can be build using minimum resources such as memory and microcontroller calculating power. RFD devices are commonly used in applications where data rates and amounts are not critical like sensor applications. The RFD device can talk only to an FFD. As IEEE802.15.4 network is part of the PAN family of standards although the coverage of the network may extend beyond the POS (Personal Operating Space), which typically defines the PAN.

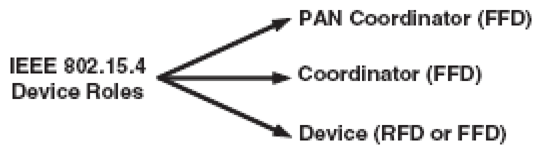


Figure 2-17: Device roles in the IEEE 802.15.4 LR-WPAN standard [6].

The wireless media has the disadvantage of propagation, deflection, scattering etc. Thus a well-defined coverage area does not exist. Small changes in position or direction may result in drastic differences in signal strength and quality of the communication link. [3].

2.8.11 Structure of the superframe

The IEEE802.15.4 LR WPAN standard allows the optional use of a superframe structure. The format of this superframe is defined by the coordinator (COO). The superframe is bounded by network beacons that are sent by the coordinator (COO) and is divided into 16 equally sized slots (Figure 2-18).

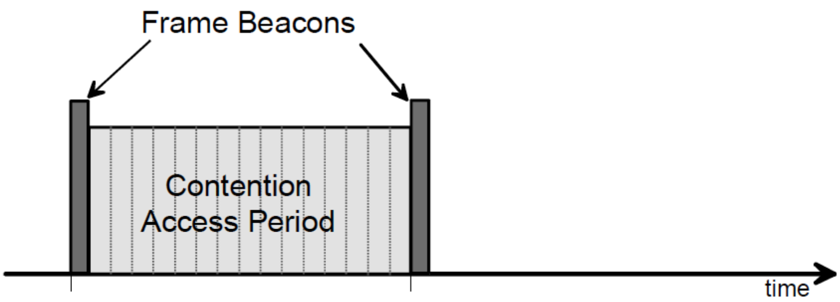


Figure 2-18: Superframe structure without GTSs [3].

Optionally the superframe may have an active and an inactive portion (Figure 2-19). During the inactive portion of the superframe the coordinator can enter a low power mode.

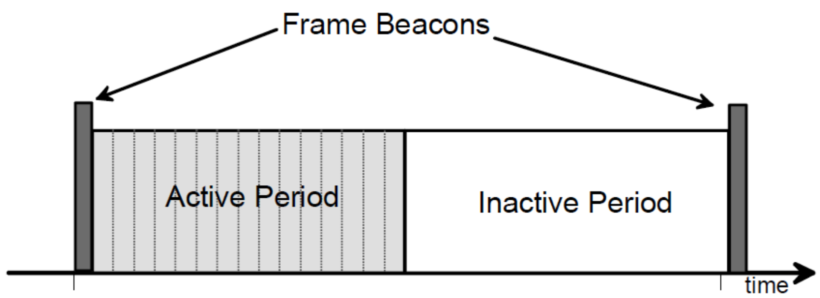


Figure 2-19: Superframe structure with active and inactive periods (portions) [3].

The beacon frame is transmitted in the first slot of each superframe. If the superframe structure is not wished to be used by a coordinator, the coordinator will turn off the beacons transmissions. The beacons are used for synchronization of the attached devices, for identification of the PAN (Personal Area Network), and for description of the structure of the superframe. Any device wishing to communicate during the contention access period (CAP) between two beacons competes with other devices using a slotted CSMA-CA mechanism. All transactions are completed by the time of the next network beacon.

For low-latency applications or applications requiring specific data bandwidth, the PAN coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). The GTSs form the contention-free period (CFP), which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP, as shown in Figure 2-20. The PAN coordinator may allocate up to seven of these GTSs, and a GTS may occupy more than one slot period.
However, a sufficient portion of the CAP remains for contention-based access of other networked devices or new devices wishing to join the network. All contention-based

transactions are completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP.

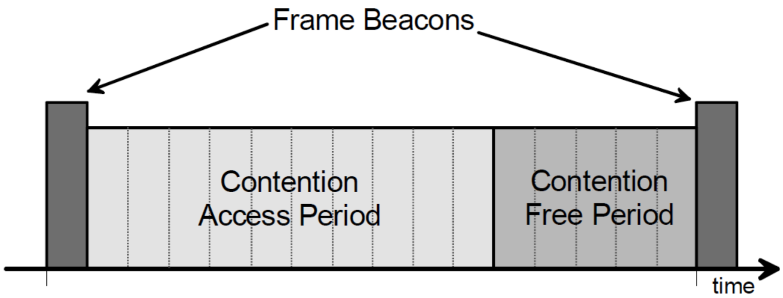


Figure 2-20: Superframe structure with GTSs [3].

The LR-WPAN defines four frame structures [3]:

- A beacon frame, used by a coordinator to transmit beacons
- A data frame, used for all transfers of data
- An acknowledgment frame, used for confirming successful frame reception
- A MAC command frame, used for handling all MAC peer entity control transfers

2.8.12 Communication between devices, Data transfer to a coordinator (COO)

In case where a device, FFD or RFD wishes to send data to the coordinator in a beacon-enabled PAN, first it listens and waits for the network beacon. When a beacon is found the device synchronizes to the superframe structure. The device transmits the data frame at the appropriate time with the use of slotted CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance). Successful reception from the coordinator may be acknowledged by a transmission of an acknowledgement frame (Figure 2-21). For more details of the CSMA-CA mechanism refer to chapter 5.5.4.1 of the IEEE802.15.4 LR standard.

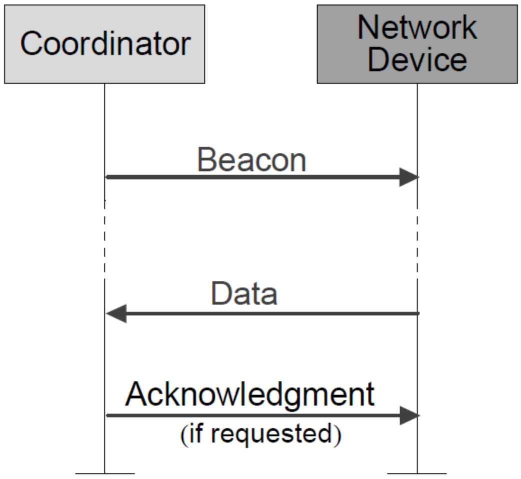


Figure 2-21: Communication in a beacon-enabled PAN [3].
(Data transferring from an RFD to the COO)

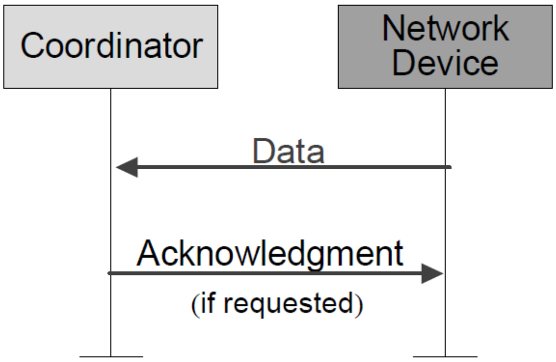


Figure 2-22: Communication in a nonbeacon-enabled PAN [3].
(Data transferring from an RFD to the COO)

A device can sent data even in a non beacon-enabled PAN. Data frame, is simple transmitted using unslotted CSMA-CA (Carrier Sense Multiple Access with Collision Avoidance) to the coordinator. The coordinator transmits then back an acknowledgement frame indicating the success of transmission (Figure 2-22).

2.8.13 Data transfer from a coordinator (COO)

In case where the coordinator wishes to transfer data to a device (RFD or FFD) in a beacon-enabled PAN it indicates in the network beacon that the data message is pending (Figure 2-23). The device listens to the network beacon and if a message is pending transmits a MAC (Medium Access Control) command requesting the data. (CSMA-CA is also used here). Successful reception is acknowledged by the coordinator by a transmission of an acknowledgement frame. The data frame is then sent immediately after the acknowledgement. The device then acknowledges the reception of the data frame [3].

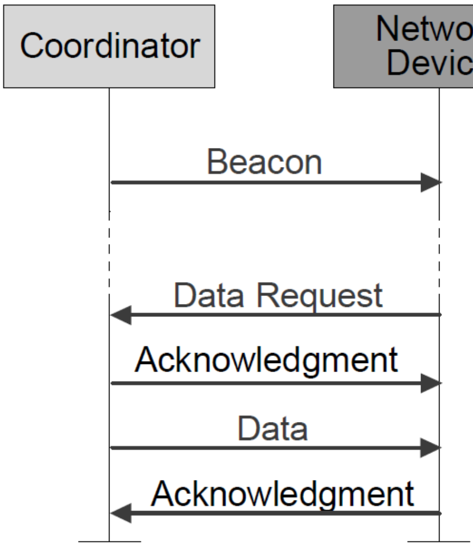


Figure 2-23: Communication in a beacon-enabled PAN [3].
(Data transferring from the COO to an FFD or RFD)

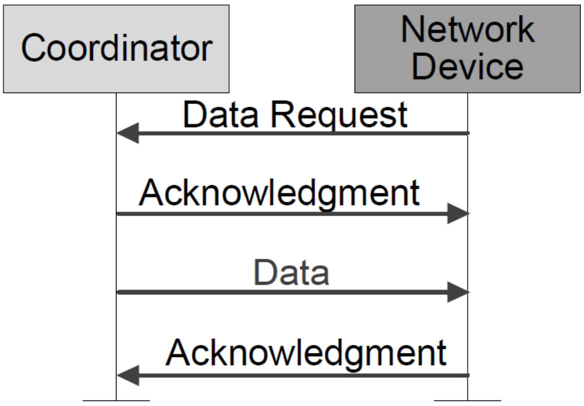


Figure 2-24: Communication in a nonbeacon-enabled PAN [3].
(Data transferring from the COO to a FFD or RDF)

In a non beacon-enabled PAN (Figure 2-24) a device transmits a MAC command requesting data (CSMA-CA is used here) to the COO. The COO acknowledges the reception and data are sent directly after the acknowledgement frame.

2.9 The ZigBee protocol

2.9.1 Introduction

The ZigBee standard is designed by the ZigBee Alliance. The ZigBee alliance is an association of companies (about hundreds in number) working together to enable reliable, cost-effective, low-power wireless network [13]. These companies are mostly semiconductor manufacturers, technology providers, OEMs (Original Equipment Manufacturers) and end users. As it will be discussed soon the ZigBee standard has common elements with the IEEE.802.15.4 LR-WPAN standard. The PHY as well the MAC layers of the IEEE.80315.4 had been adopted by the ZigBee. Therefore a ZigBee compliant device is compliant with the IEEE.802.15.4 standard as well.

Figure 2.25: Some of the ZigBee alliance members [7].

As with IEEE.802.15.4 standard, the main goals of ZigBee are low cost, low data rate, low power consumption, sort range wireless networking for home applications, wireless sensoring, remote control and many other application fields. Especially the ZigBee is targeted mainly for battery-powered applications.

The general characteristics include a typical range of 50m, a fully handshaked protocol, a large number of nodes per network (theoretically up to 65536 [16-bit addressing]), low duty cycle operation, self-healing, self-organizing, and plug-and-play devices.

2.9.2 ZigBee protocol stack architecture

2.9.2.1 Overview

As shown in figure 2-26 the ZigBee founds on the IEEE.802.15.4 LR-WPAN standard. The PHY, as well as the MAC layers are common for these standards. That means that ZigBee can take full advantage of the standards qualities of the already discussed IEEE.802.15.4 standard. Thus, there is no need of describing the PHY and MAC layers from the beginning. Each service entity exposes an interface to the upper layer through a service access point (SAP), and each SAP supports a number of service primitives to achieve the required functionality. The ZigBee stack architecture is based on the standard Open Systems Interconnection (OSI) seven-layer model but defines only those layers relevant to achieving functionality in the intended market space [10]. The description that follows concerns the NWK (NetWorK) layer and also the APL (APpLication) layer. In figure 2-27 a compact schematic of the protocol stack is shown.

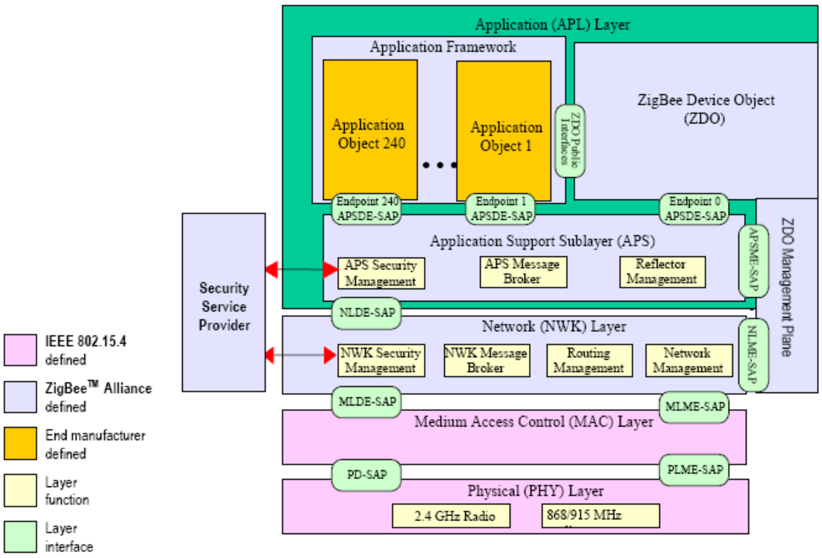


Figure 2-26: The ZigBee protocol stack architecture [10].

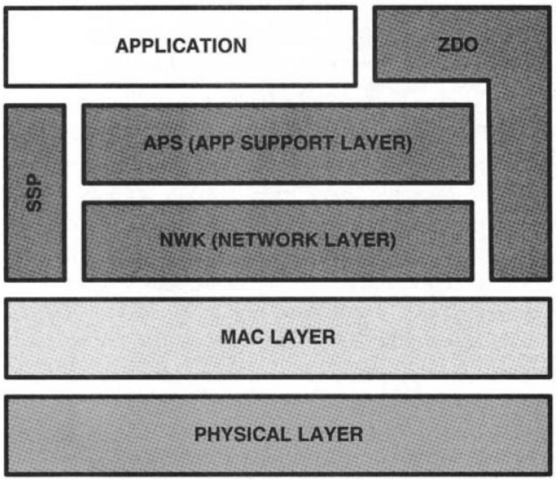


Figure 2-27: Simplified illustration of the ZigBee protocol stack [9].

2.9.3 The ZigBee network layer

The network layer is located above the IEEE.802.15.4 MAC layer (figure 2-27). It is the lowest layer of the ZigBee protocol. This layer adds routing functionality to the network. The responsibilities and functions of the NWK layer are: [10].

- Join in and leaving network.
- Apply security to frames.
- Route from-to their intended destination.
- Discover and maintain routes between devices.
- Discover one-hop neighbors.
- Store of pertinent neighbor information.
- Basic frame handling and device management.
- Allowing the devices to sleep.

The NWK layer of a ZigBee COO (Coordinator) assigns a 16-bit network address to each device in its network. The ZigBee COO, which is also the PAN COO, assigns the IEEE.802.15.4 MAC address if a new device that join its network needs a MAC address.

2.9.4 The APL (APpLication) layer

The ZigBee application layer is the highest layer of the ZigBee protocol. APL is divided in three sub-layers (Figure 2-27): The APS sublayer, the ZDO (ZigBee Device Object) and the manufacturer-defined application object.

- The APS (Application Support) layer is responsible for: a) maintain tables for binding and forwarding messages between devices, b) address mapping from 64-bit IEEE addresses to and from 16-bit NWK addresses, c) grouping address definitions. Device discovery is also executed by this sublayer. The APS provides an interface between the NWK and the APL layer through a general set of services that are used by both the ZDO and the manufacturer-defined application objects.

- The ZDO (ZigBee Device Object) is responsible for:
  a) Definition of the rule of the device within the network.
  b) Initialization and response to binding request

- Application objects are developed by the manufacturer to customize a device for various applications. Application objects control and manage the protocol layers in a ZigBee device. Up to 240 application objects can exist in a device.

2.9.5 ZigBee device types

There are three different types of ZigBee devices in a ZigBee network.

- The ZigBee coordinator (COO) which is an FFD (Full Function Device).
- The ZigBee router (ROU) which is also an FFD.
- The ZigBee end-device which is an RFD (Reduced Function Device).

A ZigBee router is a device that can act as an IEEE.802.15.4 coordinator and finally a ZigBee end device is neither a coordinator nor a router. It has the fewest capabilities thus it is the more simple and inexpensive device of the network.

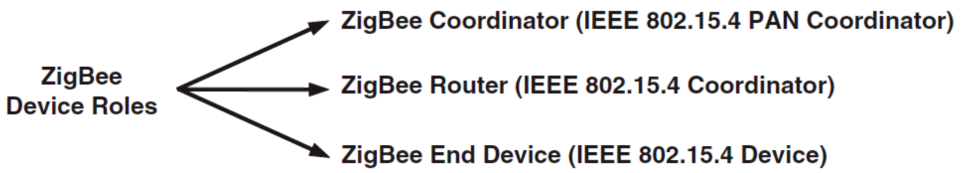


Figure 2-28: Correspondence of ZigBee to the IEEE802.15.4 LR-WPAN network devices [6].

In correspondence to the IEEE.802.15.4, (Figure 2-28) a ZigBee coordinator is an IEEE.802.15.4 PAN coordinator.

2.9.6 ZigBee network topologies

Multiple network topologies are supported by the ZigBee NWK layer including star, cluster tree and mesh topologies.

2.9.7 ZigBee star topology

In the star topology (Figure 2-29) every device in the network can communicate only with the PAN coordinator (see also subsection 2.3 IEEE.802.15.4 net topologies).

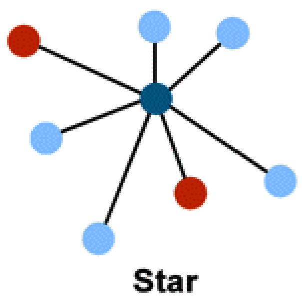


Figure 2-29: ZigBee star network topology [14].

2.9.8 ZigBee cluster-tree topology

A ZigBee cluster-tree topology (Figure 2-30) is basically multiple ZigBee star networks connected to the ZigBee coordinator by ZigBee routers. The cluster-tree topology is considered a multi-hop topology [6] [9].

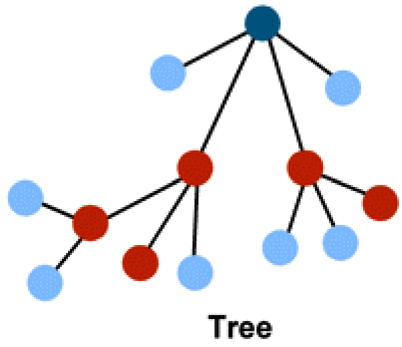


Figure 2-30: ZigBee cluster-tree network topology [14].

2.9.9 ZigBee mesh topology

In the mesh topology (Figure 2-31) there are no hierarchical relationships. Any device is allowed to attempt to contact any other device either directly or by taking advantage of routing-capable devices to relay the message on behalf of the message originator. In mesh topology the route from the source device to the destination is created on demand and can be modified if the environment changes. Mesh topology enables the network to be self-healing. This means that the network can still operate when a node is disabled for any reason or a connection gets bad. This operation is achieved thanks to routing capable devices that can operate to find an alternative path from the source device to the destination device (Figure 2-33) [6], [9].

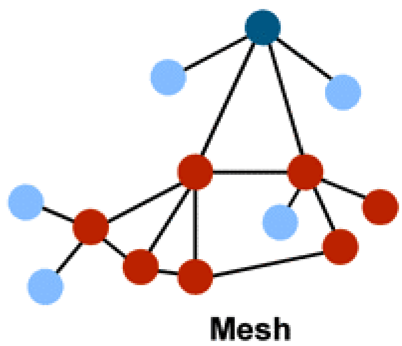


Figure 2-31: ZigBee mesh network topology [14].

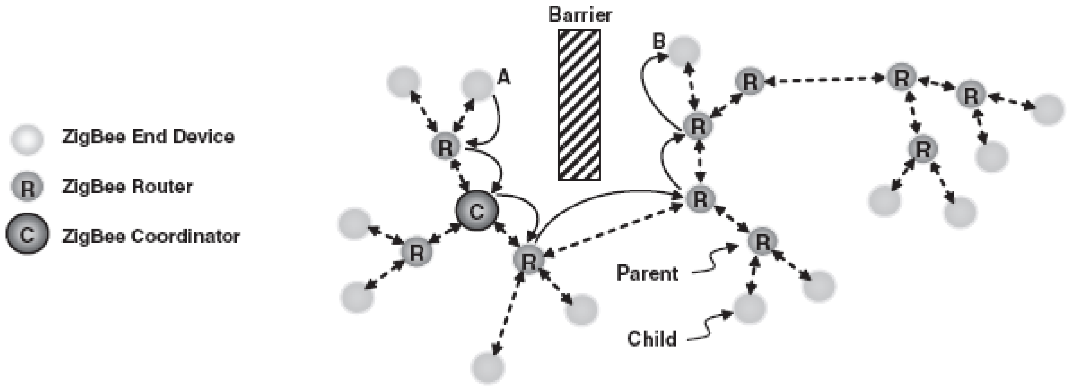


Figure 2-32: Example of a self-healing network [14].

Node A is still able to communicate with node B despite the fact that there is not a direct connection between them caused by a barrier (e.g. a moving object).

2.9.10 ZigBee Reliability

ZigBee achieves high reliability in a number of ways:

- IEEE 802.15.4 with O-QPSK and DSSS
- CSMA-CA
- 16-bit CRCs (Cyclic Redundancy Checks)
- Acknowledgments at each hop
- Mesh networking to find reliable route
- End-to-end acknowledgments to verify data made it to the destination

With mesh networking, data from a node can reach any other node in the ZigBee network, regardless of the distance as long as there are enough radios in between to pass the message along. If node A wants to communicate to node B (Figure 2-32) but is out of radio range, ZigBee automatically figures out the best path and so node A sends the information to node B, which forwards it on to node C [7].

2.9.11 Routing

Routing is the process of selecting the path through which the messages will be relayed to their destination device. ZigBee coordinator and routers are responsible for discovering and maintaining the routes in the network. ZigBee end devices are not capable to perform route discovery. Route discovery on behalf of the end device is performed by the coordinator or a router [6].

2.9.12 Routing protocols in ZigBee

Multiple routing protocols and algorithms can be applied in ZigBee networks. High reliability and security are provided by specific protocols for wireless ad-hoc networks. There are four different routing protocols, these are: [8]

a) AODV (Ad-hoc On Demand Distance Vector)

b) Cluster-tree algorithm including i) single-cluster algorithm, ii) multiple-cluster algorithm.

c) Message routing

d) Neighbor routing

2.9.13 AODV (Ad-hoc On Demand Distance Vector)

AODV is an on demand routing algorithm where the nodes are not taking part in the routing until they are needed. A node does not have to discover and maintain a route to another node until these two wishes to communicate. When a node wishes to communicate with another node it must first find the route to that node. This is done by the route discovery method. A route request packet (RREQ) is transmitted by the source node to its neighbors (Figure 2-33).

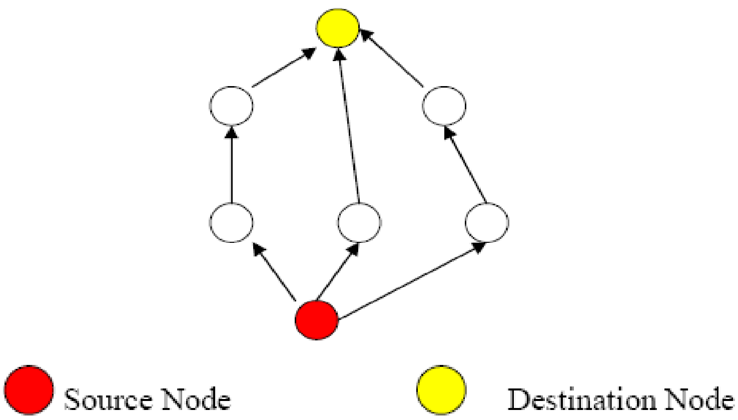


Figure 2-33: RREQ Broadcasting [8].

All nodes receive this packet which includes the source address, the source sequence number, destination sequence number, destination address, broadcast ID and hope count. Each node maintains two separate counters that take part in the route discovery process [8]. These are the sequence number and the broadcast id number. Any device which receives the RREQ will check if it is the destination. If true then it will respond with a route reply RREP command (Figure 2-34). If false then it will compare the path cost in the RREQ with any it has previously received. If the path cost in the RREQ is smaller than previous ones then the node will update its route discovery table and it will rebroadcast the RREQ.

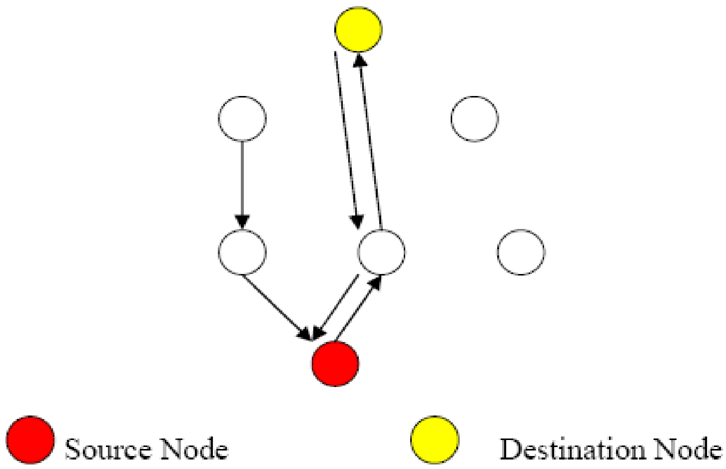


Figure 2-34: RREP generation [8].

Any device that receives a RREP command will check if it is the indented destination. If true, and the path cost is smaller than any previously received, then it will search its routing table for the responder address and set the next hop address to the device from which the RREP was received. If false, then it will search its route discovery table for the corresponding RREQ and compare the table path cost with the path cost of the RREP. If the table value is smaller than the RREP will be dropped, otherwise the device will update the table value.

2.9.14 The cluster tree algorithm

Another routing algorithm that can be applied in ZigBee networks is the cluster tree algorithm. This protocol works in the network and logical link layers of the ZigBee stack.

2.9.15 The single cluster network

The protocol starts its operation with the selection of the (CH) cluster head. After the cluster head selection, the cluster head expands links. After this procedure Hello messages are broadcasted to the other nodes (Figure 2-35). The cluster head which is the first node (initial node) waits for the response from the neighbor node. If there is no response (within a specific time period), then it will turn back to the head node again. A hello message is the equivalent of a beacon transmission of the IEEE 802.15.4 standard and contains the MAC (Medium Access Control) address of the cluster head and also it's ID.

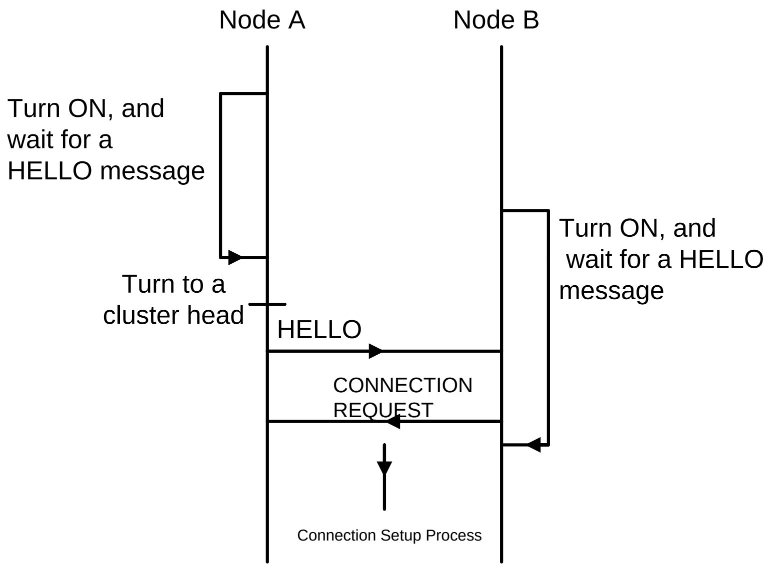


Figure 2-35: Cluster head selection process [8].

If the Hello message received from some nodes, then it will send back the connection request to the cluster head. The cluster head then sends the connection response to the nodes with assigning identification and the node becomes part of the cluster [8].

2.9.16 The multi cluster network

In the multi cluster network a DD (Designated Device) is needed to form it. This device acts as a CH (Cluster Head) on joining the network. It also sends the Hello messages to the cluster which is in the neighbor of the first cluster (node A in figure 2-36). If the second cluster accepts the Hello message, (node B in figure 2-36) then it will send a request for connection to the cluster head of the first cluster (node A). After that the cluster head requests a (CID) cluster ID to the DD. In this case the cluster head is a border node that has two logical addresses [8].

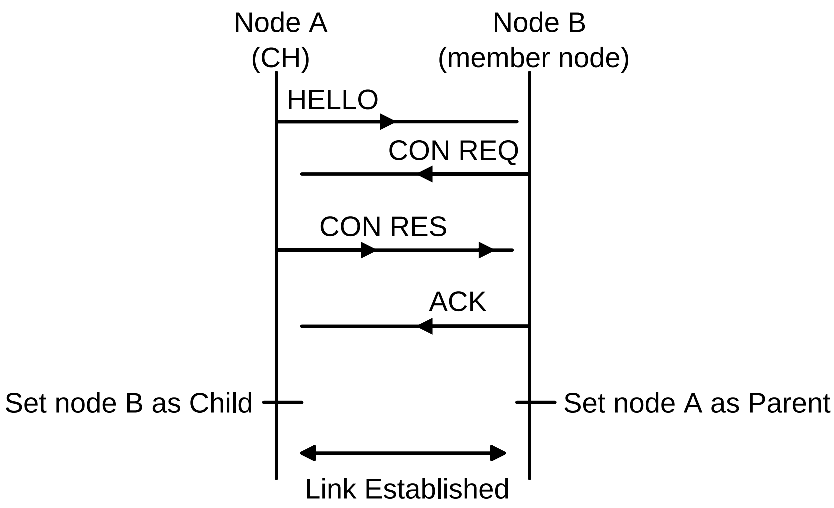


Figure 2-36: Link setup between CH and member node [8].

2.9.17 Message routing

This is the basic type of algorithm used during the routing of messages in the wireless sensor networks. The node checks the address of the destination node in the table setup by the neighbour node. If the destination is found in the table of the neighbour node, then it responds to the first node by sending success message and set up a route for exchanging messages. Otherwise, in the similar way, the messages are sent to the other nodes in a flooding manner to find out the destination so that communication can be done. For instance when the nodes acting as the ZigBee

End Devices (ZED) are in a sleep mode, then the ZigBee Routers (ZR) store the messages for them and transfer to them when they awake from the sleep mode to the active mode. It is the basic kind of algorithm used during the routing of data in the ZigBee sensor networks [13].

2.9.18 Neighbour routing

This is also another basic type of algorithm used when routing is carried out by the network layer of the ZigBee stack. The node or device acting as a ZigBee Coordinator or ZigBee Router is responsible for maintaining the status of the nodes in their neighbour. This is done by the table where the COO or Router maintains for entering the data related the neighbour ZigBee devices. The destination device can receive the messages directly from the source device if it is in the physical range of the sending device. The same procedure is followed by all the nodes along the route to destination to record the data of the neighbours in the table. In this way the possible routes to the destination are examined by recording the best route found in the routing tables maintained by all devices [13].

2.9.19 ZigBee Security

Although the ZigBee protocol lays on the IEEE.802.15.4 protocol layers (security model of the 802.15.4 MAC sublayer) that does not provide a mechanism for moving security keys, the ZigBee protocol supports a security toolbox including access control lists, data freshness timers, and an 128-bit encryption.

2.9.20 Power consumption

Because of the similarities between ZigBee and IEEE.802.15.4 in the PHY and MAC layers, ZigBee uses the already power shaving radio technology of IEEE.802.15.4. The low data rates supported by the ZigBee require not as high bandwidth as other wireless technologies. Low bandwidth leads to a low power device. Except all these, a ZigBee node is able to sleep for battery shaving for a long period of time. It wakes only to send data and sleeps again. These factors can make a ZigBee node to operate even for years on an alkaline AA (2x1.5V) battery pack.

2.9.21 The ZigBee versus other wireless technologies

Table 2-7 and figure 2-37 shows a simple comparison of ZigBee with Bluetooth, IEEE802.11.b (WI-FI), and some other technologies.

	Data Rate	Typical Range	Application Examples
ZigBee	20 to 250 Kbps	10–100 m	Wireless Sensor Networks
Bluetooth	1 to 3 Mbps	2–10 m	Wireless Headset Wireless Mouse
IEEE 802.11b	1 to 11 Mbps	30–100 m	Wireless Internet Connection

Figure 2-7: Comparison of ZigBee with Bluetooth and IEEE802.11.b (WiFi) [7].

Table 2-7, presents a comparison between ZigBee and Bluetooth, WI-FI concerning the data rate and also the typical coverage range. As for the range, ZigBee is a wireless technology indented for medium coverage applications (10-100m), while Bluetooth and WI-FI are for short and long ranges respectively.

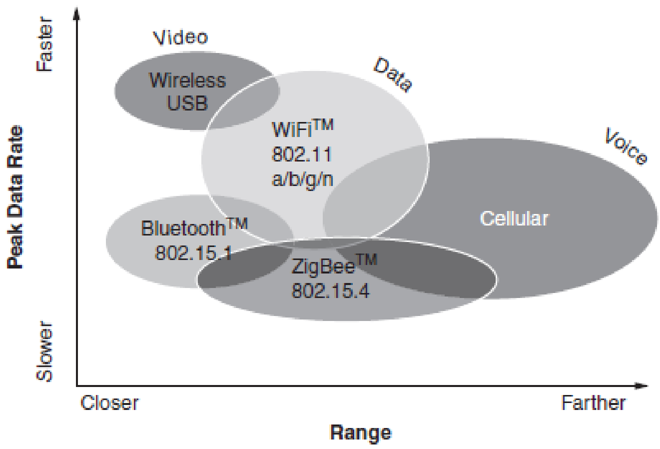


Figure 2-37: Comparison of ZigBee with other wireless technologies [7].

Each wireless technology has advantages and disadvantages versus the other. In this work, the application that is going to be described soon needs a large number of wireless devices in the same network. As already mentioned, a Bluetooth network can only support 7 devices. Also, the data rate is not a critical factor as well as the coverage range needed. While other technologies aim for faster and faster data rates, ZigBee intends to be ‘Low Rate’.

Another benefit of ZigBee is that it features a very simple architecture stack resulting in the fact that simple 8-bit microcontrollers can stand the network's functionality. Because of the low rate functionality, ZigBee is more suitable for applications that require low duty cycle and long time operation (even years running on alkaline cells).

2.10 Summary

In this chapter, a general theoretical background concerning the basic network types and network topologies had been presented. Also, sort range wireless technologies and ZigBee standard in more detail as well as basic routing protocols had been described. In the next chapter the basics of photovoltaic systems are given.

Chapter 3

Photovoltaic systems basic

3.1 Principle of operation

The operation of a solar cell is based on the photovoltaic effect (Edmund Becquerel, 1839). The photovoltaic effect is the basic physical process through which a solar cell converts sunlight into electricity. Solar cells are actually semiconductor devices where the basic material is Silicon (Si). A solar cell is basically a PN photodiode. The PN junction of this photodiode results from the “doping” that produces conduction-band or valence-band selective contacts with one becoming the *n*-side (lots of negative charge) and the other the *p*-side (lots of positive charge).

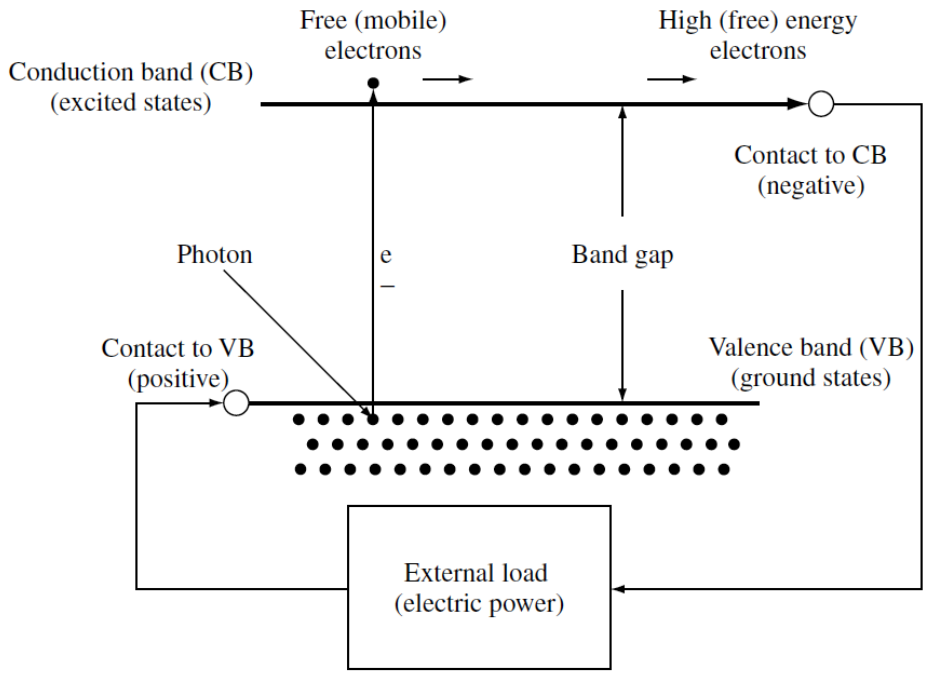


Figure 3-1: Basic operation of a solar cell [15].

Figure 3-1 depicts the movement of the electrons inside the PN photodiode region. The PN junction produces conduction or valence bonds. When the solar cell is exposed to sunlight, photons hit valence electrons. This causes the electron bonds to break and pumped to the conduction band.

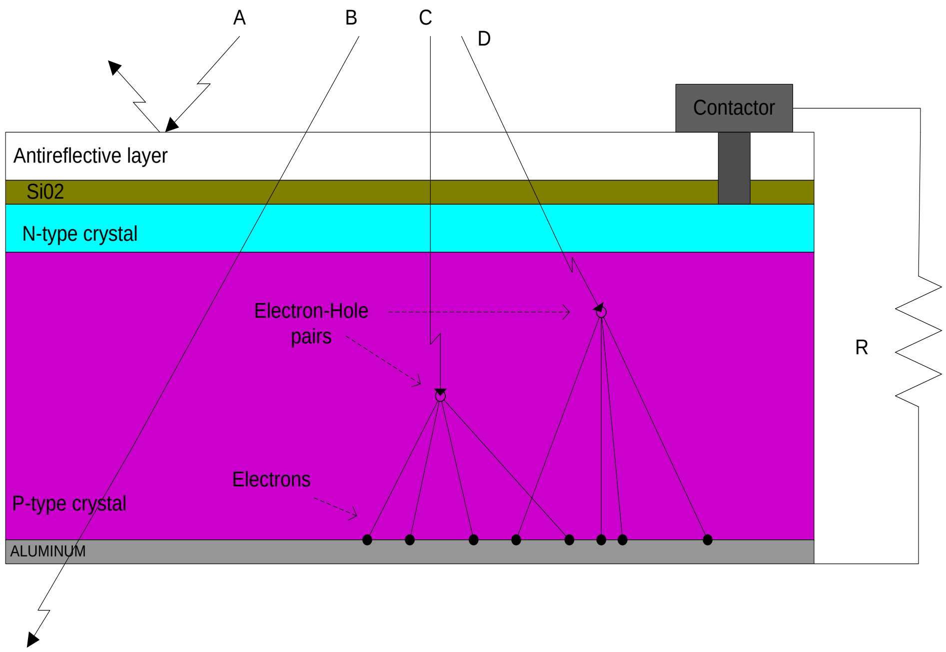


Figure 3-2: Infrastructure of a solar cell.

Figure 3-2 shows the fundamental structure of a solar cell. The *n*-side as well the *p*-side of the photodiode can be easily seen. In this figure, there are also some different wavelengths (arrows) marked as A, B, C and D. These are actually light (photons) with different wavelengths. As known the sunlight contains a wide number of different wavelengths. The energy of a photon can be expressed with the Planck-Einstein equation — , where, h=the Planck's constant, c=the speed of light and λ=the wavelength. Thus, the energy of a photon depends on its wavelength. Photons whose energy is greater than the band gap energy (the threshold energy) can excite electrons from the valence to conduction band where they can exit the device and generate electrical power. Photons with energy less than the energy gap fail to excite free electrons. Instead, that energy travels through the solar cell and is absorbed at the rear as heat [15]. So, it is obvious that only a part of the sunlight spectrum can be converted into electricity.

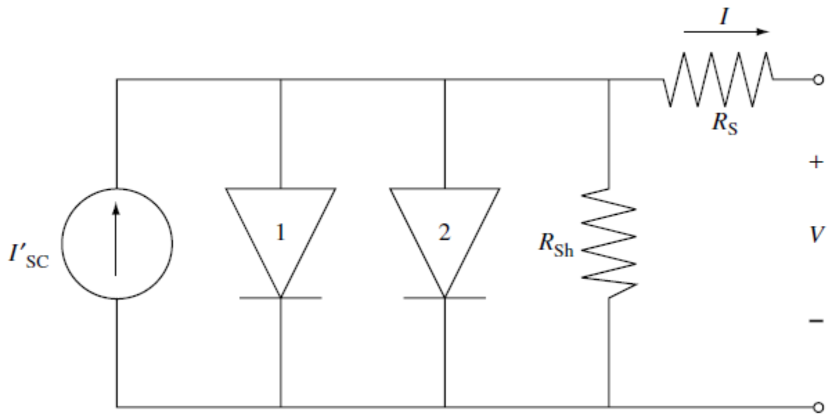


Figure 3-3: Equivalent circuit of a solar cell [16].

In figure 3-3, the circuit model (or equivalent circuit) of the solar cell is presented. By omitting diode 2 and R_{sh}, an ideal solar cell can be modeled. R_s is the series resistance of the circuit. In this case, R_s is the physical resistance of the semiconductor material of the solar cell itself and R_{sh} is a parallel resistance of the diodes. Diode 1 and 2 contains an ideality factor of '1' and '2' respectively.

3.2 Solar cell types

The basic element of a solar cell is silicon (Si). There are three basic types of solar cells. These are:

- The monocrystalline (or single crystal) solar cells.
- The polycrystalline solar cells.
- The amorphous or thin-film solar cells.

Some other types but not so popular in the photovoltaic systems are:

- The cadmium Telluride solar cells.
- The Multijunction (GaAs (Gallium Arsenide)) solar cells.
- Dye sensitised solar cells.

In monocrystalline technology, the solar cells are cut out from a piece of continuous crystal. The melted Silicon (Si), after a method called Czochralski forms a cylinder (known as ingot). This ingot is sliced into circular wafers where these wavers are actually a solar cell. Once these cells are produced, one side of the cell is printed with a positive material and the other a negative. These cells are then connected in series and continue on to become a complete solar panel.

In polycrystalline technology, polycrystalline cells are made from the similar silicon material as with monocrystalline except that instead of being grown into a single crystal**,** it is melted and poured into a mold. Polycrystalline cells are well known from their appearance. They are less uniform in appearance that monocrystalline cells.

In amorphous silicon technology, the solar cell is made with a microscopically thin deposit of silicon, instead of a thick wafer. This implementation uses very low amounts of silicon. In amorphous silicon technology, the deposited silicon can be placed on a sheet of metal or glass, thus eliminating the need of slicing in order to produce wafers. Also there is no need for mechanical connection between cells that is a result of the deposition of the cells next to each other.

Cadmium Telluride (CdTe) cells can be manufactured with the same deposition procedure as with amorphous silicon but with the difference that the semiconductor compound is formed from Cadmium and Tellurium. CdTe is not as efficient as crystalline silicon, but CdTe panels perform significantly better in high temperatures due to a lower temperature coefficient.

GaAs is used for production of high efficiency solar cells. It is often utilized in concentrated PV systems and space applications. Their efficiency is up to 25%, and up to 28% at concentrated solar radiation.

3.3 The PV module

Since the power of a single solar cell being small, several of them must be electrically associated to make a practical generator. The module is the building unit for generators that can be purchased in the market, that is, it is the real PV product. In a module, the solar cells are connected in series [15]. The output voltage of a single cell is around 0.5 Volt. Thus, a total of 36 solar cells are needed to be connected in series to produce an open circuit voltage (Voc) of 18 Volts at maximum power. Also this is a common module configuration. Figure 3-4 shows the connection procedure of solar cells to form a PV module. After cell finishing, tinned copper ribbons (tabs) are soldered to the bus bars at the front. Two tabs per cell are employed thus providing redundancy that allows current to flow in case electrical continuity is broken because of some failure. Tabs also provide a nonrigid link between cells that allow thermal expansions to be accommodated. In figure 3-4b, the series interconnection of the cells is shown. The rear tabs of the front cell are soldered to the front tabs of the cell that follows. The strings are interconnected with auxiliary tabs to form the cell matrix. This can consist of a single series string or several strings (Figure 3-4c).

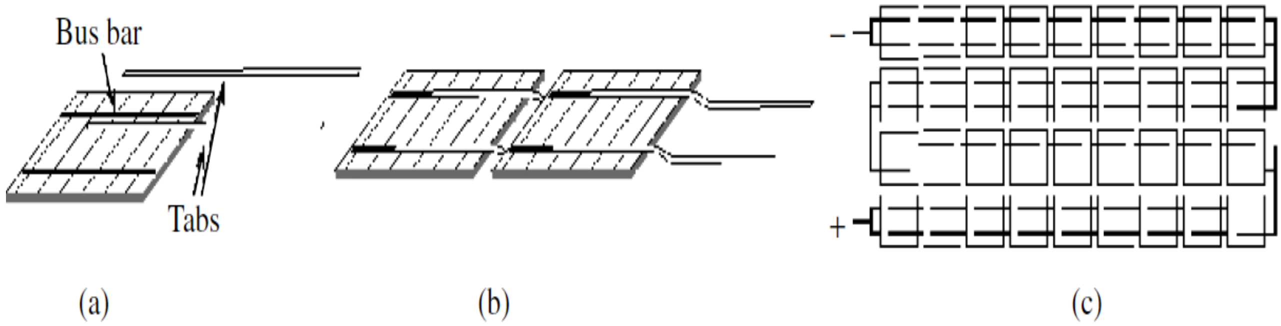


Figure 3-4: (a) Cell interconnection with tabs; (b) two cells in series; and (c) layout of 36 series-connected cells [15].

Finally, the series connected solar cells are encapsulated in a metallic casing for protection from humidity, dust and mechanical reinforcement (Figure 3-5).

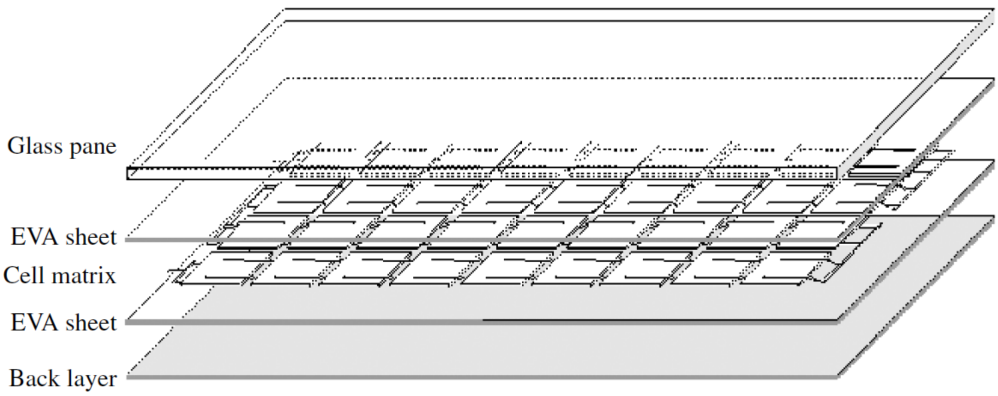


Figure 3-5: Structure of a PV module [15].

3.4 PV arrays

As mentioned above, the average output voltage of a PV module is about 15Volts (Voc). If a higher voltage desired, multiple modules are connected in series. On the other hand, if higher currents are desired, the PV modules can be connected in parallel. So, a PV array is the linked connection of multiple PV modules. Figure 3-9 shows a PV array of 9 PV modules on a houses roof. In figure 3-10 a PV array of totally 28 PV modules is shown.

3.5 Photovoltaic systems

Photovoltaic systems are solar energy systems witch either supply power directly to electrical equipment or appliances, or feed energy into the public electricity grid (grid connected systems).

The power range of a photovoltaic system begins from few mW (milliwatts) of power, to several Kw (Kilowatts). Large area photovoltaic power stations exceed the range of KW and supplies with power in the MW range.

In general, photovoltaic systems are considered to be an expensive method of electric power production. However, the small need of maintenance and the continuously growing PV market all over the world make this technology especially versatile and economically viable [15].

3.6 Types of photovoltaic systems

3.6.1 Grid independent photovoltaic systems. (Stand alone systems)

This type of photovoltaic (Figure 3-6) system is generally used in applications where there is no power access to the public electricity grid. A decentralized small house in an area far away from the electric power network (e.g. located in an isolated area such as a mountain) is a good example.

Another example of a grid-independent photovoltaic system can be the power supply system of a radio repeater station or a cell phone network antenna. These kinds of repeaters are usually located in areas with high altitude for better broadcast coverage like mountain regions. Thus a standalone PV system may be the best solution for this case.

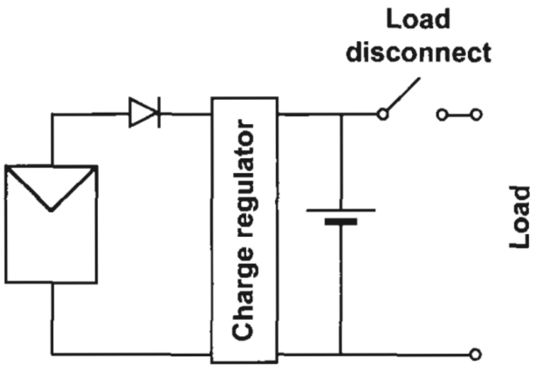


Figure 3-6: Typical configuration of a standalone photovoltaic system [16].

Figure 3-6 shows a simple circuit diagram of a standalone system. Current generated from the PV panel, flows through the diode to the charge regulator. The charge regulator is an electronic device which controls the charging cycle of the battery and also (in this system) supplies the electrical load.

3.6.2 Hybrid photovoltaic systems

Hybrid photovoltaic systems are used in applications where higher power is needed and/or the equipment to be fed needs an alternative high voltage to operate (usually 110-230 AC volts). This kind of systems uses the combination of photovoltaic panels and a diesel generator. Some hybrid systems may use a wind turbine generator or a hydroelectric generator in cooperation with the photovoltaic panels. A battery bank ensures that power is available continuously.

A hybrid system is a reliable, completed and simultaneously a competitive solution for a medium load application as a house can be. The system can run only on the photovoltaic panels but when the load needs are higher than the maximum power output of the modules, then the diesel generator starts and supplies the load with the extra power needed.

Figure 3-7 shows a hybrid system. Batteries are used here to provide energy storage when the photovoltaic panels or the generator are not on use (e.g. during night).

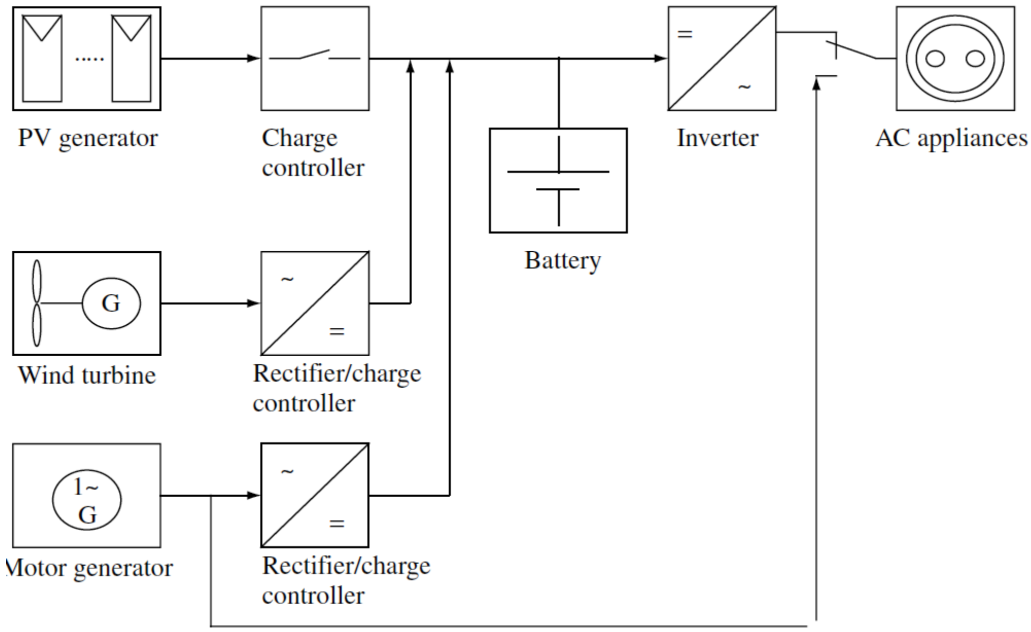


Figure 3-7: Block diagram of a hybrid system [15].

In the system above, the AC appliances can be supplied directly from the motor generator or from the PV panels and/or the wind generator. The rectifier/charge controller converts the AC current generated from the wind generator into DC and maintains the battery voltage at normal operating voltage. When the motor generator is running, the load is supplied but also the battery is charging through an extra rectifier/controller.

3.6.3 Decentralized Grid Connected Photovoltaic systems

This type of photovoltaic system, (Figure 3-8) is permanently connected to the public electricity grid (grid connection). Energy storage is not necessary and so no battery bank needed (depending on the application). On sunny days the photovoltaic panels provide power for the electric appliances and all the excess energy is supplied to the public grid. At night the house draws power from the grid or from the battery bank (if used).

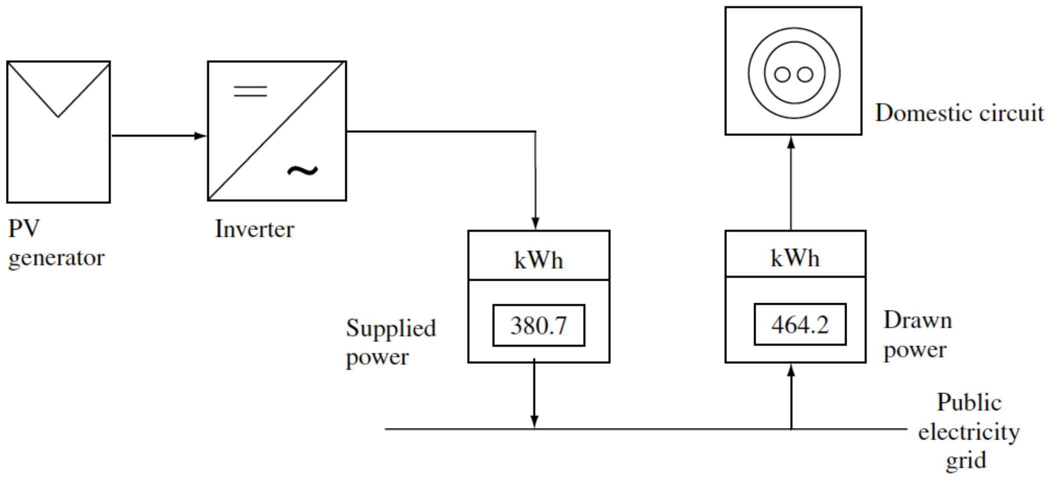


Figure 3-8: A grid connected PV system [15]

Here, the PV modules powers the inverter. The inverter converts the DC voltage into an AC voltage with a frequency that is the same with that of the public electric grid (usually 50Hz or 60Hz). The supplied power reading is monitored and stored with a Wh meter. The consumed from the domestic circuit power is also monitored. The electric company customer can be benefited from the fact that the value of the electric power that he produced (from the PV system) can be subtracted from the monthly electric bill.

3.6.4 Central Grid Connected Systems

In contrast with the systems discussed previously that use small area and low power outputs, the central grid connected systems are used to feed directly the medium voltage (=20KV), or the high voltage (=150KV) grid. This system would be a photovoltaic power station in the range of KW or MW [15].

3.7 The components of a photovoltaic system

The main components of a PV system (including the PV modules) are:

a) The charge controller

b) The inverter

c) The battery

d) The tracking system (optional)

3.7.1 The charge controller

As soon as a photovoltaic system includes batteries a charge controller must be used. The fundamental operation of a charge controller is to operate the battery within the safe limits with respect to overcharging and deep discharging. A charge controller is responsible hence for controlling the charging voltage and current. This operation is not a simple one because current and voltage at the output of the photovoltaic module is not stable and depends on insolation and on the fluctuations of the load. Figures 3-9 and 3-10 shows a linear and a switch mode charge controller respectively.

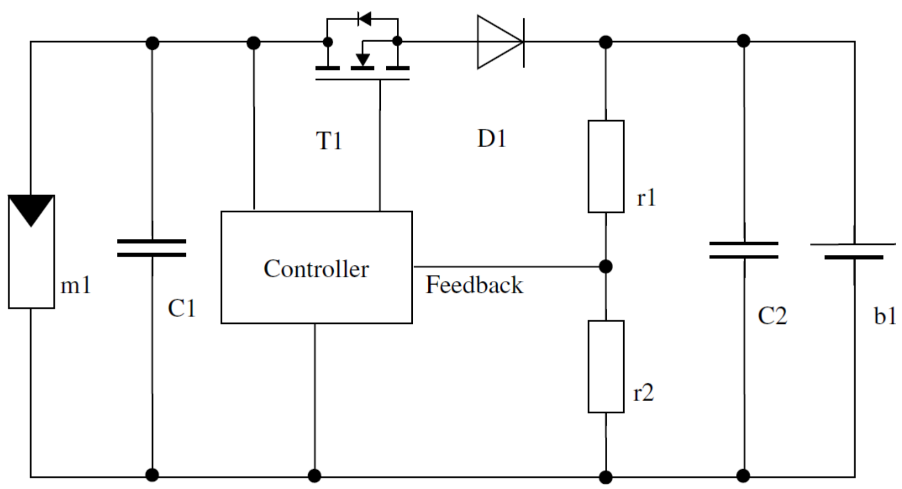


Figure 3-9: A series linear charge controller [15]

The main components of the linear charge controller of figure 3-9 are Mosfet T1 and the controller. R1 and R2 forms a voltage divider in order to provide a feedback signal to the controller. The controller is usually a microcontroller chip. The feedback signal is applied to an ADC input and depending on the voltage at the battery terminals the microcontroller outputs a suitable voltage (Vgate) to the Mosfets gate. The resistors, the microcontroller and the Mosfet form a control loop. C1 and C2 are bypassing capacitors. This type of controllers has the disadvantage of low efficiency as part of the power is converted into heat at the Mosfet.

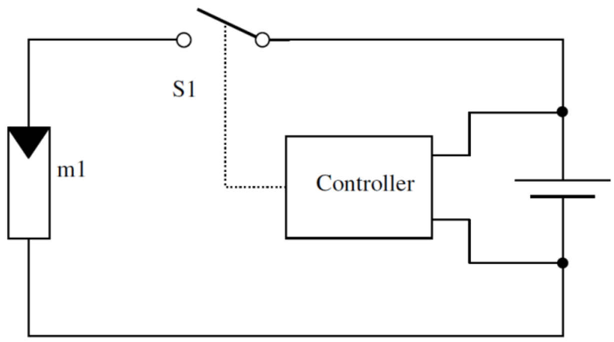


Figure 3-10: A series switch mode charge controller [16]

A more sophisticated system is that of figure 3-10. A microcontroller triggers the input of a switching element (transistor, fet, mosfet) with a suitable frequency and duty cycle. The most common controlling signals are Pulse Width Modulated (PWM). This type of controllers tends to have a high efficiency (somewhere between 85%-98%).

For a charge controller some design criteria must be kept in mind for a designer or a purchaser. Some of these criteria are:

- The charge controller should be able to charge totally flat batteries.
- The charge controller should be able to automatically perform gassing charging or equilibration charging.
- The output voltage must be kept in safe values.
- The charge controller should be able to check the battery temperature.
- The charge controller should offer a deep discharge protection
- The average efficiency of the charge controller should be >96% under rated charging as well as discharging condition.
- Reverse polarity protection must also be kept in mind.

3.7.2 The inverter

The inverter is a device that converts the DC (Direct Current) coming from the photovoltaic modules (or from the batteries), to an AC (Alternating Current). Most equipment and appliances in a house or industry needs AC current to operate. In addition, in the case of a grid connected photovoltaic system, its output, should be at the same voltage level and at the same frequency with that of the public electrical grid.

The inversion process is achieved by inversion of the DC polarity in a desired AC frequency. Thus an inverter should be able to provide constant voltage, current, and frequency to the load.

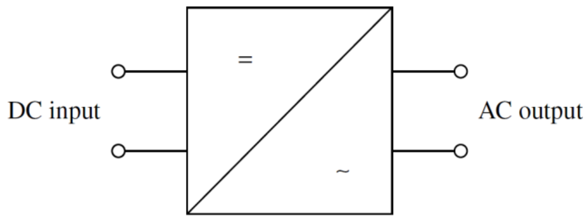


Figure 3-11: The schematic symbol of the inverter [15]

The symbol of an inverter where can be found on any schematic diagram is shown in figure 3-11. The “=” symbol represents the ” symbol represents the AC output.

3.7.2.1 Inverter types

Two main categories of inverters (depending on the application) exist.

3.7.2.2 The grid connected photovoltaic system inverter

The inverter of this type is the second most important component of a grid connected photovoltaic system after the solar generator (PV modules). Its task is to convert the DC voltage coming from the solar generator to an AC voltage at a frequency usually of 50Hz or 60Hz. A classical configuration of this type of inverter is shown in figure 3-12.

These types of inverter are equipped with circuits for continuous adjustment of the optimum working point on the I-V characteristic curve shifts depending on the solar radiation. This operation is called MPPT (Maximum power point tracking). Describing of the MPPT algorithm is out of the scope of this thesis. For detailed description of the MPPT operation please refer to [15] page 871 and [16] page 578.

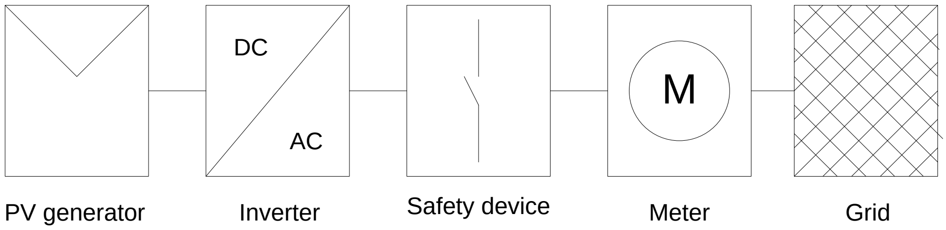


Figure 3-12: General structure of a grid connected photovoltaic system [15]

As shown in figure 3-12, the system is parted from the solar generator (PV modules), the inverter, the safety protection device (fuses and circuit breakers) and an electric meter (Wh). The power feeds the grid can be calculated by multiplying the actual power of the PV generator with the actual efficiency of the inverter. The inverter efficiency is a parameter that must be considered. This is because the total current from the PV generator flows through the inverter and its properties fundamentally affect the behavior of operating results of the PV system.

3.7.2.3 Stand alone system inverter

This type of inverters is often operating with batteries as it should provide a constant voltage and frequency to the load. In a typical domestic power supply, the ratio of the peak power to the average power is about 25:1, so the inverter must have a high efficiency of approximately 90%, particularly in the partial load range (5–10% of the rated power). Only a few inverters satisfy this condition together with a sinusoidal output voltage and the capacity to withstand short-term, double to triple overloading. Depending on the requirements, both sinusoidal and rectangular waveforms can be used [15]. For more details about the output form of an inverter see sub clauses following.

3.7.3 Types of inverter (depending on the principle of operation)

Finally, all inverters are categorized by the type of the output they produce. These categories are:

- Square wave type
- Modified sine wave (or quasi sine) type
- Pure sine wave type.

3.7.3.1 The square wave inverter

The square wave inverter is the most simple and cheap inverter configuration. Its output is actually a square wave (Figure 3-13) and obviously this kind of output is not suitable for all types of electric-electronic equipment and appliances. This is mostly because the resulting output contains a large amount of harmonic frequencies. A square wave inverter will run simple appliances like tools with universal motors and some types of lamps (excluding electronic and fluorescent) with no problem.

Figure 3-19 shows a typical schematic circuit of a square wave inverter [15].

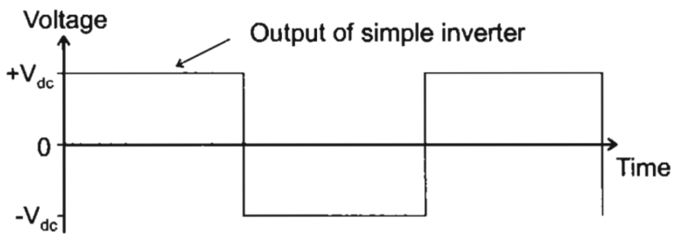


Figure 3-13: Output of a square wave inverter [16]

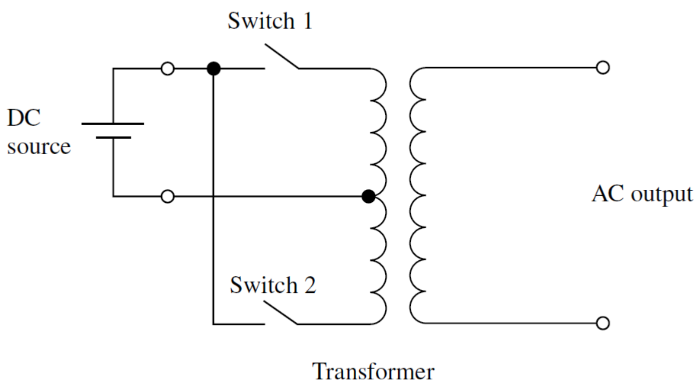


Figure 3-14: Simplified circuit schematic of a square wave inverter [15]

The principle of operation of the square wave inverter is much simple. As known a transformer cannot operate with a DC voltage because of the magnetization of the iron core. The two switches at the primary winding of the transformer, changing the polarity of the DC voltage very quickly (at a specified frequency) resulting in the creation of a variable polarity DC voltage that can pass to the secondary winding without magnetizing the transformers core. Thus, the output voltage is much more like an AC than a DC.

3.7.3.2 The quasi sine wave inverter

A more sophisticated and higher quality inverter is the quasi sine or modified sine wave inverter. Its output is a better approximation of a pure sine wave than the previous inverter (Figure 3-15). The equivalent sine wave has the same r.m.s. value as the modified square wave. Most equipment will operate well on this inverter like equipment contain motors, however this inverter may cause noise in some fluorescent lamps, audio systems, TV sets, and there is a possibility of faulty operation in some electronic devices. In figure 3-16 a simplified schematic circuit of a modified sine wave inverter is shown.

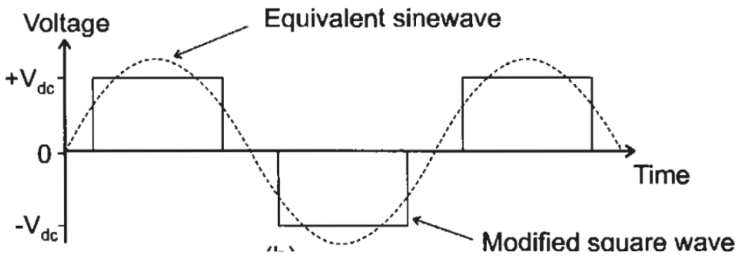


Figure 3-15: Output of a modified sine wave inverter [16]

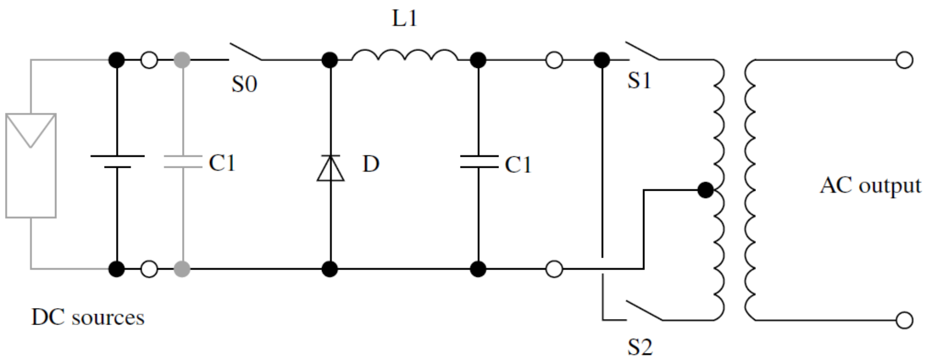


Figure 3-16: Simplified schematic circuit of a modified sine wave inverter [15].

The circuit of the modified sine wave inverter is a little more complicated. Although the similarities (S1, S2 and the transformer), this topology contains in addition a step down DC-DC converter. This converter steps down the high DC voltage coming from the PV modules at a desired level. Switch S0, diode D, inductor L and capacitor C1 forms this converter. By controlling the frequency and duty cycle of S0, the output voltage can be adjusted. As shown in figure 3-15, the voltage passes from zero for a longer time than that of the square wave output in figure 3-13.

3.7.3.3 The pure sine wave inverter

A step closer to the sine wave of the grid AC current can be obtained with the use of a pure sine wave inverter. Pure sine wave inverters produce AC voltage with low total harmonic distortion (typically below 3%). They are more expensive and used when there is a need for clean sinusoidal output for some sensitive devices such as medical equipment, laser printers, stereos, etc. Figure 3-17 shows a circuit of a sine wave inverter.

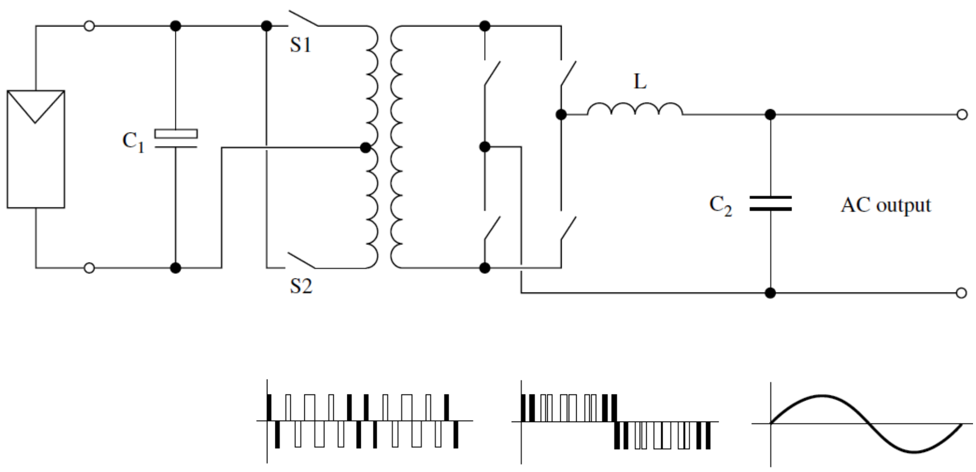


Figure 3-17: A sine wave inverter using a high frequency PWM signal [15]

The most sophisticated implementation of all is the pure sine wave inverter circuit. At the transformers primary side, the classical topology of the simple inverter exists. However, at the secondary side, there is an H bridge that is formed by switching elements (diodes, transistors or fets). This bridge is controlled by PWM signals in such a sequence that the output waveform looks like that in figure above. Finally, inductor L and capacitor C2 forms a low pass filter that eliminates the high frequency harmonics resulting in a pure sine wave output.

3.8 Batteries

Batteries are used in most stand-alone PV systems, and are in many cases the least understood and the most vulnerable component of the system. Most design faults (e.g. under sizing the PV array or specifying the wrong type of controller) and operating faults (e.g. use of more daily electrical energy than was designed for or simply some breakdown in the PV array or charge controller) will lead to ill-health, if not permanent failure, of the battery. In these cases, the battery is then often blamed for the failure of the system to deliver the promised regular amount of electrical energy, and the type of battery used in such a failed system can acquire, quite unfairly, a bad reputation as a ‘PV battery’ [16].

In a photovoltaic system the battery performs three basic functions.

- It acts as a buffer store to eliminate the mismatch between power available from the PV array and power demand from the load

- The battery provides a reserve of energy (system autonomy) that can be used during a few days of very cloudy weather or, in an emergency, if some part of the PV system fails.

- The battery prevents large, possibly damaging, voltage fluctuations.

Discharge and charge rates are convenient scales to compare currents at which batteries are charged, independent of battery capacity. They are expressed as a number of hours, e.g. the 10 hour rate, the 240 hour rate, etc. The current to which they correspond is the appropriate total discharge capacity divided by the number of hours:
Rate = Capacity (Ah)/ Time (h)
For example, C/10 (10 hour rate) is a current equal to the rated capacity in Ah divided by 10 [17].

3.8.1 Types of batteries for photovoltaic systems

Describing and analyzing the principle of operation and also the technology of each battery for a PV system it is out of the scope of this Thesis. The scope of this subclause is to show the basic battery technologies used today in PV systems. However, a simple reference to the most used batteries for PV systems and a short comparison of these types will follow next.

Some examples of rechargeable battery systems are:

- Lead-acid

- Nickel-cadmium
- Nickel-hydride

Only lead-acid and to a small extent nickel-cadmium batteries are used in PV systems. The family of lead acid batteries includes the following sub-types:

- Lead-antimony
- Lead-calcium
- Lead-antimony-calcium
- Gelled
- AGM (Absorbed Glass Mat)

A short description about these types follows next.

Lead-Antimony

Lead-antimony batteries are a type of lead-acid battery which uses antimony (Sb) as the primary alloying element with lead in the plate grids. The use of lead-antimony alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids, and excellent deep discharge and high discharge rate performance. Disadvantages of lead-antimony batteries are a high self-discharge rate, and as the result of necessary overcharge, require frequent water additions depending on the temperature and amount of overcharge [64].

Lead-Calcium

Lead-calcium batteries are a type of lead-acid battery which uses calcium (Ca) as the primary alloying element with lead in the plate grids. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids, a low self-discharge rate, and reduced gassing resulting in lower water loss and lower maintenance requirements than for lead-antimony batteries. Disadvantages of lead-calcium batteries include poor charge acceptance after deep discharges and shortened battery life at higher operating temperatures and if discharged to greater than 25% depth of discharge repeatedly [64].

Lead-Antimony/Lead-Calcium Hybrid

These are typically flooded batteries, with capacity ratings of over 200 ampere-hours. A common design for this battery type uses lead-calcium tubular positive electrodes and pasted lead-antimony negative plates. This design combines the advantages of both lead-calcium and lead-antimony design, including good deep cycle performance, low water loss and long life. Stratification and sulfation can also be a problem with these batteries, and must be treated accordingly. These batteries are sometimes used in PV systems with larger capacity and deep cycle requirements [64].

Gelled Batteries

Initially designed for electronic instruments and consumer devices, gelled lead-acid batteries typically use lead-calcium grids. The electrolyte is 'gelled' by the addition of silicon dioxide to the electrolyte, which is then added to the battery in a warm liquid form and gels as it cools. Gelled batteries use an internal recombinant process to limit gas escape from the battery, reducing water loss [64].

AGM (Absorbed Glass Mat)

Another sealed, or valve regulated lead-acid battery, the electrolyte in an AGM battery is absorbed in glass mats which are sandwiched in layers between the plates. However, the electrolyte is not gelled. Similar in other respects to gelled batteries, AGM batteries are also intolerant to overcharge and high operating temperatures. A key feature of AGM batteries is the phenomenon of internal gas recombination. As a charging lead-acid battery nears full state of charge, hydrogen and oxygen gasses are produced by the reactions at the negative and positive plates, respectively. In a flooded battery, these gasses escape from the battery through the vents, thus requiring periodic water additions. In an AGM battery the excellent ion transport properties of the liquid electrolyte held suspended in the glass mats, the oxygen molecules can migrate from the positive plate and recombine with the slowly evolving hydrogen at the negative plate and form water again [64].

Each battery type has design and performance features suited for particular applications. Again, no one type of battery is ideal for a PV system applications. The designer must consider the advantages and disadvantages of different batteries with respect to the requirements of a particular application. Some of the considerations include lifetime, deep cycle performance, tolerance to high temperatures and overcharge, maintenance and many others. Table 3-1 summarizes some of the key characteristics of the different battery types [64].

Battery type	Advantages	Disadvantages
Flooded Lead-acid		
Lead-Antimony	low cost, wide availability, good deep cycle and high temperature performance, can replenish electrolyte	high water loss and maintenance
Lead-Calcium Open Vent	low cost, wide availability, low water loss, can replenish electrolyte	poor deep cycle performance, intolerant to high temperatures and overcharge
Lead-Calcium Sealed Vent	low cost, wide availability, low water loss	poor deep cycle performance, intolerant to high temperatures and overcharge, can not replenish electrolyte
Lead Antimony-calcium Hybrid	medium cost, low water loss	limited availability, potential for stratification
Captive Electrolyte Lead-Acid		
Gelled	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
AGM (Absorbed Glass Mat)	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Nickel-Cadmium		
Sealed Sintered-Plate	wide availability, excellent low and high temperature performance, maintenance free	only available in low capacities, high cost, suffer from 'memory' effect
Flooded Pocket-Plate	excellent deep cycle and low and high temperature performance, tolerance to overcharge	limited availability, high cost, water additions required

Table 3-1: Characteristics of different battery types [64].

3.8.2 Batteries lifetime

In most industrial PV systems positive grid corrosion rather than cycle life limits the battery lifetime when tubular plate batteries are used. If flat plate batteries are used in Solar Home Systems (mostly PV lighting), the cycle life often does limit the battery lifetime, especially when a low battery capacity (low autonomy) is specified. It is sometimes less easy to predict the lifetime of sealed batteries due to ‘dry out’ and negative capacity loss. It is necessary to know both the cycle life at some deep discharge depth and the life on standby duty at some reference temperature for a particular battery type in order to make an accurate estimate of the lifetime in a particular PV system. Such information should be obtained from the battery supplier and suitable derating factors applied to them for PV system use. Specific PV system details required for the battery lifetime calculation are the average daily depth of discharge and the average battery temperature. These can only be estimated accurately after the PV system has been specified in some detail. [16].

3.9 Tracking systems

In order to increase the average output power of a photovoltaic system, a tracking system should be used. Tracking systems are able to increase the average power production making them an attractive solution for further efficiency improvement. The main task of a tracking system is to make the photovoltaic array able to follow the suns track during the day. In a photovoltaic system were a tracking system is used the PV modules are mounded on a moving platform (Figure 3-18). The movement of the platform is achieved with the help of motors, servos, or actuators (electric or hydraulic).

Figure 3-18: The moving platform of a tracking system

The control system of a tracking system is mainly based on microcontroller’s circuits. Photodiodes or photoresistors are used to sense the suns movement. The output of these sensors is the input for a microcontroller. The microcontroller controls a motor driver and the motor is energized.

3.10 Photovoltaic monitoring systems

There is a variety of monitoring devices for PV systems commercially available. The most common monitoring device is the charge controller with integrated LCD voltage and current meter (Figure 3-19).

Figure 3-19: A Steca Tarom charge controller.

Although the above device is a charge controller, it also features basic monitoring operations such as voltage, current and temperature readings. These readings represents only the total power production of the whole PV system thus, it is not possible for the user to have detailed information about the power conditions in a string of the PV installation.

Other monitoring devices are that of figures 3-20 and 3-21. These are remote displays that are wirelessly connected to the inverter of the PV system and displays parameters such as voltages, currents and temperatures [16].

Figure 3-20: A remote PV output display [16]

Figure 3-21: A wireless PV output display [16]

A type of monitoring system is that of figure 3-22. This display usually a large LDC monitor can be found in public buildings where the electricity production wanted to be shown to the public. It shows the power produced in a simple and no so technical way in order to show people the benefits of PV systems.

Figure 3-22: Public display from Fronius showing the PV power production [16]

3.11 Summary

This chapter provided a description about the types of photovoltaic systems as well as basic components of such systems. Hybrid and conventional Photovoltaic systems included in this chapter. Also, a brief theoretical background concerning the conversion of the DC to AC energy presented. The next chapter provides reader a description and also a first view of the PV monitoring system.

Chapter 4

System description

4.1 The scope of the ZigBee PV monitoring system

As already mentioned in the abstract and in section 1.2 of this thesis, the scope is to develop and design a monitoring and controlling system for PV systems that is based on a wireless technology. This technology is of course ZigBee.

The scope of this monitoring system is to act as an ordinary conventional monitoring system but not only that. This monitoring system has the ability to monitor continuously the state of each PV module separately in real time. Thanks to this functionality, the user is able to observe the health of each PV module and also its current power efficiency.

Many monitoring (data-acquisition) systems have been proposed and developed. The main task of these systems is to monitor and collect data concerning the performance of the PV plant in real time. Those kinds of systems give only a general performance monitoring image. They do not provide information about the performance and state of each individual PV module. In some cases, a specific PV module in a large scale PV plant may produce no or lower energy levels than expected. In this case, in monitoring system architectures that are already available, the system will be able to sense and monitor the lower current or voltage reading but it has no ability to locate the source of the problem. This is mainly because current and voltage sensors are connected at the output of a PV array that might be part of several PV modules. In this case it is obvious that a maintenance operator is needed to manually locate the defective part.

Failures as well as disoperation of any component that consist the PV system can be identified immediately. As it is will be described, the system estimates and monitors the state of the PV plant through a strain forward process contrary to other systems that base their operation on indirectly methods such as complicated statistical algorithms and comparisons of current performances with previous.

Some other parameters that are being monitored by the system are:

- PV module output voltage
- PV module output current

- PV module temperature
- Ambient temperature
- The total output voltage of all PV modules (array) of the PV system
- The total output current of all PV modules (array) of the PV system
- Inverter output voltage
- Inverter output current
- Inverter temperature
- Battery voltage
- Battery charging current
- Battery temperature
- Relative humidity
- Dust air concentration

The system provides two relay controlled outputs that can be used to control the motors, servos or the actuators of a tracking system and also a set of hall-effect angle sensors that are used to provide feedback to the tracking controller.

The system is connected to a PC and all parameters of the PV system can be accessed through an internet connection (optionally).

4.2 Main parts of the ZigBee monitoring system

In this thesis, the PV monitoring system being presented is installed in a PV system of an average output of 600Watts. The PV system is located at the roof of the TEI (Technical Educational Institute) (Figure 4-1). It is an array of six Shell SM-100 single crystal modules [56] with an output power of 100Watts each and maximum output open circuit voltage of 21Volts (Voc). The panels are connected in parallel. A solar tracker is not used here. The central unit of the monitoring system, as well as the PC is located at the reusable energy recourses laboratory of the Technical Educational Institute.

Figure 4-1: The six module PV array.

In this study, PV monitoring system architecture consists of two (2) basic blocks; the PV area sector (PVAS) and the central station sector (CSS):

a) ***PV area sector:*** This is actually the PV plant area where basic monitoring parameters are monitored. An alternative title instead of PVAS could be the (ZigBee modules area) and this is because each PV module in the plant is equipped with a ZigBee module and a set of sensors. The PVAS is part of ZigBee end devices (ZED) and a ZigBee router node (ROUT) that serves all ZED's as a sink to the ZigBee coordinator (COO).

b) ***Central Station sector*****:** It can be assumed that CSS is the control station of a PV system. In such a station, various components of a PV system like the inverter, the batteries and the battery charger could be found. In the CSS the ZigBee coordinator module, the host PC and the remote measurement board (REMB) are located.

In case of a decentralized stand alone or grid connected PV system, where there is no internet connection access, a GSM (Global System for Mobile communications) modem can be used for data transferring.

As previously mentioned, each PV panel has its own set of sensors connected to a PCB where a ZigBee module is placed. This ZigBee module is the end device of the ZigBee WPAN (ZED) (Figure 4-2).

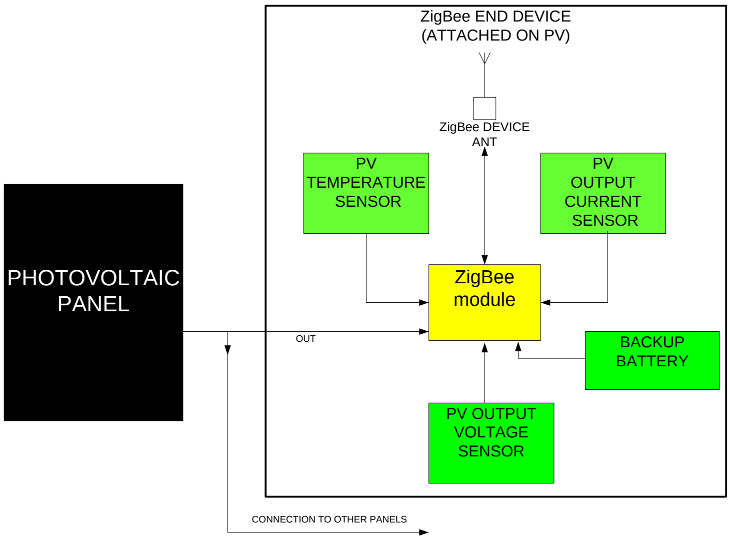


Figure 4-2: Simplified diagram of a ZED.

Figure 4-2, shows the block diagram of a ZED. Voltage and current sensors are connected to the output of the PV panel. Each sensors output is directly connected to an analog input of the ZigBee module and all readings are transmitted to the router board. A temperature sensor monitors the temperature of the PV panel and its output is also connected to an analog input of the ZigBee module.

In the present system of 6 PV modules array, the 5 of these PV modules are equipped with an end device (ZED).The 6th panel carries the network router device (ROUT) (Figure 4-3) where it serves all the other nodes as the networks data sink to the coordinator.
The router is a slight more complex device because of the extra functionality. That is the relay controlled output for the tracking system and also measurements of air dust concentration and angle position.

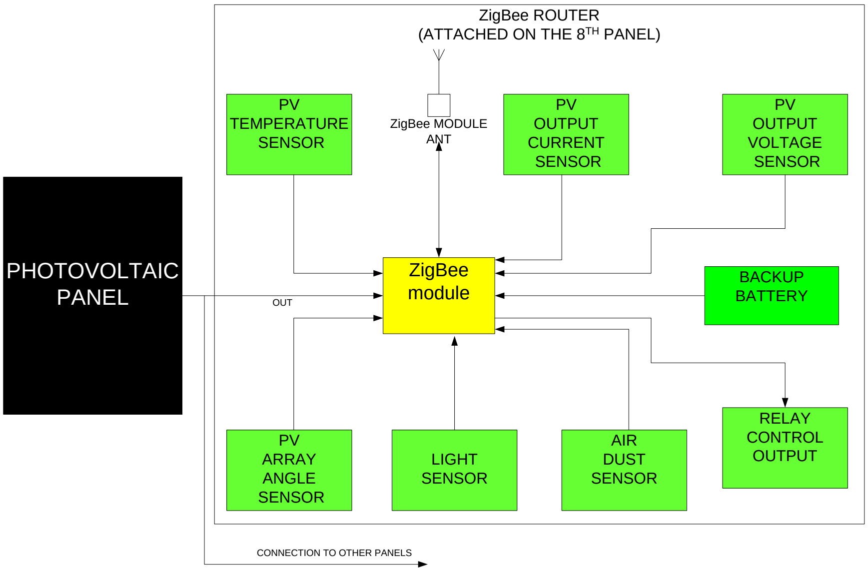


Figure 4-3: Simplified diagram of the router.

In figure 4-3, the block diagram of the router is shown. Here too, the central component is the ZigBee module. As with ZED, voltage and current sensors are connected to the output of the PV panel. Each sensors output is directly connected to an analog input of the ZigBee module and all readings are transmitted to the ZigBee coordinator. A temperature sensor monitors the temperature of the PV panel and its output is also connected to an analog input of the ZigBee module. Extra functionality is achieved with angle, light and air dust concentration sensors. In addition, a battery can maintain the router board to operate constantly even during night.

In the central station sector (CSS), the ZigBee coordinator device board (COO), the host PC, and other sensor equipment are positioned (Figure 4-4).

The coordinator collects all data of the end devices (ZED) through the router (ROUT) and supplies the host PC. The host PC runs the suitable GUI software platform where monitoring and data logging are implemented.

Also in the control station unit an Ethernet gateway module can placed optionally. It will function as a device for connection to the internet.

If an internet connection line is not available, then a GSM modem can be used instead for data transferring.

The coordinator module is capable of monitoring voltage and current values as well as temperature come from the PV electrical system which is parted from the charger controller, the battery, and the inverter.

Finally, figure 4-5 illustrates the measurement points at the control station.

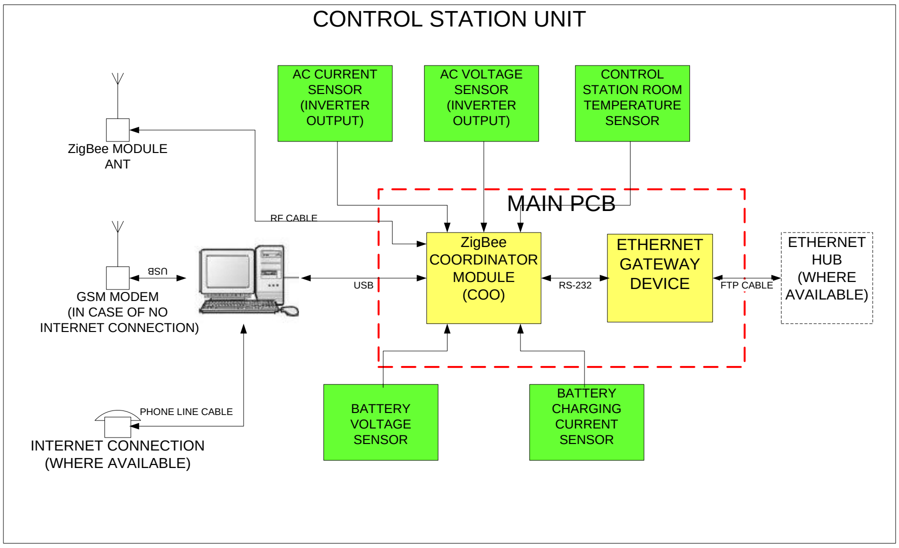


Figure 4-4: Block diagram of the CSS.

The CSS diagram is shown above. The red dashed line represents the main board of the ZigBee network coordinator. The set of sensors in the green blocks comprise another board that is called REMB (Remote Board) and it is usually located away from the main coordinator board. All sensors in the REMB are connected to the coordinator ZigBee module to analog inputs and all measurements are sent to the PC. A description of the REMB will be discussed later.

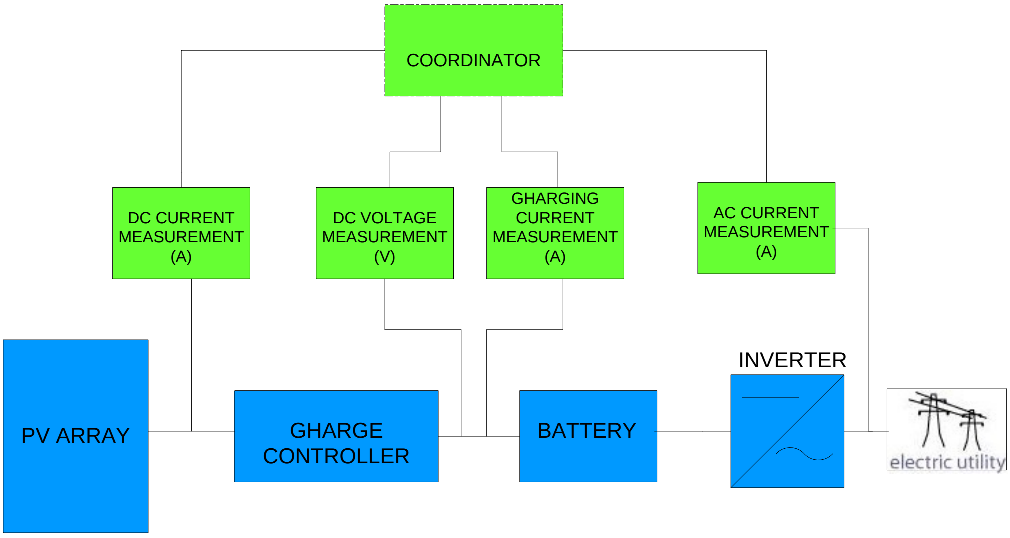


Figure 4-5: Measurement points at the CSS.

In the figure above, the blue blocks consist a basic PV system. The PV array, the charge controller, the battery and the inverter are all parts of a PV system as described in chapter 3. The green blocks represent not parts of the system but the measurement points in the CSS. It is also only an image of the monitoring points of the CSS. Furthermore, the current of the PV array is measured. Also, the voltage and current in the output of the charge controller are measured. Finally, the AC output current that is the actual output of the whole PV system is monitored constantly.

4.3 Summary

This chapter gave a simplified description of the main parts of the PV monitoring system. The system is divided in two subsystems that are the PVAS and CSS. A more detailed description of each part of the systems hardware follows next.

The Hardware

4.4 Introduction

In this chapter a detailed description of the hardware part of the monitoring system will follow. At the first subsection there is a brief description of the ZigBee modules that have been used. The hardware section of chapter 4 is divided in three parts where the first is dedicated to the COO board and REMB, the second to the ROUTER board and the third to the End devices boards.

4.5 The Telegesis ZigBee module

All hardware concerning the implementation of networking is based on the ETRX2 ZigBee module from Telegesis [18].

The Telegesis ETRX2 ZigBee module is a low power 2.4GHz ISM (Industrial Scientific Medical) band transceiver. The heart of this module is the EMBER EM250 IC [19] [20]. This IC solution offers a microprocessor and an RF circuitry in the same package. The module has been designed to be integrated into any device and provide a low cost, low power, wireless networking solution using the EMBER ZigBee platform consisting of the single chip combined with a meshing stack. Thanks to the AT-style command line, there is no need of complex software engineering. Using the default preloaded firmware; the ETRX2 is controlled using a simple AT command interface and (mostly) non volatile S-registers. Because of its advanced characteristics, the module has no need of a host microcontroller (in most cases of applications).

4.5.1 Hardware description of the ETRX2 module

The block diagram of the ETRX2 module is shown in figure 4-6. The main component of this module is the EM250 single chip ZigBee/IEEE802.15.4 solution [20] that is a combination of an RF transceiver with a microprocessor. The module is equipped with an LDO (Low Drop Out) regulator set at 1.8Volts for powering the EM250. Although the EM250 already contains an internal LDO regulator, the module can be supplied with an additional integrated onboard LDO regulator or DC/DC converter in case of a higher input voltage is required. The internal voltage regulator of the EM250 can be replaced by an ultra low quiescent current regulator if desired for further low current consumption.

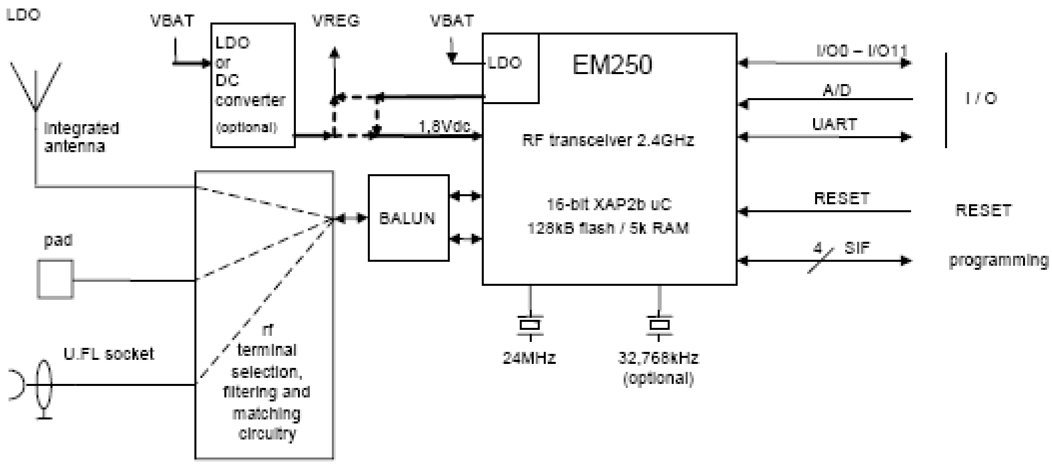


Figure 4-6: Block diagram of the ETRX2 ZigBee module [17].

RF front-end circuitry is also included. The user has the ability to select between three antenna configurations. Depending on the module type, the RF output terminal, can be a U.FL male socket, a 50ohm pad terminal (included in the modules pinout), or an integrated antenna.

All I/O pins of the EM250 are accessible on the module’s pads. The pre-loaded Telegesis AT Command Interface defines those I/O’s as described below. More information about the AT command instruction set will be given in appendix.

ADC

The module has two analog inputs A/D1 and A/D2. Readings with reference to the internal 1.2V reference voltage can be made locally as well as over the air.

An extra ADC (Analog to Digital Converter) is available that can be used for monitoring the modules supply voltage.

I/O

Pins I/O11 down to I/O0 are bi-directional I/O ports which can be controlled locally as well as remotely by accessing local as well as remote S-registers. The functionality of the I/Os can be controlled using three single 16-bit registers representing the data direction, the output buffer and the input buffer.

UART

The AT style command interpreter can be accessed via the TXD and RXD pins. The ETRX2 can buffer up to 128 bytes of incoming data in a software FIFO buffer and uses XON/XOFF or hardware flow control.

Interrupt

User configurable edges on pins I/O0 and I/O1 can cause interrupts if this function is enabled in the S-Registers.

Reset

Pulling the reset pin low will cause the module to restart.

PWM

I/O3 can alternatively act as a special function pin which can generate output waveforms up to 12MHz or act as a PWM (Pulse Width Modulation). This functionality can be controlled locally as well as remotely by accessing local as well as remote S-registers.

Antenna

Matching is provided to match the radio to the integrated antenna or to an optional external general purpose 2.4GHz antenna.

Power

The module is able to operate from 3.6V down to 2.1V which makes it ideally suited for battery-powered applications.

SIF

Interface for programming and real-time debugging the EM250.

The modules pinout is shown in table 4-1.

ETRX2 Pad	Function	EM250 GPIO	ETRX2 Harwin Pin
1	GND	GND	
2	Antenna		
3	GND	GND	
4	I/O9	GPIO 0 (21)	1
5	Vreg {1}		2
6	GND	GND	3
7	Vcc		10
8	GND	GND	3
9	A/D1	GPIO 4 (26)	4
10	A/D2	GPIO 5 (27)	5
11	I/O7	GPIO 3 (25)	6
12	I/O6	GPIO 2 (24)	7
13	I/O5	GPIO 1 (22)	8
14	I/O4	GPIO 12 (20)	9
15		GND	
16		SIF CLK	
17		SIF MISO	
18		SIF MOSI	
19		SIF LOADB	
ETRX2 Pad	Function	EM250 GPIO	ETRX2 Harwin Pin
20		GND	
21	I/O8	GPIO 6 (29)	11
22	I/O2	GPIO 11 (19)	12
23	I/O3	GPIO 13 (43)	13
24	Reset	(13)	14
25	I/O1	GPIO 14 (42)	15
26	I/O0	GPIO 8 (31)	16
27	TXD	GPIO 9 (32)	18
28	RXD	GPIO 10 (33)	17
29	GND	GND	3
30	I/O10	GPIO 15 (41)	19
31	I/O11	GPIO 16 (40)	20
32	GND	GND	
33	RXTXSW	(11)	
34	GND	GND	
35	GND	GND	
36	GND	GND	
37	GND	GND	
38	N/C	GPIO 7 (30)	

Table 4-1: ETRX2 pinout [17].

The table above shows the pinout of the ETRX2 ZigBee module. Also, the respective pins of the EM250 chip are given. The ETRX2 module is an SM (Surface Mount) component. If the user wishes to use the module as a plug-in solution, a Harwin 1.27mm pitch connector can be soldered on the modules extra soldering pads.

Below, some basic features of the ETRX2 module are shown as given in the Telegesis datasheet [17].

- Small form factor, SMT (Surface Mount Technology) module 37.5 x 20.5 x 3.2 mm.
- Optional board-to-board or board-to-cable connector.
- 3 RF output options: Integrated ceramic antenna, Hirose U.FL coaxial connector or single port 50Ω pad.
- XAP2b microcontroller with non intrusive debug interface (SIF).
- 128k flash and 5kbytes of SRAM.
- UART interface with DMA, hardware I^2C and SPI accessible with custom firmware.
- Wide supply voltage range (2.1 to 3.6V).
- Module comes with standard Telegesis AT-style software interface based on the EmberNet meshing stack.
- Can act as ZigBee End Device, Router or Coordinator
- 12 general-purpose I/O lines and 2 analogue inputs (all 17 GPIOs of the EM250 are accessible).
- Supports 4 different power modes for extended battery life.
- Current consumption below 1µA in deep sleep mode with self wakeup.
- Firmware upgrades via RS232 or over the air (password protected).
- Hardware supported encryption (AES-128).
- Tested for CE and FCC compliance (with integrated antenna), FCC modular approval.
- Operating temperature range: -40°C to +85°C.
- Options include: On board low power voltage regulator, DC/DC regulator and watch crystal.

4.5.2 The EM250 chipset

The EM250 is a single-chip solution that integrates a 2.4GHz, IEEE 802.15.4-compliant transceiver with a 16-bit XAP2b microprocessor [20]. It contains integrated Flash and RAM memory and peripherals of use to designers of ZigBee-based applications.

This transceiver utilizes an efficient architecture that exceeds the dynamic range requirements imposed by the IEEE 802.15.4-2003 standard by over 15dB. The integrated receive channel filtering allows for co-existence with other communication standards in the 2.4GHz spectrum such as IEEE 802.11g and Bluetooth. The integrated regulator, VCO (Variable Crystal Oscillator), loop filter, and power amplifier keep the external component count low. An optional high performance radio mode (boost mode) is software selectable to boost dynamic range by a further 3dB.

The XAP2bmicroprocessor is a power-optimized core integrated in the EM250. It supports two different modes of operation. System Mode and Application Mode.

The EmberZNet stack runs in System Mode with full access to all areas of the chip. Application code runs in Application Mode with limited access to the EM250 resources, this allows for the scheduling of events by the application developer while preventing modification of restricted areas of memory and registers.

The EM250 has 128kB of embedded Flash memory and 5kB of integrated RAM for data and program storage. The EM250 software stack employs an effective wear-levelling algorithm in order to optimize the lifetime of the embedded Flash.

To maintain the strict timing requirements imposed by ZigBee and the IEEE 802.15.4-2003 standard, the EM250 integrates a number of MAC functions into the hardware. The MAC hardware handles automatic ACK (Acknowledgement) transmission and reception, automatic backoff delay, and clear channel assessment for transmission, as well as automatic filtering of received packets. In addition, the EM250 allows for true MAC level debugging by integrating the Packet Trace Interface.

To support user-defined applications, a number of peripherals such as GPIO, UART, SPI, I_2C, ADC, and general purpose timers are integrated. Also, an integrated voltage regulator, power-on-reset circuitry, sleep timer, and low-power sleep modes are available. The deep sleep mode draws less than 1μA, allowing devices to achieve long battery life. [20].

4.6 Development tools

During the development of this project the following equipment had been used:

- A Telegesis development kit for ZigBee technology (TG-ETRX2DVK-Plus).
- Telegesis terminal software program.
- Microsoft .NET Framework Version 1.1.
- A Hameg 30MHz analog oscilloscope (HM 303-4).

- A Hameg function generator (HM 8030-5) 0.5Hz-5MHz.
- A Fluke (114) multimeter.
- A Hameg (HM 8040-3) triple output power supply.
- A Fujitsu-Siemens laptop (1.4 GHz AMD CPU, 512 MB RAM).
- 6 Photovoltaic modules (Shell SM-100) 12V.
- A STECA (Sollarix 9001) inverter.
- A STECA Tarom 245 charge controller.
- EpzS Ceac-Fulmen Solar batteries.

All PCBs had been designed with Protel 99’ SE.

4.6.1 The Telegesis development kit for ZigBee technology

The Telegesis development kit had been proved a simple but extremely useful tool during the development end evaluation phase of this project. The kit, (Figure 4-7) comes with one main development board, three carrier boards, one ETRX2 module in USB (Universal Serial Bus) stick form, two ETRX2 modules with Harwin connectors, and other peripherals.

Figure 4-7: The Telegesis development kit [18].

The kit gives the user the ability to develop and test every application that comes in mind. I/O devices such as LEDs, switches, buzzers, potentiometers are available. Various electrical measurements are easy to be taken. The USB bridge that is included in the main board offers an easy way for connection to the PC. However all boards comes with an additional (RS-232) serial port.

4.7 Hardware description of the system's coordinator (COO)

4.7.1 Introduction

At the CSS (Central Station Sector) the ZigBee WPAN coordinator board is located. In this sector, a second board, called REMB (Remote Board) is also located. The REMB is a PCB (separated from the COO board), equipped with a number of sensors for measurement of voltages, currents and temperatures of the inverter and the PV system batteries. Further description of the REMB will be given in next subsection.

4.7.2 The COO board circuit

The block diagram, as well as the schematic diagram of the COO board are shown in figure 4-8 and figure 4-9 respectively. Figure 4-10 shows a photo of the final configuration of the COO board.

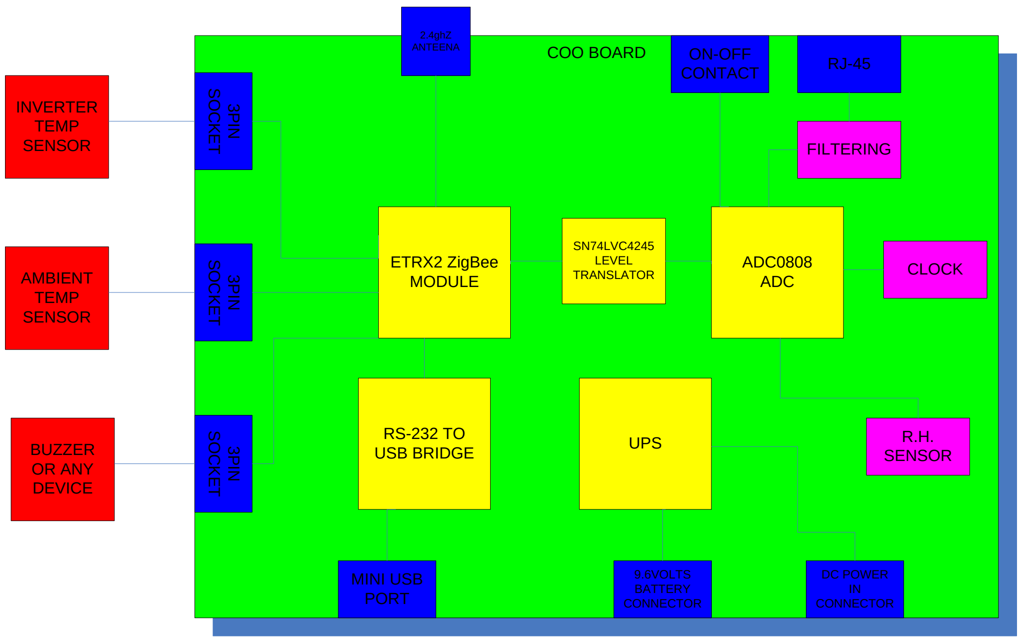


Figure 4-8: COO board block diagram.

The block diagram of the COO board is shown in figure 4-8. In yellow blocks, there are main parts of the board. The blue blocks indicate sockets and connectors. The red blocks are external input components (sensors) or output components like a buzzer, a relay or any auxiliary device. Back to yellow blocks, the ETRX2 module is connected to a USB port through an RS-232 to USB bridge. All data from the monitored PV system will pass through this port to the PC. A level translator is used as an interface between ERTX2 and the ADC. An uninterruptable power unit (UPS) is used for the supply of the board. An RJ-45 connector offers connection of the COO board with the REMB. The REMB carries another set of sensors and it will be discussed later. The relative humidity sensor is connected to an input of the ADC. The COO board can also support two extra sensors like temperature. Any type of sensor can be connected to these inputs.

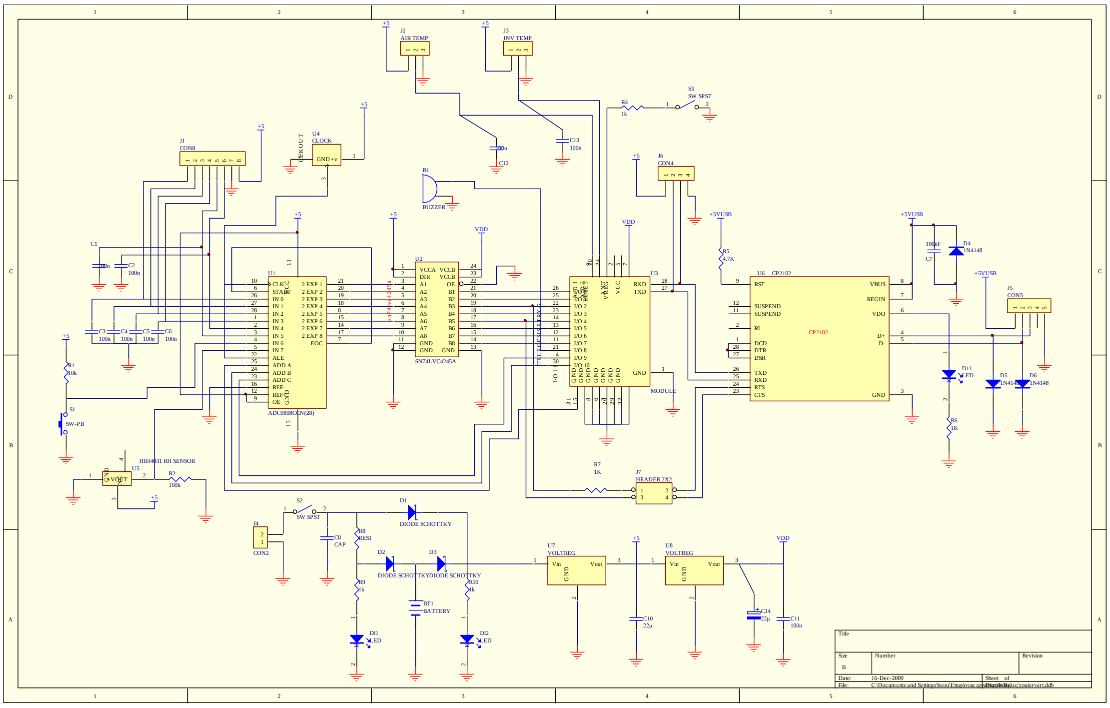


Figure 4-9: Schematic diagram of the COO board.

At the center of the block diagram, there is an ETRX2HR-PA ZigBee module (U3). This module is the ZigBee network coordinator. The module comes with a U.FL socket for connection to an external antenna (no intergraded antenna included). Another characteristic of this module is the PA lettering. This lettering indicates the boosted version of the module (Power Amplified). U3 is directly connected to the 3.2Volt bus of the circuit.

4.7.2.1 Parts of the COO board

The main parts (blocks) of the COO board are:

- The ZigBee module.
- The ADC (Analog to Digital Converter).
- The voltage level translator.
- The serial (RS-232) port.
- The RS-232 to USB interface.
- The relative humidity sensor.
- The temperature sensors.
- The UPS-power supply.
- The battery.

A full description of each block will follow next.

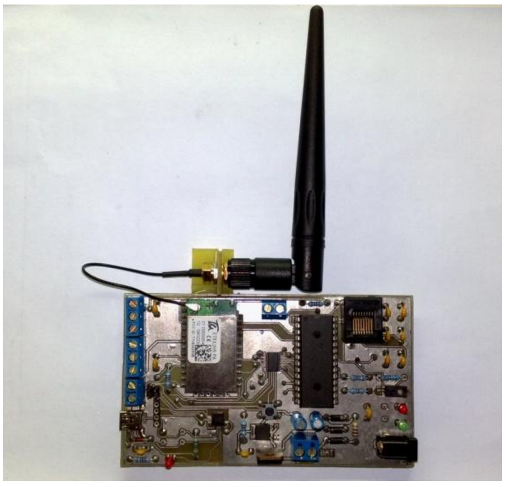


Figure 4-10: General view of the COO board.

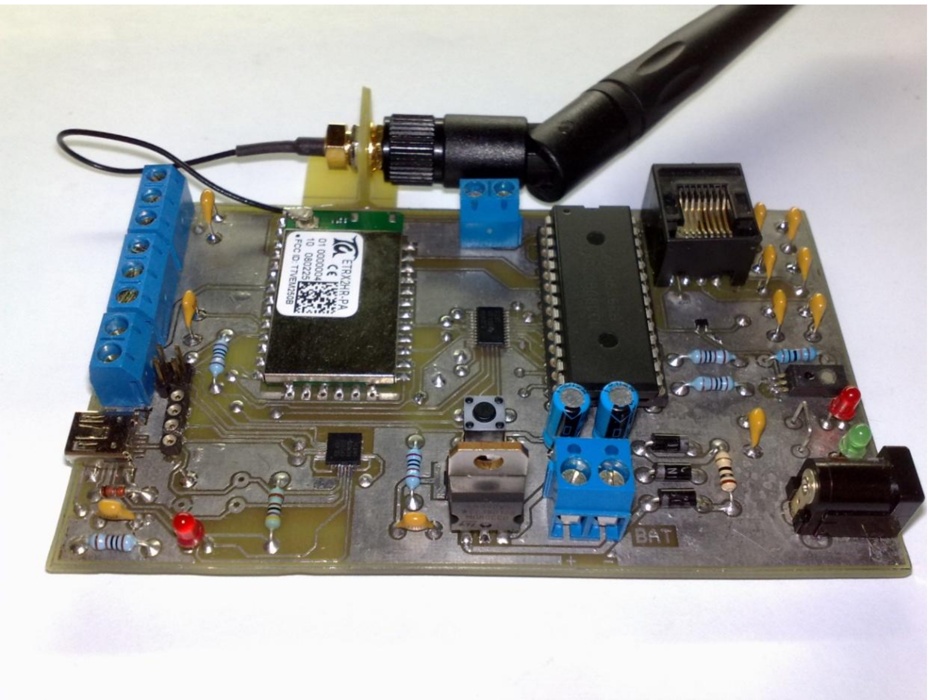


Figure 4-11: Detailed view of the COO board.

4.7.2.2 Description of the parts

4.7.2.3The ADC

The ADC used here to convert the output signals of the sensors to a digital form is an 8-bit successive approximation with parallel output bus ADC of National Semiconductors [21] [22]. The ADC0808CCN (Figure 4-12) is in fact a data acquisition device in monolithic CMOS technology with an 8-bit analog-to-digital converter, an 8 channel multiplexer and microprocessor compatible control logic. The converter features a high impedance chopper stabilized comparator, a 256R voltage divider with analog switch tree and a successive approximation register. The 8-channel multiplexer can directly access any of 8-single-ended analog signals. The device eliminates the need for external zero and full-scale adjustments. Easy interfacing to microprocessors is provided by the latched and decoded multiplexer address inputs and latched TTL TRI-STATE outputs [23].

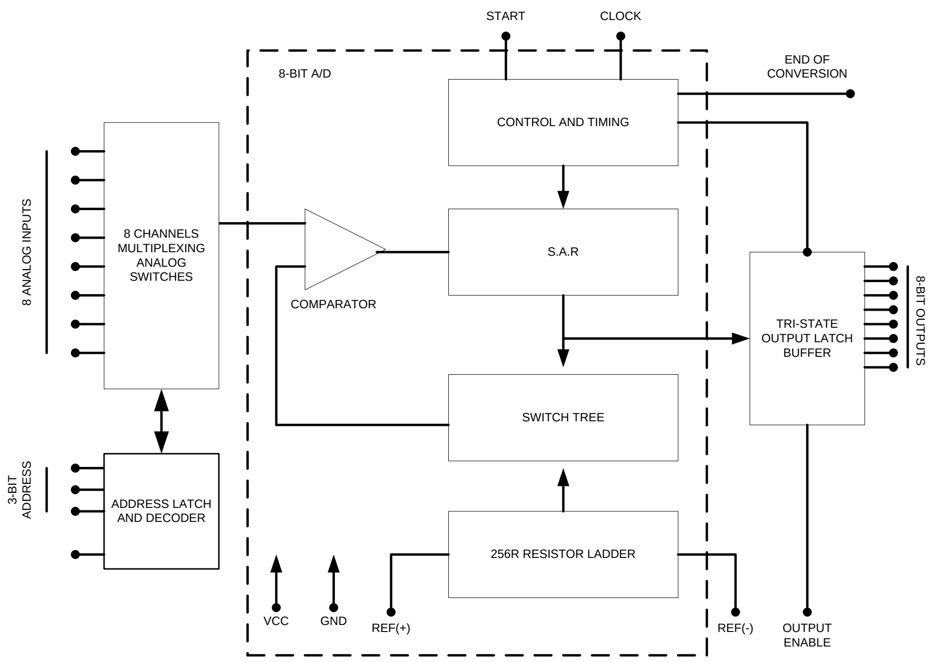


Figure 4-12: Block diagram of the ADC0808 [23].

In the COO board, there is a variety of sensors. Using the ADC0808CCN there is no need of an external channel multiplexer to select an output coming from a specific sensor. As shown in the schematic diagram the desired sensor output is selected through a 3-bit control bus (pins 23, 24, 25 on the U1) coming from the ZigBee module (pins4, 30, 31 on the U3). Pins 8, 14,15,17,18,19,20,21, of U1 are the 8-bit bus output of the ADC connected to the U2 (voltage level translator). End of conversion pin (7 on U1) is directly connected to the start conversion pin (6 on U1) thus the ADC is able to operate in a stand alone continuous conversion mode.

During the designing phase of the ADC parts of this project a variety of components coming from other manufacturers like Texas Instruments [24] and Analog devices [25] had been tested. Although these devices are more advanced, faster, and smaller than the ADC0808CCN that is a bulky DIP-40 component, the last had been chosen for the ease of use, the built-in input selector and mostly for the continuous conversion operation mode. Thanks to this mode, the component is able to operate as a stand alone device and thus there is no need for an extra microcontroller or an extra pin from the ETRX2 module to control the ADC. U1 is directly connected to the 5Volt bus.

4.7.2.4 Clock device for the ADC0808CCN

The ADC0808CCN requires clock pulses (any frequency in the range 10 KHz to 1280 KHz) to inputs CLK and ALE (pins 10 and 22 respectively). The clock signal can be supplied from en external oscillator. As shown in the schematic diagram, (Figure 4-13), this external oscillator is the U4. This component is the MAX7375AXR604 [27] 3-pin silicon oscillator from Maxim [26]. The MAX7375 is a silicon oscillator, intended as a low cost improvement replacing ceramic resonators, crystals, and crystal oscillator modules used as the clock source for microcontrollers, ADCs and UARTs in 3V, 3.3V, and 5V applications.

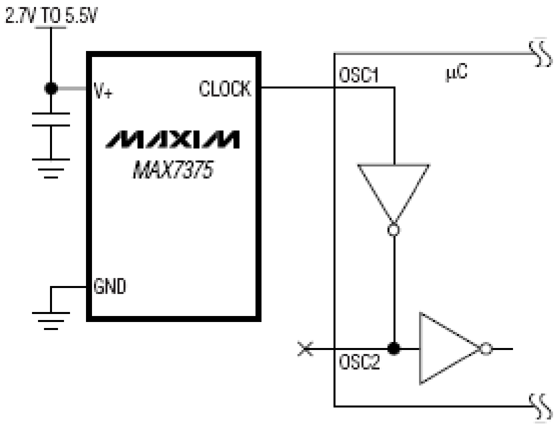


Figure 4-13: Typical application circuit [27].

The MAX7375 is an ideal crystal replacement cased in a tiny SMD (Surface Mount Device) SC-70 package measuring only 2.2mm x 1.35mm saving valuable space in the PCB. Using the U4 the need of external balancing capacitors and resistors that are critical in case of a crystal oscillator had been eliminated. U4 is directly supplied from the 5Volt bus. Figure 4-8 shows a typical application of the MAX7375. The device can just be connected to the input of any device that needs a clock source.

4.7.2.5 The voltage level translator

As mentioned in subsection 4.5.1, the ETRX2 module I/Os works fine when the logic inputs voltages for 'low' and 'high' conditions are not violate a specific range. The maximum input voltage for the 'high' state must not exceed the maximum input supply voltage of the module that is 3.6Volts [17]. As given in the ADC0808CCN data sheet, the output voltage at the 8-bit bus for a ‘high’ state is the supply voltage that is 5Volts. It is obvious that the 5Volts at the 8-bit bus of the ADC0808CCN must be equalized with the maximum I/O input voltages of the ETRX2. This can be easily achieved with the use of the SN74LVC4245A octal bus transceiver and 3.3V to 5V shifter [28] (Figure 4-14) by Texas Instruments [24]. This 8-bit (octal) non-inverting bus transceiver contains two separate supply rails. B port has V_{CCB}, which is set at 3.3 V, and A port has V_{CCA}, which is set at 5 V. This allows for translation from a 3.3-V to a 5-V environment, and vice versa. The SN74LVC4245A is designed for asynchronous communication between data buses.

The device transmits data from the A bus to the B bus or from the B bus to the A bus, depending on the logic level at the direction-control (DIR) input (Table 4-2). The output-enable (OE) input can be used to disable the device so the buses are effectively isolated. The control circuitry (DIR, OE) is powered by V_{CCA}. The designer uses the data paths for pins 2–11 and 14–23 of the SN74LVC4245A to align with the conventional ‘245 pinout [28]. Figure 4-10 shows the block diagram of the SN74LVC4245A (only one of eight channels shown).

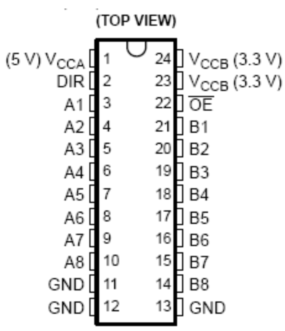


Figure 4-14: SN74LVC4245A pinout

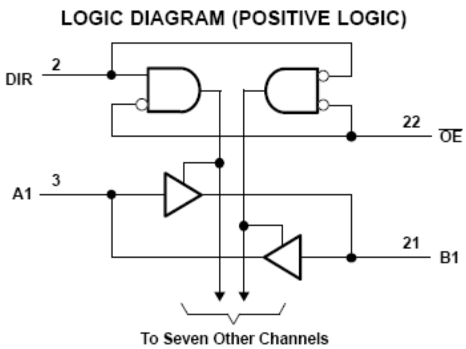


Figure 4-15: Block diagram

INPUTS		
OE	DIR	OPERATION
L	L	B data to A bus
H	L	A data to B bus
H	X	Isolation

Table 4-2: Function table

During the designing phase, the first attempt to equalize the logic levels of the ADC0808CCN end ETRX2 was the connection of eight 3.2volts Zener diodes at the data bus.

This solution seemed to work fine but the extra current that flew through each diode during the voltage regulation (approximately 2mA per diode), increased the current consumption at (2mA x 8=16mA, when all bits 'high') over the total power consumption.

4.7.2.6 The serial port

The ETRX2 ZigBee module supports communication with other devices via the RS-232 serial port. In the schematic diagram (Figure 4-9), J6 is actually a socket made from Swiss round connector for connection of the COO board to a PC via a serial cable. Pins 2 and 3 of the socket are connected to pins 27 and 28 of ETRX2 module respectively. Pin 1 of the socket, is used to deliver power from the 5Volt bus to the RS-232 driver-receiver that is enclosed in the male socket of the serial cable. (Further details about the serial cable are given in chapter 4.11).

4.7.2.7 The RS-232 to USB interface

Extra versatility concerning the communication of the COO board with a PC can be obtained with the addition of a USB to UART (Universal Asynchronous Receiver-Transmitter) bridge. This function can be easily work with the CP2102 single-chip USB to UART bridge [29] by Silicon Labs [30].

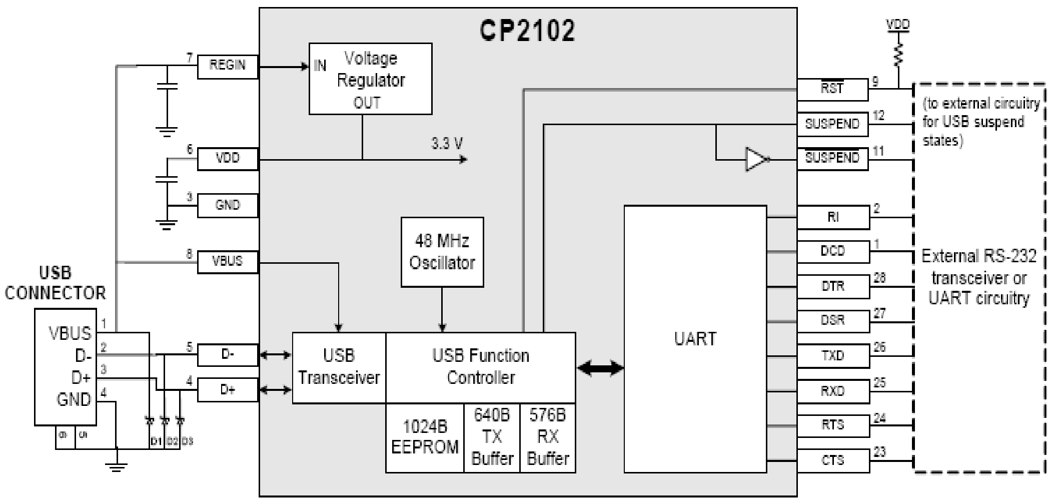


Figure 4-16: Block diagram of CP2102 [29].

The CP2102 (U6), (Figure 4-16) is a highly-integrated USB-to-UART Bridge Controller providing a simple solution for updating RS-232 designs to USB using a minimum of components and PCB space. The CP2102 includes a USB 2.0 full-speed function controller, USB transceiver, oscillator, EEPROM, and asynchronous serial data bus (UART) with full modem control signals in a compact 5 x 5 mm QFN-28 package. No other external USB components are required.

The on-chip EEPROM may be used to customize the USB Vendor ID, Product ID, Product Description String, Power Descriptor, Device Release Number, and Device Serial Number as desired for OEM applications (see next subclause). The EEPROM is programmed on-board via the USB allowing the programming step to be easily integrated into the product manufacturing and testing process. Royalty-free Virtual COM Port (VCP) device drivers provided by Silicon Laboratories allow a CP2102-based product to appear as a COM port to PC applications. The CP2102 UART interface implements all RS-232 signals, including control and handshaking signals, so existing system firmware does not need to be modified. In many existing RS-232 designs, all that is required to update the design from RS-232 to USB is to replace the RS-232 level-translator with the CP2102 [29].

As shown in the schematic diagram (Figure 4-17), the CP2102 (U6) is connected in such a way that can operate as a stand alone device. This means that the input power supply comes directly from the USB port of the PC. A red LED (Light Emitting Diode), indicates the connection to the USB port. D5, D6 are schottky ESD (Electrostatic Sensitive Device) protection diodes.

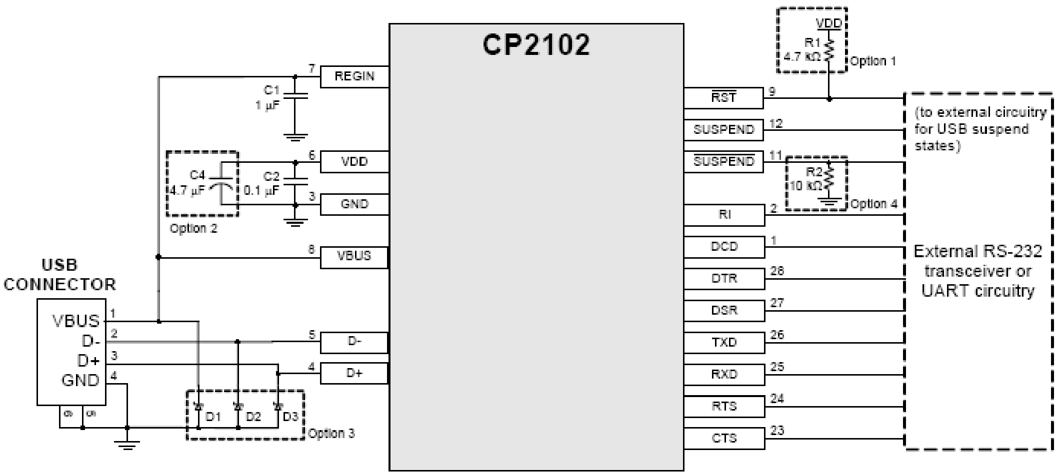


Figure 4-17: Typical connection diagram [29].

A typical connection of the CP2102 chip is shown above. At the left, there is the USB port. At the right there are the UART lines to the RS-232 device.

4.7.2.8 CP2102 programming

In order for the CP2102 to work properly, the chip software driver must first be installed in the PC. This software is free and is available in the Silicon Labs site. A number of tools and application are available too. Optionally, the user is able to write to the on-chip EEPROM and customize various parameters. Application AN220 [32], is a software tool that provides access to the chip via the USB port. No external programmers are needed.

4.7.2.9 Relative humidity sensor

A relative humidity sensor is an extra feature for the COO board. This feature can be useful when the user wishes to have humidity <picture> of the environment near to the COO board. The Honeywell HIH4031 [33] relative humidity sensor, is a compact SMT device designed for a variety of applications requiring humidity measurements like HVAC (Heating, Ventilation and Air Conditioning), metrology, medical equipment and other. This device offers a near linear voltage output versus % relative humidity (Figure 4-18). The output voltage at 0%RH is about 0.7Volt and reaches 3.7Volts at 100%RH.

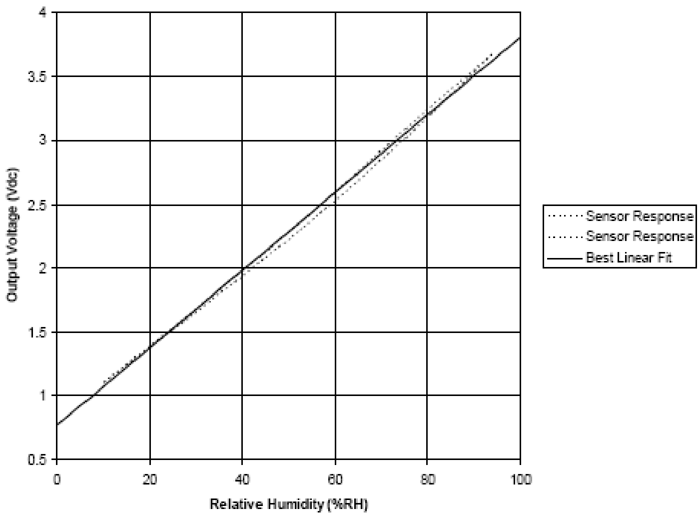


Figure 4-18: Typical output voltage versus relative humidity (@25C)

Back to the schematic diagram (Figure 4-9), R2 is the output load of the HIH4031 (U5). The sensor output is connected to pin5 (input 7) of the ADC0808CCN.

4.7.2.10 UPS-Power supply, Battery

The COO board requires two different voltages to operate like 5 and 3.2Volts. It is essential for the COO board to operate constantly, therefore, a basic UPS (Uninterruptible Power supply) circuit added to it. This fundamental UPS is actually an 'OR' gate that is formed by three schottky diodes 1N 5818 the D1, D2, and D3 [34]. When the circuit is powered from mains, (12Volts DC 1A) at socket J4, D1 and D2 are in 'ON' state while D3 is 'OFF'. The COO board then is directly powered from mains while the battery is charging through D2 and current limiting resistor R8. Two LEDs, D11 (green), and D12 (red) are glow to indicate that the battery is charging and the COO is powered from mains. In case of mains power failure, diodes D1 and D2 are in 'OFF' state while D3 is 'ON'. In this case the COO is powered from the battery and LED D12 (RED) is glowing indicating that the COO runs on battery. The battery can be a 12Volts Ni-MH pack, a lead acid or a sealed type.

4.7.2.11 Voltage regulators

Two different voltages are taken out from two linear voltage regulators. These are the LM4940V5 ultra low-dropout linear voltage regulator for 5Volts output by ST (U7) [35] [36], and the LM1117 low-dropout linear regulator for 3.3Volts by National Semiconductors (U8) [22] [61].

4.8 Hardware description of REMB

4.8.1 Introduction

The REMB is the second part of the CSS and is a board where all sensors are connected (Figure 4-19). As shown in block diagram, a number of sensors like current and temperature are separated from the REMB. This is mainly because the measurement points (e.g. inverter voltage, current, or temperature) may be located far from REMB. The connection of sensors to the REMB is done through shielded stereo audio cables. The reason why the CSS is divided into two parts (COO board and REMB) is mainly because with this implementation all dangerous high voltages and currents are kept isolated from COO board and REMB where the user might have access when the system is on. Other reason is that interferences from high voltages and currents are kept away from the ETRX2 module and the PC. Connection between REMB and COO board is done with a UTP Ethernet cable.

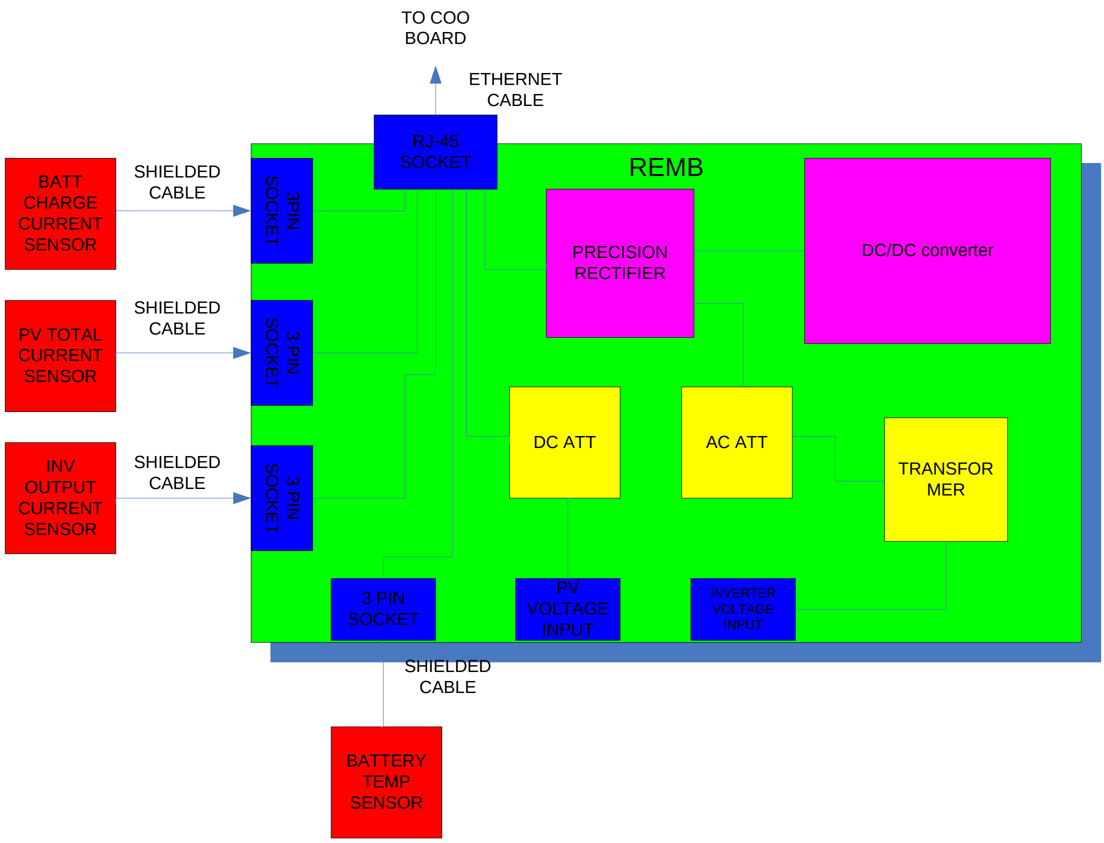


Figure 4-19: Block diagram of REMB.

In the block diagram of figure 4-19, the blue blocks represents sockets or connectors. The RJ-45 connector is used for the communication between The REMB and the COO boards. The DC attenuator as well as the AC attenuator are simple voltage dividers. These dividers are used to interface the high voltages of the PV array and also of the AC inverter output to a voltage range that does not exceeds the maximum input voltage of the ADC at the COO board. The DC/DC converter supplies a precision rectifier. Further explanation of each block follows.

4.8.2 Parts of the REMB

The main parts (blocks) of the REMB are:

- The DC voltage divider.
- The AC voltage divider.

- The Precision rectifier.
- The DC/DC inverter.
- The PVs total current sensor.
- The battery charging current sensor.
- The inverter output current sensor.
- The battery temperature sensor.

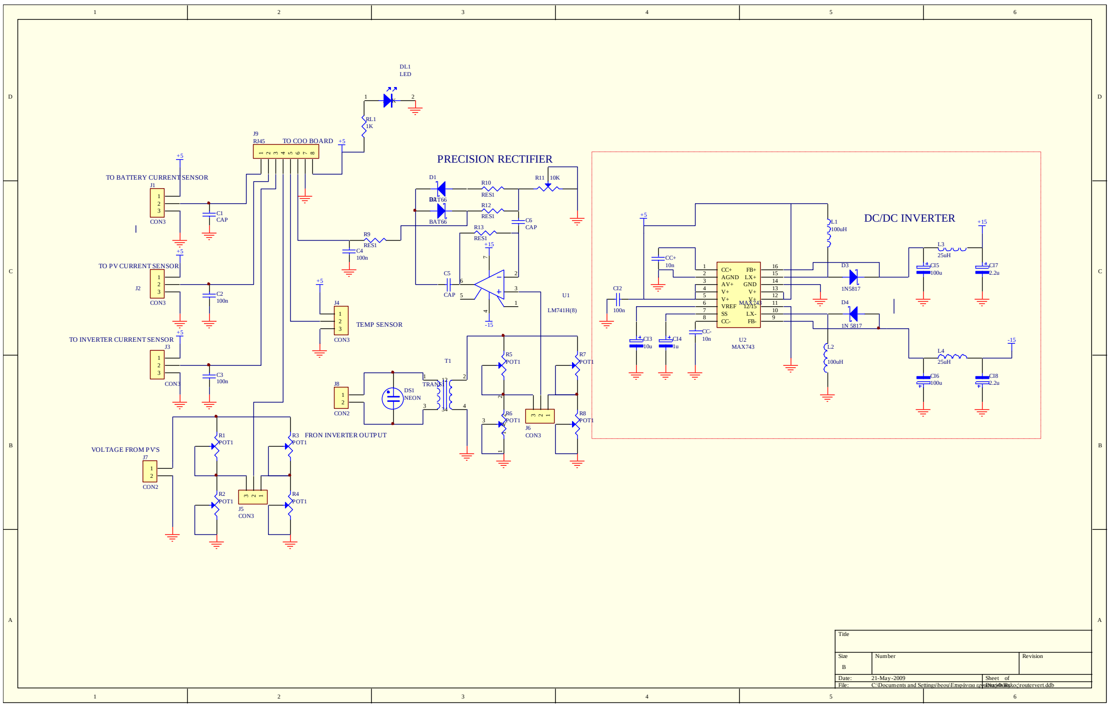


Figure 4-20: Schematic diagram of REMB.

The red dashed lined box in figure 4-20, is the DC/DC converter. An operational amplifier forms the precision rectifier. A transformer and adjustable voltage dividers lowers the high monitored voltages.

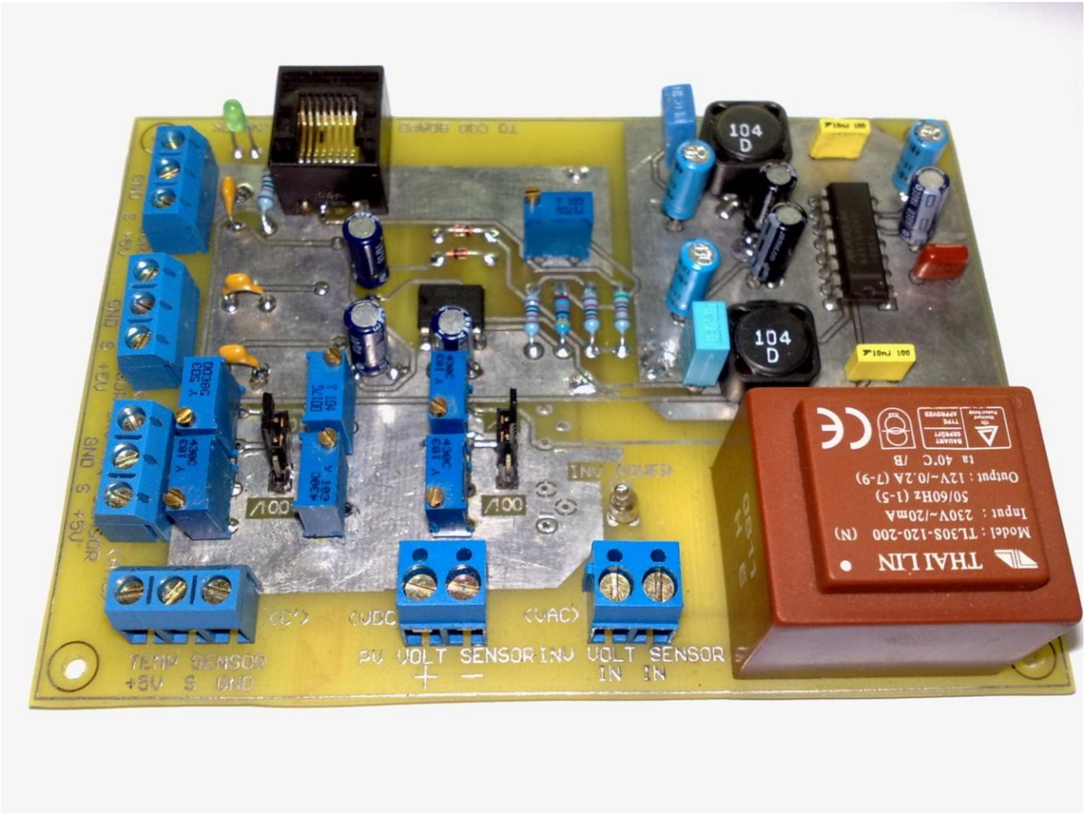


Figure 4-21: General view of the REMB.

In this picture the transformer, the connectors, the precision rectifier and the DC/DC circuitry of the REMB are easily visible.

4.8.2.1 The DC voltage divider

As already known, the output voltage of a PV (Photovoltaic System), may vary depending on the connection of the PV panels in a PV array. Although the most usual voltages of 12Volts and 24Volts the DC output might be much higher if the PV panels are connected in series. Because of the limited maximum input voltage of the ADC0808CCN (5Volts, also see [23]), the DC voltage from the PV system to be measured has first to be attenuated. This can be done with a voltage divider. There are two voltage dividers for DC attenuation here. The first is formed from trimmers R1 and R2 (Figure 4-20). The second is formed from trimmers R3 and R4. One of these dividers can be selected moving jumper J5. The input to output voltage ratio can be adjusted by the trimmers. Here, ratios of 10 or 100 are preset. That means that for an output voltage of 15Volts from the PV system, the voltage divider will output 1.5Volts. As shown in the schematic diagram (Figure 4-20), the voltage divider output is connected to pin4 of an RJ-45 socket. Via an Ethernet cable the sensed voltage will reach input 3 (pin1) of ADC0808CCN at the COO board.

4.8.2.2 The AC voltage divider

The output voltage of an inverter in a typical PV system is usually 120-220Volts AC. This voltage is prohibitive for the input of the ADC0808CCN as with for all ADCs. As with previous attenuator, here too the high AC voltage has to be attenuated. A simple transformer T1, (Figure 4-20) attenuates the AC voltage to approximately 12 volts. Two voltage dividers (trimmers R5, R6, R7, and R8) further attenuate this voltage to a ratio of 10 or 100. The voltage from dividers is driven to the precision rectifier. The neon lamp DS1 indicates that the inverters output is active.

4.8.2.3 Precision rectifier

The output of the AC voltage divider drives the non-inverting input (pin3) of the LM741 operational amplifier [22] [37] [38] (Figure 4-20). This operational amplifier circuitry is designed to operate as a precision rectifier. The precision rectifier is capable of rectifying very small AC signals. The DC output signal from the precision rectifier is connected to pin6 of the RJ-45 socket. Via the Ethernet cable the sensed voltage will reach input 4 (pin2) of ADC0808CCN in the COO board. D1 and D2 are BAT66 schottky diodes that are actually a full wave rectifier. R9 and C4 form a low-pass filter. Trimmer R11 is used for calibration of the precision rectifier. The LM741 requires a symmetric (+/-15Volts) power supply.

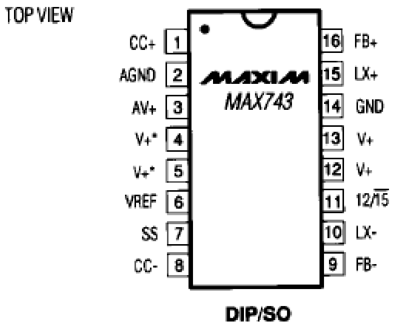
4.8.2.4 The DC/DC inverter

The required symmetric voltage for the LM741 is supplied from the DC/DC inverter circuit. This circuit is based on the MAX743 dual output, switch-mode regulator [26] [39] (Figure 4-20).

The MAX743 DC-DC converter IC contains all the active circuitry needed to build small, dual-output power supplies. Relying on simple two terminal inductors rather than transformers, the MAX743 regulates both outputs independently to within +/-4% over all conditions of line voltage, temperature, and load current. The MAX743 typically provides 75% to 82% efficiency over most of the load range. It operates with current mode feedback at

200 KHz, so it can be used with small, lightweight external components. Also, ripple and noise are easy to filter.

Thermal shutdown prevents overheating, and cycle-by-cycle current sensing protects the internal power switch transistors. Other features include under voltage lock-out and programmable soft start [39]. A typical connection of the MAX743 is shown in figure 4-22. In the schematic diagram (Figure 4-20) D3 and D4 are 1N5818 schottky diodes. L1 and L2 are 100nH MSS1260T-104NL SMT power inductors [40] from Coilcraft [41]. Figures 4-22, 4-23, and 4-24 shows the pinout and the block diagram of the MAX743.



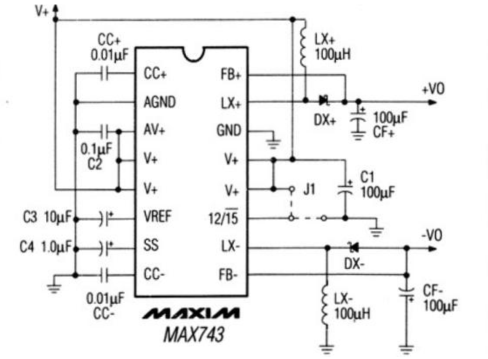


Figure 4-22: MAX743 pinout [39**].** **Figure 4-23**: Typical connection [39].

The pinout and a typical connection are depicted above. A pair of inductors, diodes and some capacitors is enough to form a low cost DC/DC converter

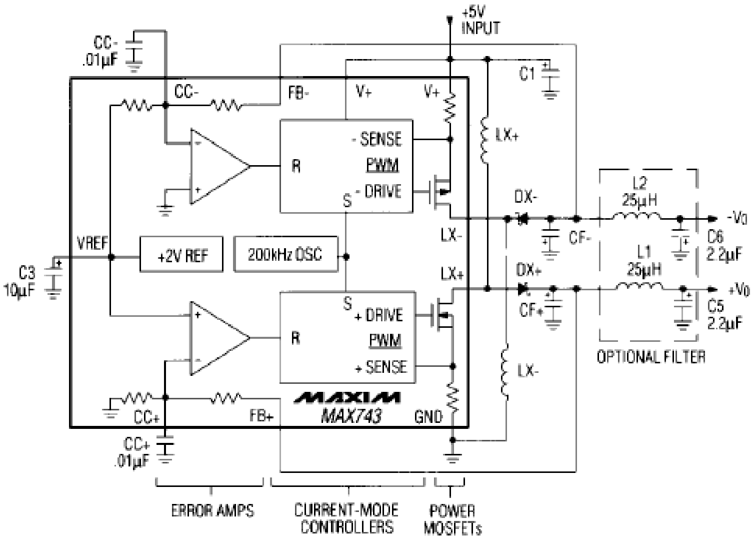


Figure 4-24: MAX743 block diagram [39].

Above, the internal circuitry of the MAX743 is shown. Two operational amplifiers (error amplifiers) are fed through a feedback resistor in order to form a closed loop control. The output is controlled by two FETs that are driven by PWM signals.

4.8.2.5 PV total current sensor

Another parameter that is being monitored by the system is the PV array total output current. The basic component of this sensor is the ACS756SCA-100B fully Integrated, Hall Effect-Based Linear Current Sensor with High Voltage Isolation and a Low-Resistance Current Conductor [42] by Allegro Microsystems [43].

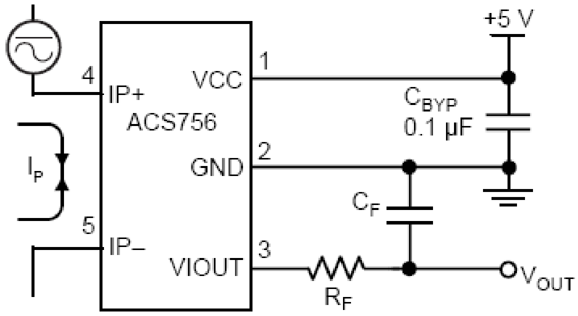


Figure 4-25: Typical application [42].

The Allegro ACS75x family of current sensors provides economical and precise solutions for current sensing in industrial, automotive, commercial, and communications systems. The device package allows for easy implementation by the user. Typical applications include motor control, load detection and management, power supplies, and over-current fault protection. The device consists of (see block diagram Figure 4-26) a precision, low-offset linear Hall sensor circuit with a copper conduction path located near the die. Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. A precise, proportional voltage is provided by the low-offset, chopper-stabilized BiCMOS Hall IC, which is programmed for accuracy at the factory.

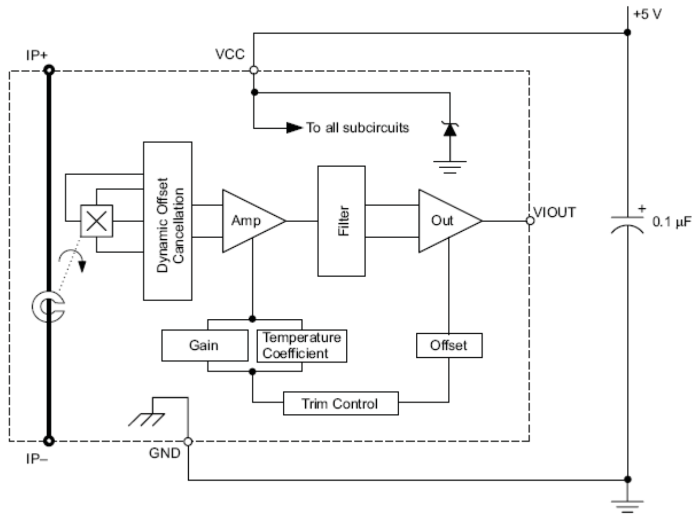


Figure 4-26: ACS756 block diagram [42].

The thickness of the copper conductor allows survival of the device at up to 5 over-current conditions. The terminals of the conductive path are electrically isolated from the sensor leads (pins 1 through 3). This allows the ACS75x family of sensors to be used in applications requiring electrical isolation without the use of opto-isolators or other costly isolation techniques [42]. The sensor is designed for measuring currents of up to 500Amps. This covers the need of current measurement in the case of a high power PV system where multiple PV modules might be connected in parallel. The current sensor is connected to connector J2 in the REMB via a stereo audio shielded cable. The sensor is connected in series to the PV array cable at measurement ((+) (pin4)) and ((-) (pin5)) lids (8mm bolts) see figure 4-32.

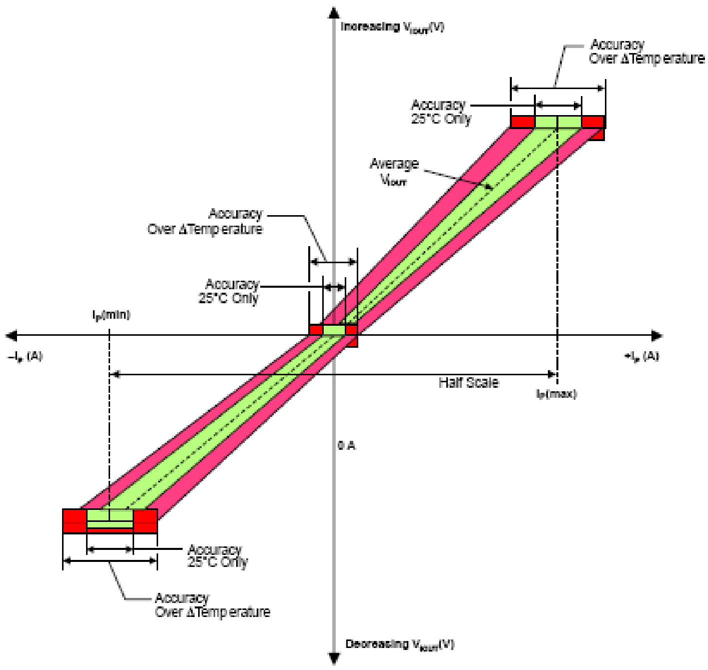


Figure 4-27: Output voltage versus sensed current [42].

The output of the device (Figure 4-27) has a positive slope (>VCC / 2) when an increasing current flows through the primary copper conduction path (from terminal 4 to terminal 5), which is the path used for current sensing. The internal resistance of this conductive path is typically 130μΩ, providing low power loss.

4.8.2.5.1 Construction data of the current sensor

The ACS5756-100 has a current sensing limit of 100Amps.Usually the maximum output current of a number of arrays may exceed this range. If a larger current measurement range is desired then a current divider must be used. The current divider simply splits the current path. In present application, the maximum sensed current was defined to be 500Amps. That means that the current divider has to divide the total current (Itot) by a ratio of 5. The 1/5th of total current (100Amps) passing R1 in figure 4-28 is the sensed current (Isense). Because of the high current, the use of resistors is prohibitive. Instead of resistors, the physical resistance of the sensor itself may be used. This physical resistance can be adjusted selecting the appropriate dimensions of a shunt resistor.

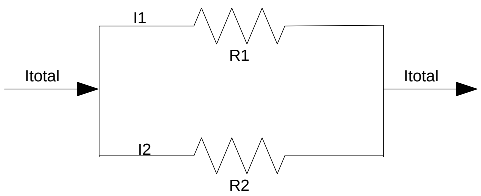


Figure 4-28: A simple current divider.

According to Allegro Microsystems application note AN295036 [44], the ACS756 must be placed in a 1mm thick copper bus bar as shown in figure 4-28. The total current (Itot), is divided to Isens and Ishunt.

The trace layout dimensions for dividing a current path to measure a given fraction of the total current can be calculated using the equations below (reference circuit of figure 4-29).

Given:

- Isens, measured proportion of Itot (A)
- Lsens1 , length of sense subpath side 1 (m)
- Lsens2 , length of sense subpath side 2 (m)
- Lshunt , length of shunt subpath (m)
- c , resistivity (typical) of the copper trace material (m)
- Rprimary , resistance (typical) of the primary conductance path in the sensor ()
- T , thickness (typical) of traces (m)
- Wsens , width of sense traces (both sides) (m)

The ratio of the resistance of the sense current subpath,

- Rsens (Ω), the shunt current path,
- Rshunt (Ω), is defined by the equation for a current divider circuit.

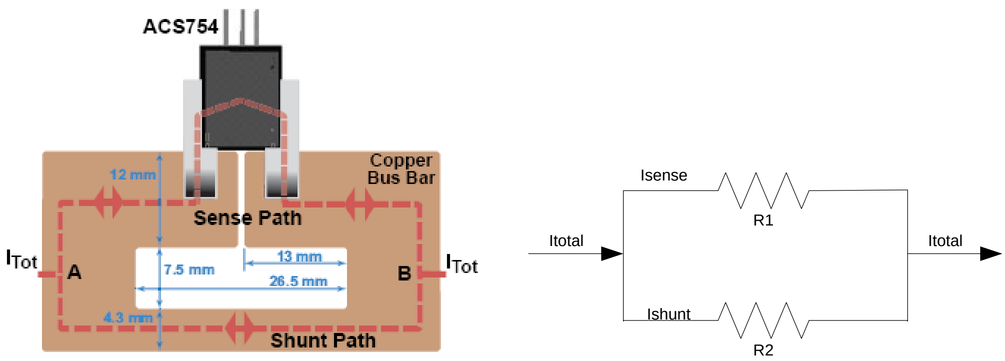


Figure 4-29: The copper bus bar (configuration for the ACS754 shown here) and its equivalent circuit [44].

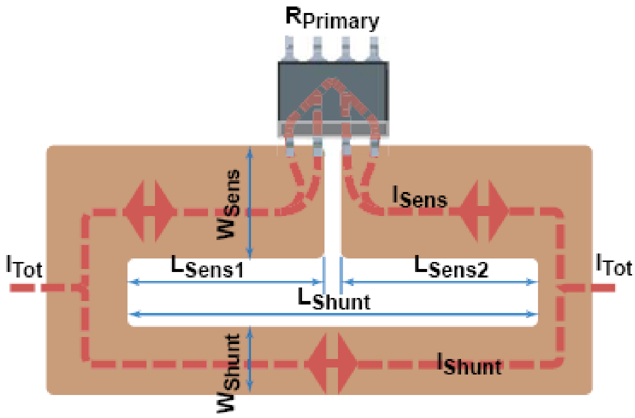


Figure 4-30: Reference circuit for calculation of trace layout dimensions [44].

Following equations 1, 2, 3 and 4, that is given in the application note,

, (1)

, (2)

, (3)

, (4)

the result is a bus bar with the following dimensions:

Lsens 20mm

Wsens 2.5mm

Ishunt 41mm

Wshunt 8mm

Thickness 1mm

Having these dimensions, the physical resistance of R1 and R2, (Figure 4-31) will be 100µΩ and 25µΩ respectively. Figure 4-32 shows the mechanical diagram of the bus bar.

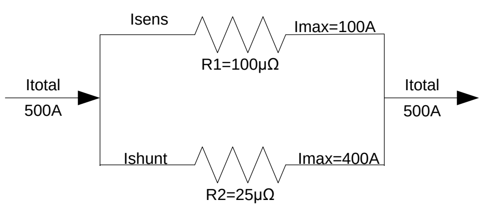


Figure 4-31: Final current divider equivalent circuit.

The equivalent circuit of the final current divider. The copper path allows passing of 100 and 400 Amps respectively.

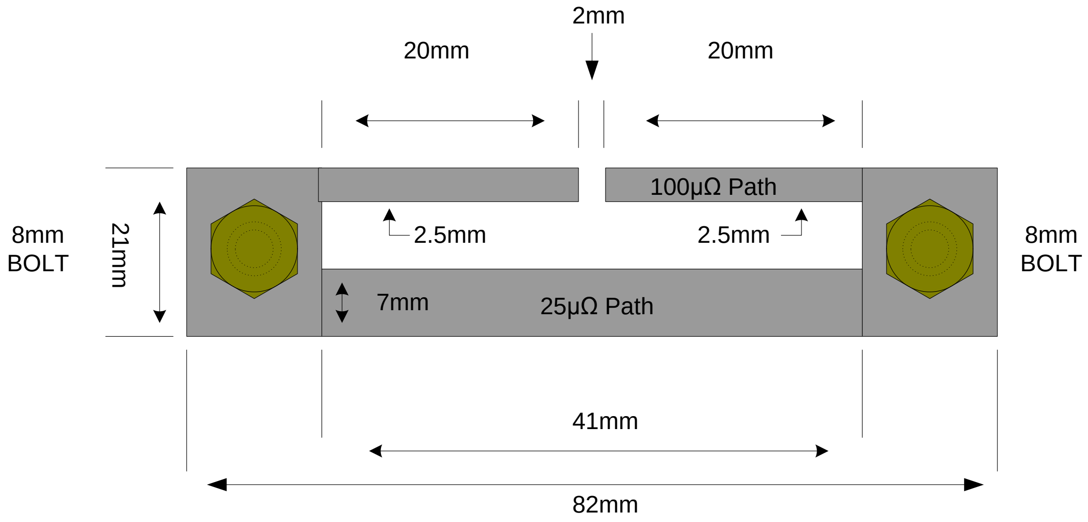


Figure 4-32: Mechanical drawing of the bus bar.

The final mechanical design of the current sensor is depicted above. The grey region is actually the copper bus bar. Two bolts will secure the cable coming from the PV array.

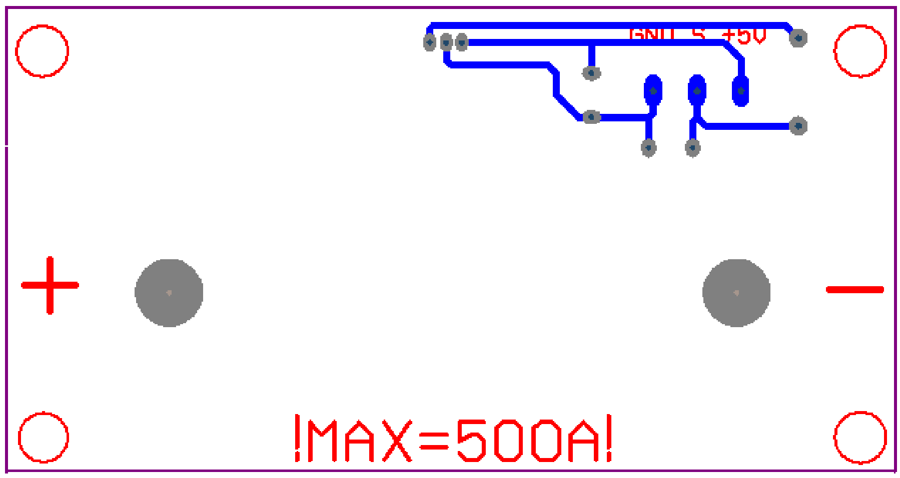


Figure 4-33: PCB layout.

Top (red) and bottom (blue) layers shown.

The copper bus bar, the sensor chip, bolts and connector are all based in a PCB measuring 11x7 cm. Note the filtering capacitors and the bias resistor.

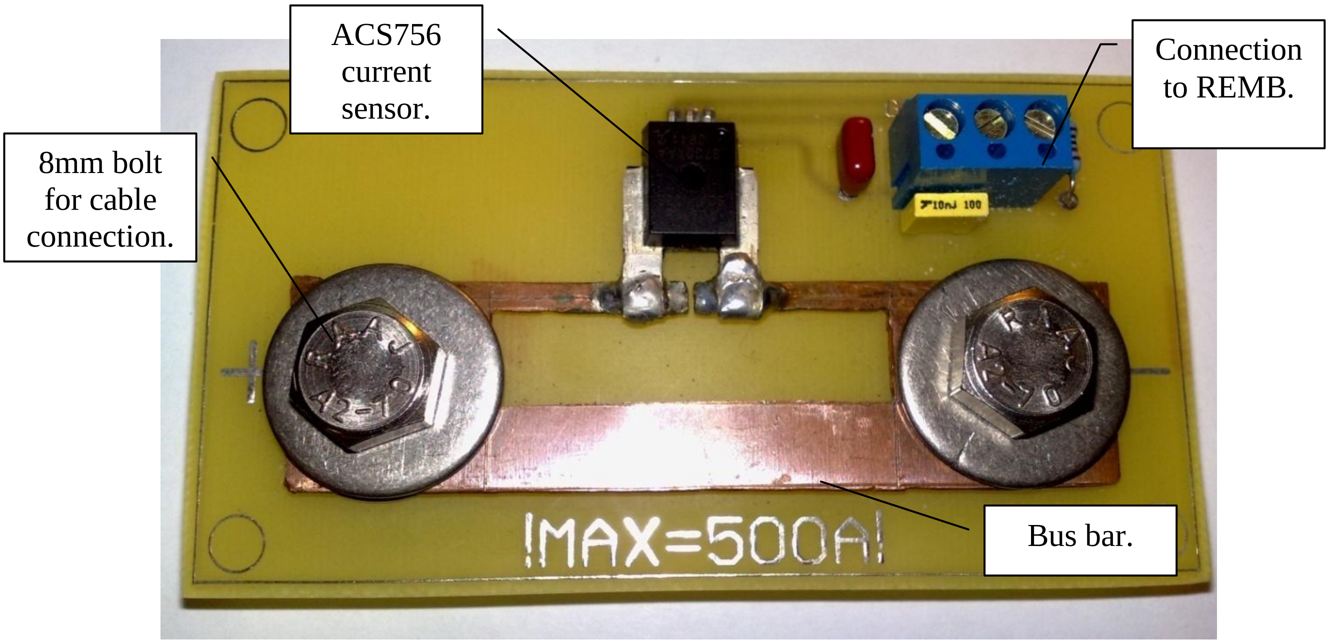


Figure 4-34: The finished current sensor.

4.8.2.6 Battery charging current sensor

This sensor is based on the ACS713ELCTR-30A-T [45]. This IC has the same principle of operation with that of ACS754 and ACS756. However, there are some slight differences in the internal circuitry. Because the charging currents are low, the sensor has the ability to measure currents up to 30Amps. The ACS713 comes in a SOIC-8 package and the internal resistance of the conductive path (pins 1, 2 through pins 3, 4) is 1.2mΩ typical.

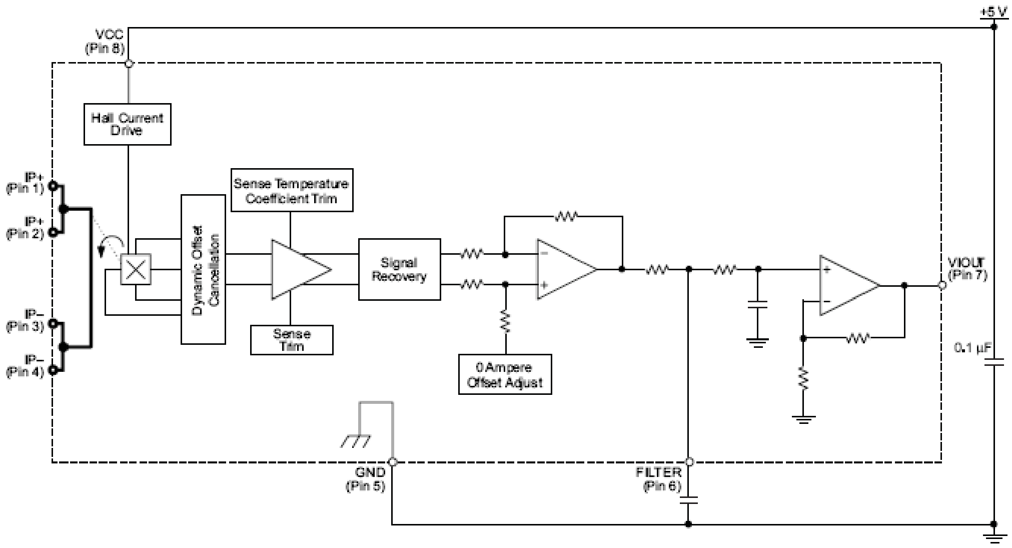


Figure 4-35: Block diagram of ACS713 [45].

The bolted line is the current path. While the current flows through this path, a magnetic field is generated that is proportional to the current value. A Hall-effect sensor receives the magnetic field. The output of the Hall sensor is then filtered and amplified.
In figure 4-36 the output voltage versus the sensed current characteristic is shown. Figure 4-37, 4-38 shows the PCB layout and figure 4-39 shows a photo of the current sensor.

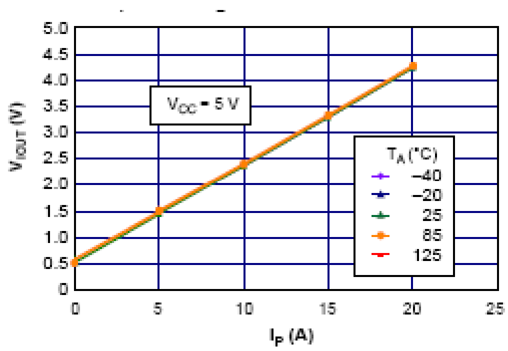


Figure 4-36: Output voltage versus sensed current [45].

The above graph depicts the output behavior versus the input current. As clearly showed the output is linear.

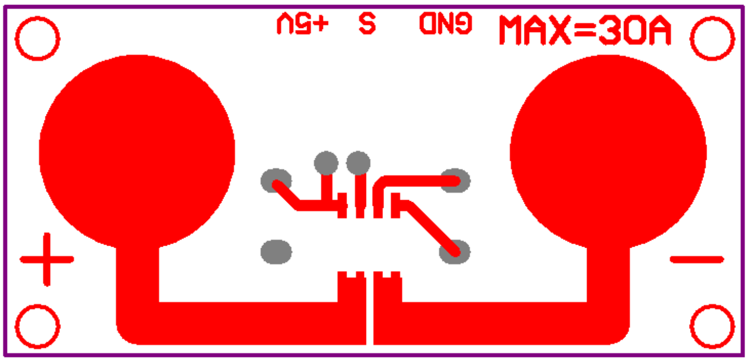


Figure 4-37: PCB layout (Top layer).

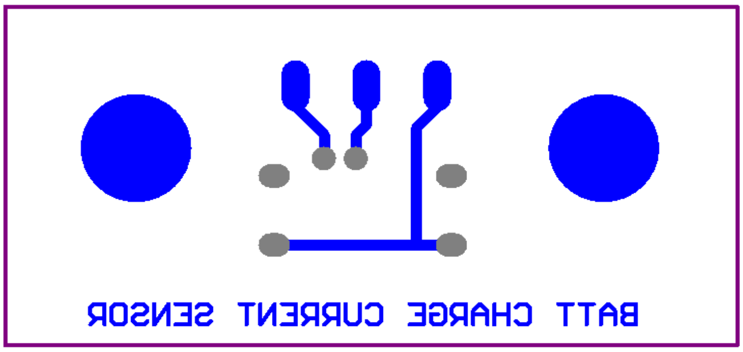


Figure 4-38: PCB layout (Bottom layer).

Figure 4-39: The battery charging current sensor

In figures 4-37 and 4-38, the red and blue layouts represent the top and bottom layer of the sensors PCB respectively. The final form of the battery charge sensor is on figure 4-39. The current path that is passing through the chip is clearly visible. Filtering capacitors are near to the connector of the pcb.

4.8.2.7 Inverter current sensor

The output current of the inverter is also monitored. This sensor is based on the ACS754 Hall Effect current sensor [42]. The ACS754 is equivalent to ACS756 for further data refer to [42] and [46]. The sensor is able to measure currents up to 100Amps. No resistor divider is used here. Figure 4-40 and 4-41 shows the PCB layout and figure 4-42 shows a photo of the current sensor.

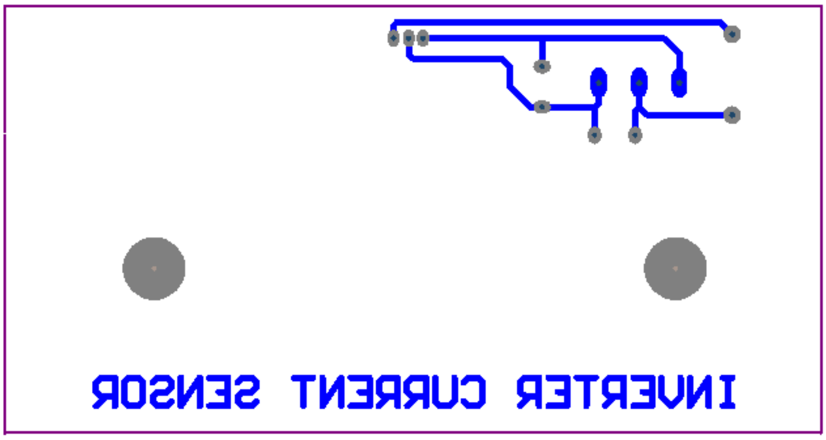


Figure 4-40: PCB layout (Bottom layer).

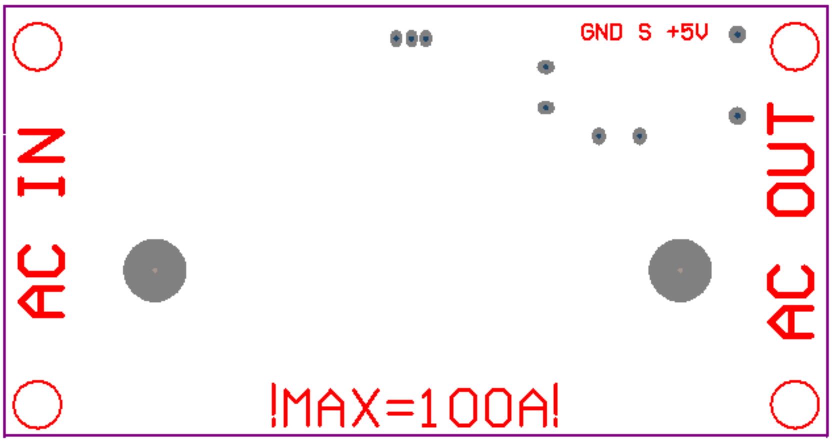


Figure 4-41: PCB layout (Top layer).

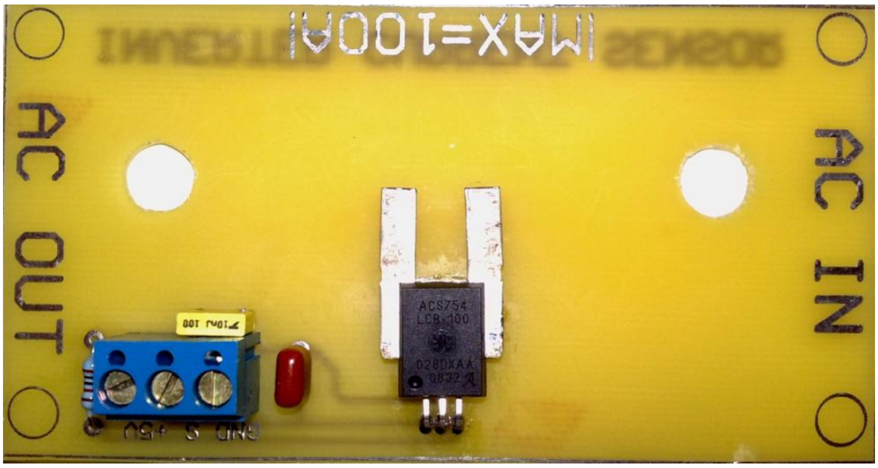


Figure 4-42: The inverter current sensor.

The above AC current sensor has the same configuration with that of the DC current sensor. The only part that is different between them is the sensor chip and also the bus bar (not pictured here)

4.8.2.8 The battery temperature sensor

A parameter that is vital and worth to be monitored is the battery temperature. A simple temperature sensor based on the LM35 [48] from national semiconductors [22] is used here.
The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. The LM35 thus has an advantage over linear temperature sensors calibrated in ° Kelvin, as the user is not required to subtract a large constant voltage from its output to obtain convenient Centigrade scaling. The LM35 does not require any external calibration or trimming to provide typical accuracies of ±1⁄4°C at room temperature and ±3⁄4°C over a full −55 to +150°C temperature range. Low cost is assured by trimming and calibration at the wafer level. The LM35's low output impedance, linear output, and precise inherent calibration make interfacing to readout or control circuitry especially easy. It can be used with single power supplies, or with plus and minus supplies. As it draws only 60 µA from its supply, it has very low self-heating, less than 0.1°C in still air. The LM35 is rated to operate over a −55° to +150°C temperature range, while the LM35C is rated for a −40° to +110°C range (−10° with improved accuracy) [48]. The block as well as the schematic diagram of the temperature sensor and the block diagram of the LM35 are shown in figures 4-43 and 4-44.

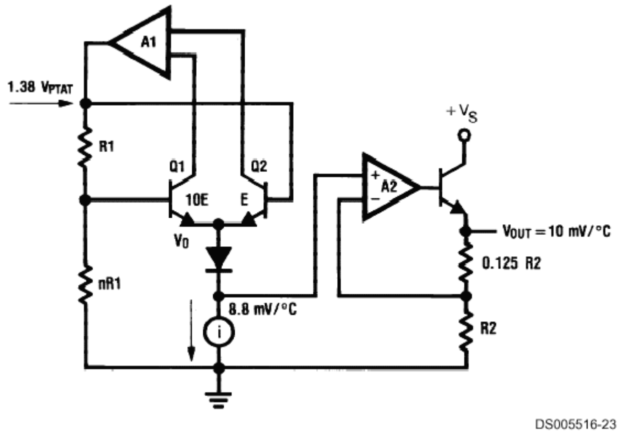


Figure 4-43: Block diagram of the LM35 [48].

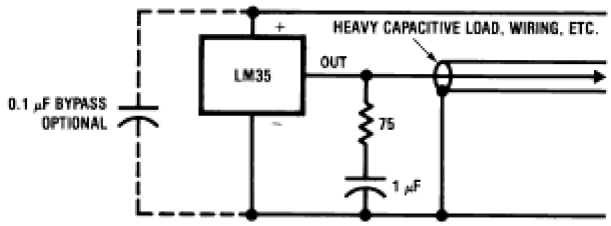


Figure 4-44: Schematic diagram of LM35 based temperature sensor [48].

For protection of the sensor from the acid environment the LM35 is secured and soldered in an audio stereo 6.2mm female pin plug (Figure 4-45). The probe is connected to the REMB via an audio stereo shielded cable.

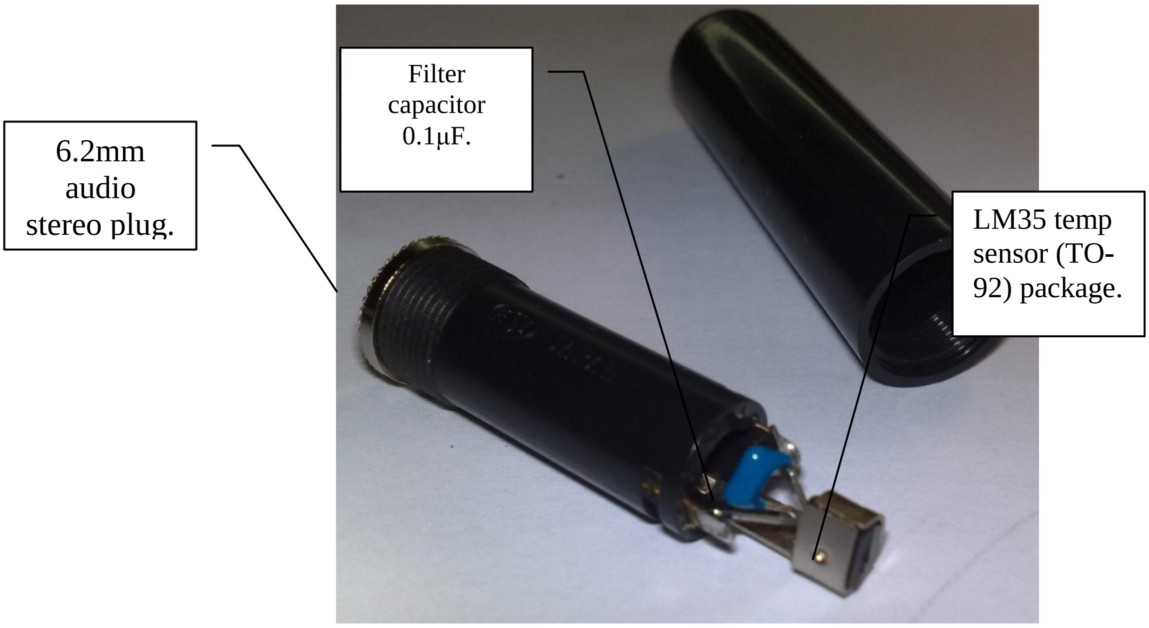


Figure 4-45: The LM35 in the female plug.

The female plug contains the LM35 chip and the 0.1µF capacitor. The 1µF capacitor and the 75Ω resistor of the schematic diagram are placed into the male 6.2mm stereo plug (Figure 4-46).

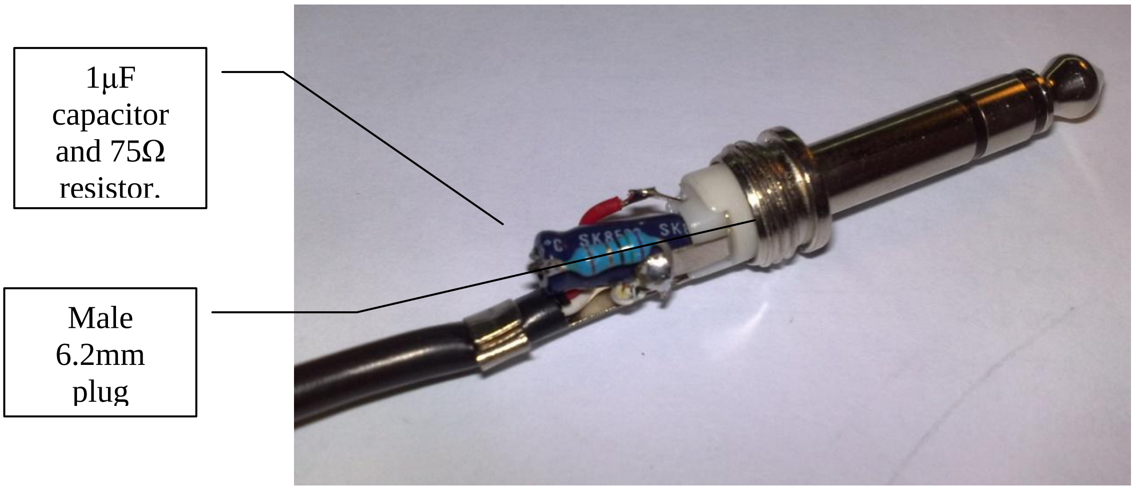


Figure 4-46: Components soldered into male stereo plug.

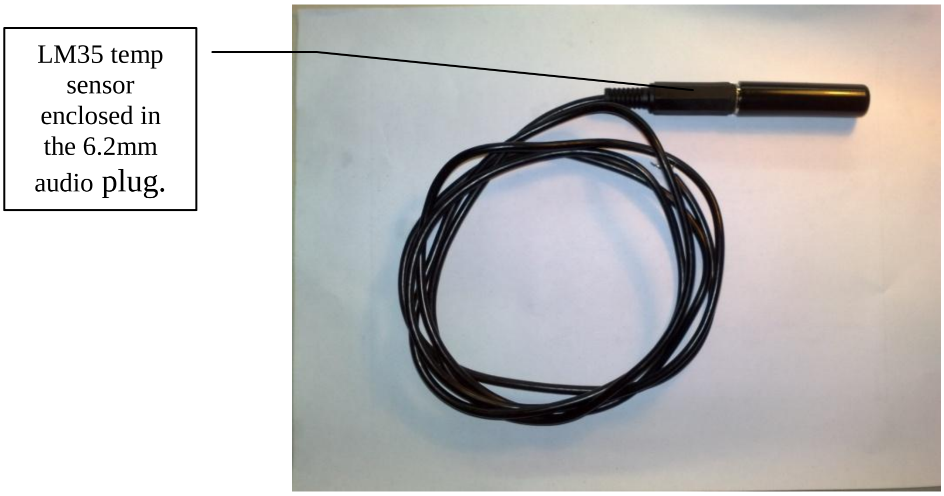


Figure 4-47: The temperature probe.

The finished temperature probe has a 2m long cable. The end of the cable is connected to the REMB. The battery temperature sensor is actually a measuring probe. This probe can be placed in the battery bank or attached to a standalone battery

4.9 Hardware description of router (ROUT)

4.9.1 Introduction

As described in the beginning this chapter, the router serves all end devices as a data sink to the COO board. The Router has extra functionality compared to end devices. Except current, voltage and temperature, the router can monitor the air dust concentration and also the angle of the PV array in case of a tracking system used. In addition the router is equipped with two relay controlled outputs.

Figure 4-48 shows the block diagram of the router (ROUT). The schematic diagrams are given in figures 4-49 and 4-50.

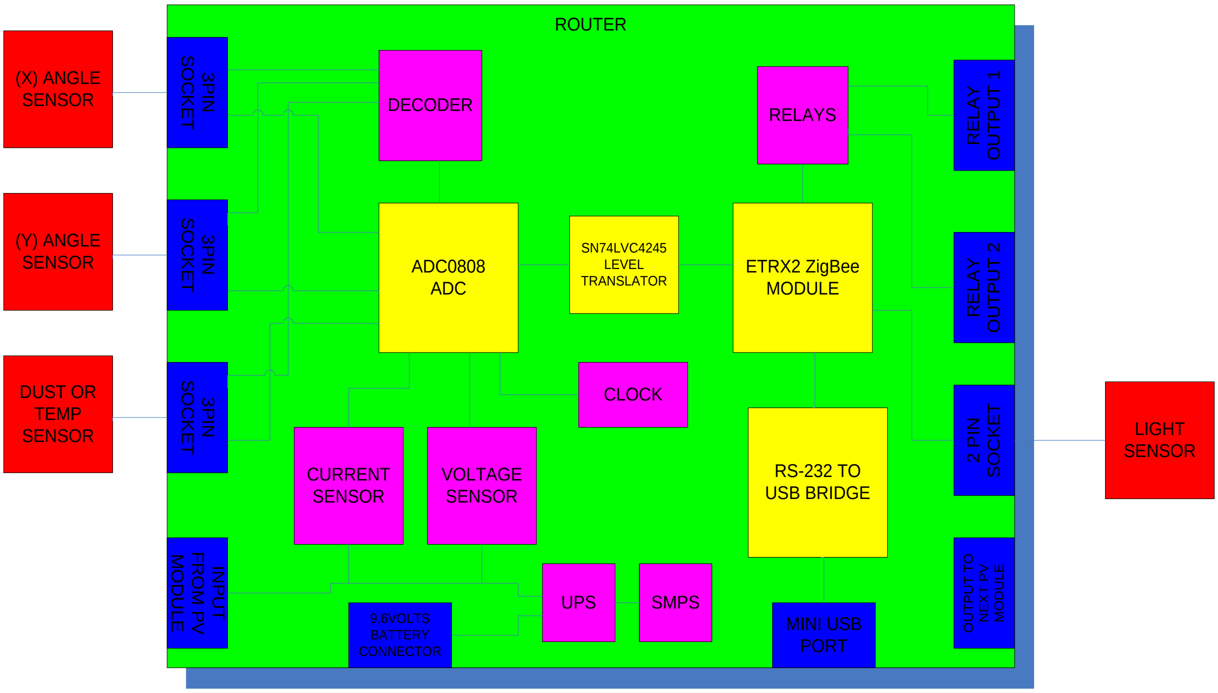


Figure 4-48: Block diagram of router.

The block diagram of the router board is shown in figure 4-48. In yellow blocks, there are main parts of the board. The blue blocks indicate sockets and connectors. The red blocks are external input components like light, dust and angle sensors. Back to yellow blocks, the ETRX2 module is connected to a USB port through an RS-232 to USB bridge. Through this port the user can update the firmware of the ETRX2 and also can observe monitor parameters to a PC. A level translator is used as an interface between ERTX2 and the ADC. An uninterruptable power unit (UPS) is used for the supply of the board. The router board carries another set of sensors and it will be discussed later. The router board can also support one extra sensor that is a light sensor or a pyranometer. As shown, there are also two outputs that are controlled by two relays and can be used to control a solar tracking system. The decoder block simply selects the input from a sensor to be measured.

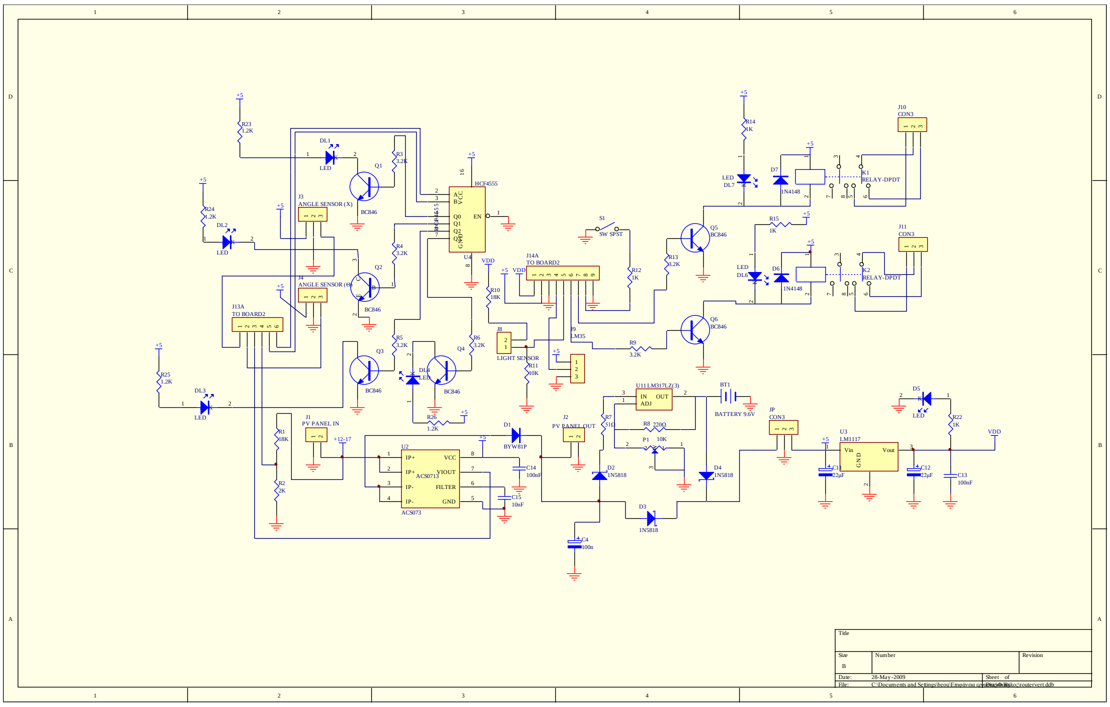


Figure 4-49: Schematic diagram of router (main PCB)

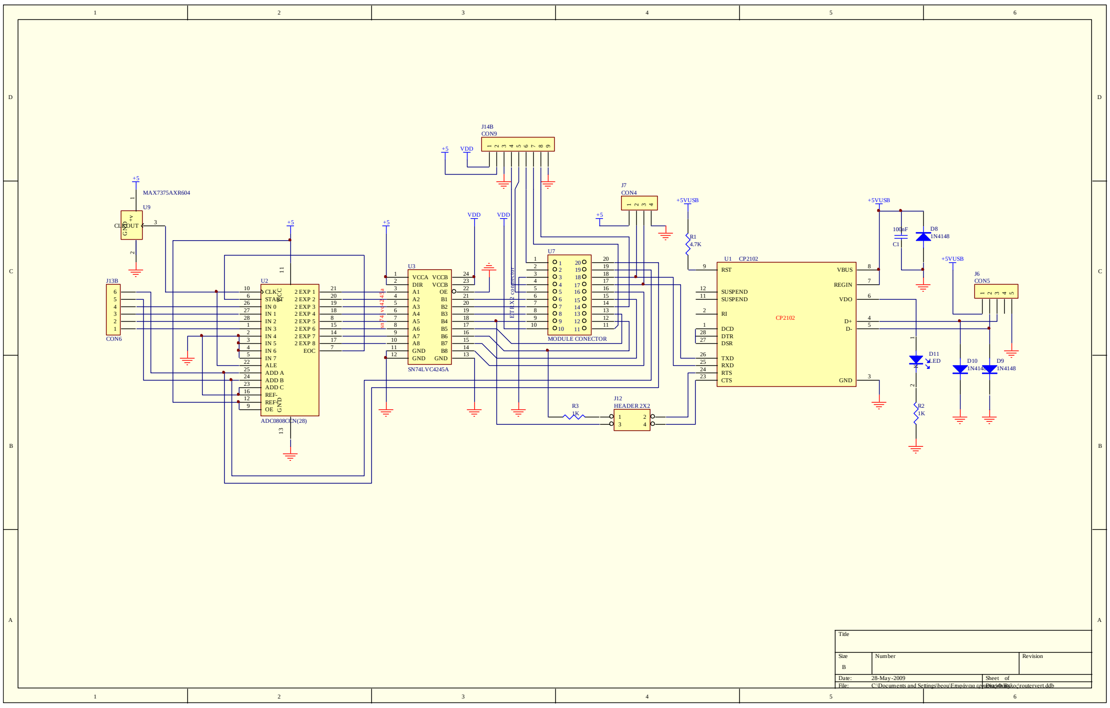


Figure 4-50: Schematic diagram of router (upper PCB)

As shown in figures 4-49, 4-50 and 4-51 the router is a device that is parted from 3 PCBs.

- The main PCB.
- The upper PCB.

- The SMPS (Switch Mode Power Supply) PCB.

This solution offers construction simplicity and also saves space.

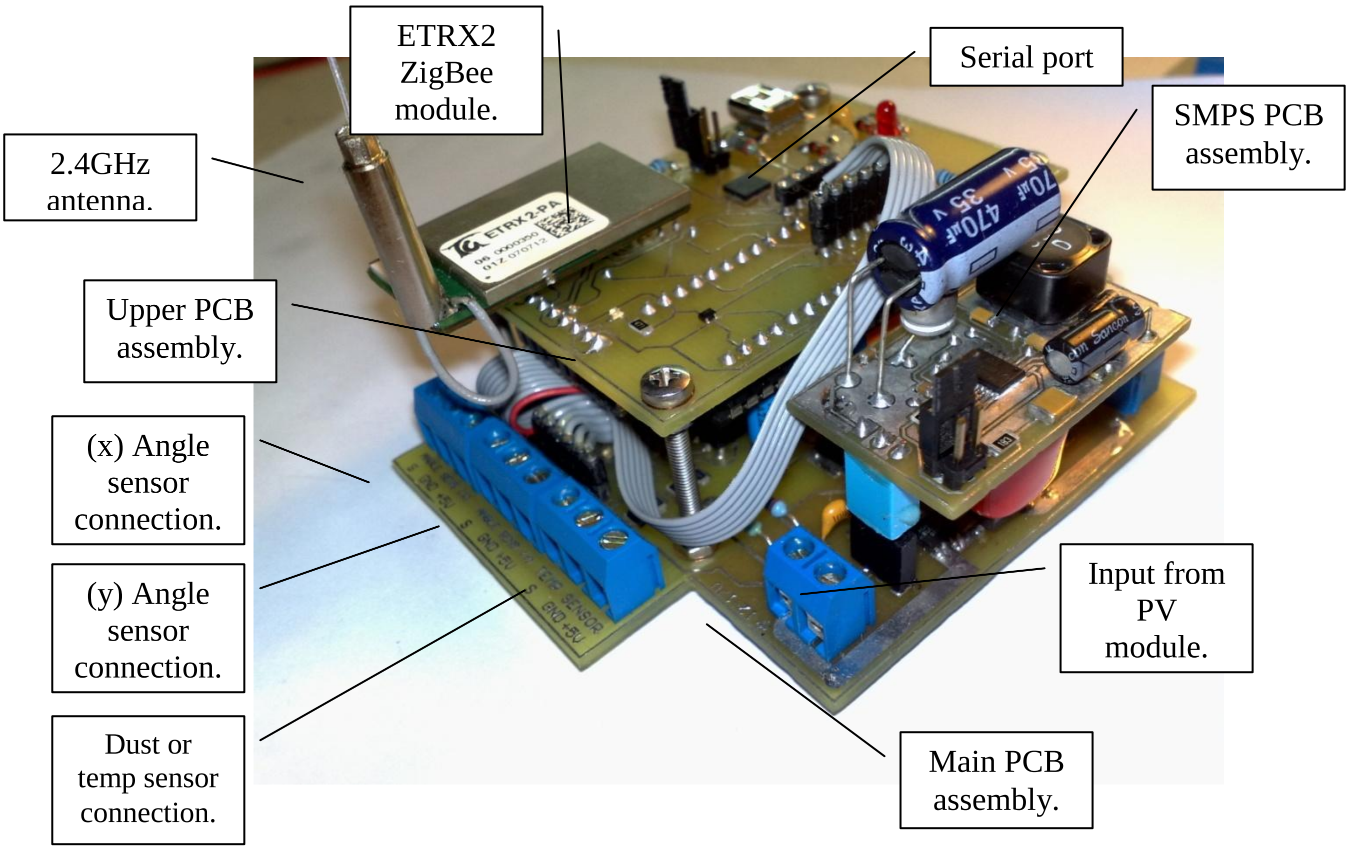


Figure 4-51: General view of the router (a)

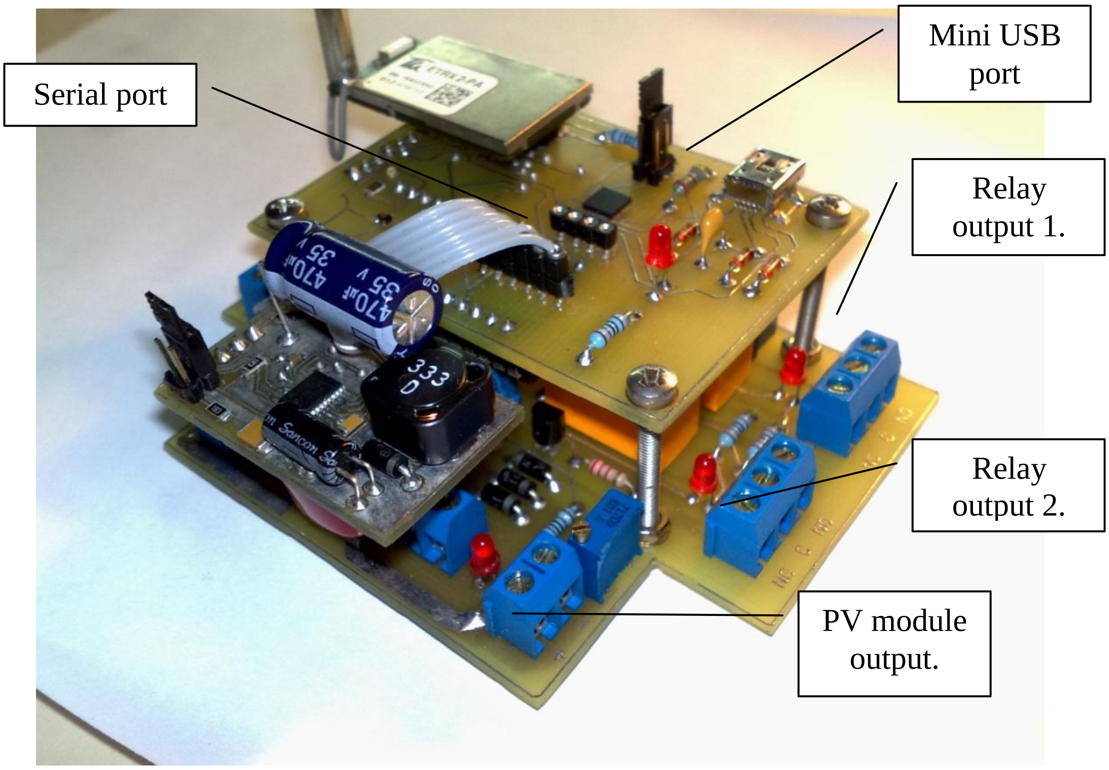


Figure 4-52: General view of the router (b)

4.9.2 Parts of the ROUTER

The main parts of the router are:

- The routers ZigBee module.
- The ADC (Analog to Digital Converter).
- The voltage level translator.
- The serial (RS-232) port.
- The RS-232 to USB interface.
- The input selection decoder.
- The light sensor.
- The PV module temperature sensors.
- The air dust concentration sensor.
- The angle sensors.
- The current sensor.
- The voltage sensor.
- The relay outputs.
- The UPS.

- SMPS.
- The battery charger.

4.9.2.1 The routers ZigBee module

As with the COO board, the router uses the same ETRX2 module type. The only difference is that the ZigBee module of the router comes with a harwin connector for plug in operation when the COO board module is soldered directly on the PCB as an SMT device. Further details and description of the module are available on chapter 4.5.

4.9.2.2 The ADC converter

The router uses the ADC0808CCN analog to digital converter that is the same with the COO ADC. Further detail can be found in chapter 4.7.2.3 as well as in references [21], [22].

4.9.2.3 The voltage level translator

The same voltage level translator IC with that of COO board is used here. Further details can be found on chapter 4.7.2.5 as well as in references [28], [24].

4.9.2.4 The RS-232 to USB interface

The router uses the CP-2102 RS-232 to USB interface. Further details can be found in chapter 4.7.2.6 as well as in references [29], [30].

4.9.2.5 The input selection decoder indicator

This part of router provides a mean of indication with the aid of LEDs corresponding to the input been selected, and thus the sensor been read from the ADC chip. If for example, the GUI commands router to return a temperature reading, the corresponding LED will illuminate.

4.9.2.6 The light (illumination) sensor

A simple way to monitor the sun illumination level is with a simple LDR (Light Depended Resistor) circuit. The LDR light sensor can be placed somewhere in the face of the PV module. The LDR light sensor has the form of a probe.

Via a twisted pair cable the sensor is connected to socket J8 on main PCB as shown in the schematic diagram (Figure 4-49). The LDR with resistors R10 and R11 forms a voltage divider where the voltage output is proportional to the suns light illumination. The output of this voltage divider is applied to pin 5 of the ETRX2 module. A silicon pyranometer is a more suitable device for solar radiation measurement than a photoresistor. During the development of this work such a pyranometer was not available. The replacement can be easily with just calibrating resistors R10 and R11.

4.9.2.7 The PV module temperature sensor

The temperature of a PV module is a critical factor that inflects its output efficiency. The sensor used for monitoring the PV module temperature is the same with that described in chapter 4.8.2.8 (battery temperature sensor). The circuitry is the same, however the only difference is that the module temperature sensor has not the form of a probe. Simply the sensor IC (LM35) is attached to the back side of the PV module with an adhesive epoxy resin. This solution allows heat to be easily transferred from the module to the sensor providing accurate and reliable temperature measurement. Further details concerning the operation of the LM35 can be found in chapter 4.8.2.8 as well as in reference [48].

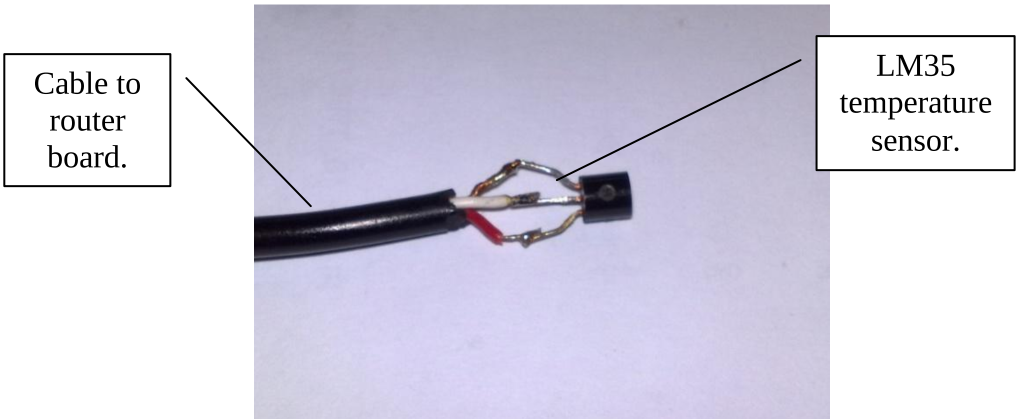


Figure 4-53: The PV temperature sensor.

4.9.2.8 The air dust concentration sensor

The router can monitor the dust concentration over the air. Dust monitoring is not a critical factor for the PV system operation; however this measurement might be useful for statistical purposes or even as a warning system. For e.g. high dust levels in the air may deposit dust in the transparent surfaces of the PV modules, affecting the efficiency.

For dust monitoring, the Sharp GP2Y1010AU [49], dust sensor is used here (Figure 4-56). The sensors output has a near linear characteristic versus dust density (Figure 4-55).

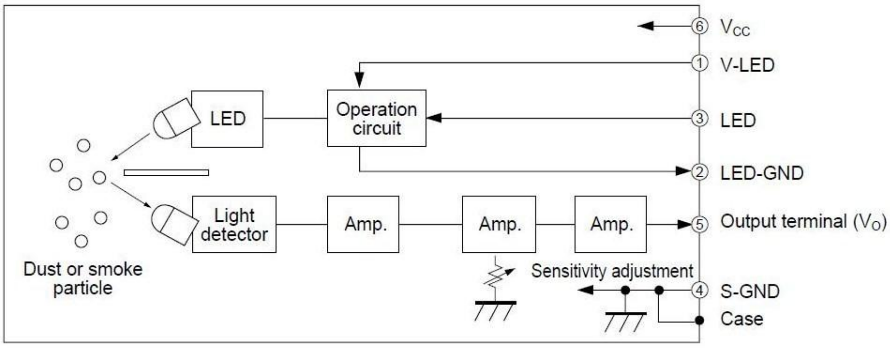


Figure 4-54: The GP2Y1010AU block diagram [49].

The principle of operation is simple. Dust particles are detected by a photodiode when the light of an infrared LED is scattered by the particles themselves (Figure 4-54). High dust density causes higher light scattering. The scattered light is amplified by three amplification stages. A variable resistor allows for sensitivity adjustment. The sensor sensitivity is typically 0.5Volt/(0.1gr/m^3). The dust sensor can be connected to J9 in the router main PCB (schematic diagram figure 4-19).

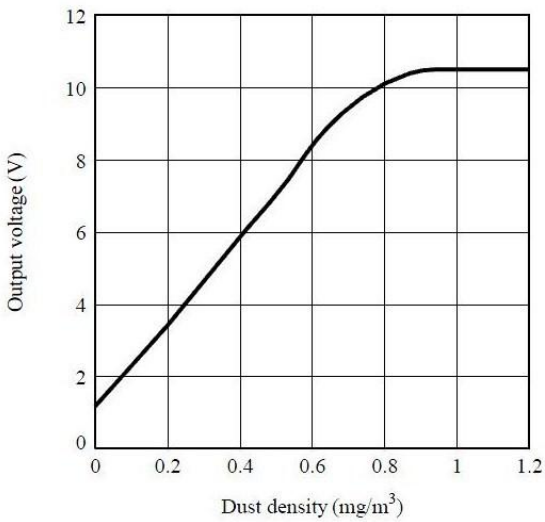


Figure 4-55: Output voltage versus dust density [49].
(12Volt version shown here)

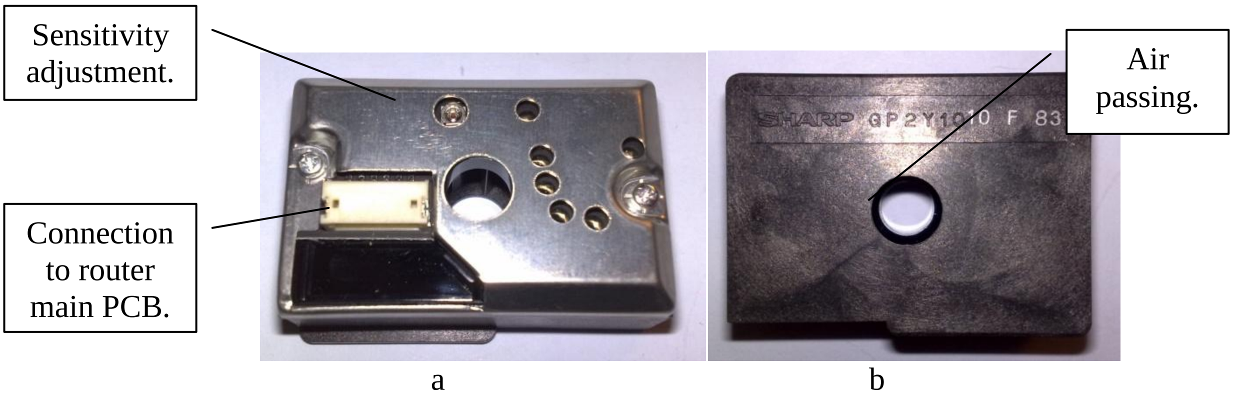


Figure 4-56: Back side of dust sensor (a), frond side of dust sensor (b).

The output versus the dust concentration (in mg/m^3) is depicted in figure 4-55. From 1.5 Volts the output tends to be linear. The actual form of the dust sensor is shown above. For better results and robustness to weather conditions a suitable case must be designed.

4.9.2.9 The angle sensors

As with many systems, a tracking system in order to operate needs a feedback source. The feedback signals for a tracking system are the x and y positions of the PV array. These angle readings can be obtained from the x and y angle sensors. The basic component of these kinds of sensors is the IC-MA angular hall sensor/encoder [50] from IC-haus [51].

The CMOS device IC-MA consists of a quadruple hall sensor array which has been optimized for the magnetic measurement of angles of rotation. This array permits error-tolerant adjustment of the magnet, reducing assembly efforts. The integrated signal conditioning unit provides a differential sine/cosine signal at the output. The sensor generates one sine cycle per each full rotation of the magnet, enabling the angle to be clearly determined. At the same time the internal amplitude control unit produces regulated output amplitude of 2Vp-p regardless of variations in the magnetic field strength, supply voltage and temperature. Furthermore, signals to be assessed and also report any magnet loss. With the aid of the integrated 8-bit sine/digital converter the angle of rotation is determined from the sine/cosine signals. This is output via an incremental interface in a number of selectable resolutions. The absolute angle of rotation can be converted back to a linear analog output signal using the internal D/A converter [50]. Figure 4-57 shows the block diagram of IC-MA.

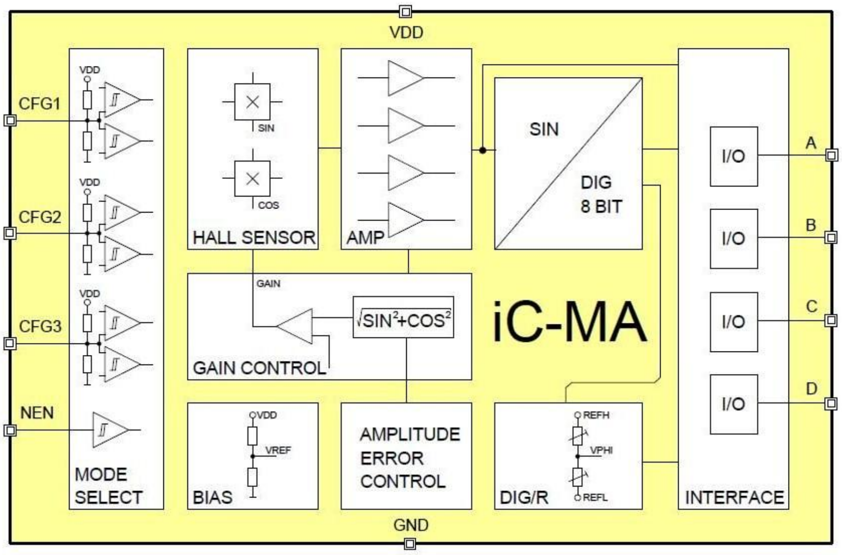


Figure 4-57: IC-MA block diagram [50].

4.9.2.9.1 Principle of operation

IC-MA has four Hall sensors which are used to determine angles and to convert the magnetic field into a measurable Hall voltage. Only the z component of the magnetic field is assessed, where the line of magnetic flux pass through two facing Hall sensors in the opposite direction. An example of magnetic flux is given in figure 4-58. The Hall sensors have been arranged in such a way that the assembly of the magnet with IC-MA is extremely tolerant. Two Hall sensors combined generate a differential Hall signal. If the magnet is rotated along its longitudinal axis, sine and cosine output voltages are created which can be used to determine angles [50].

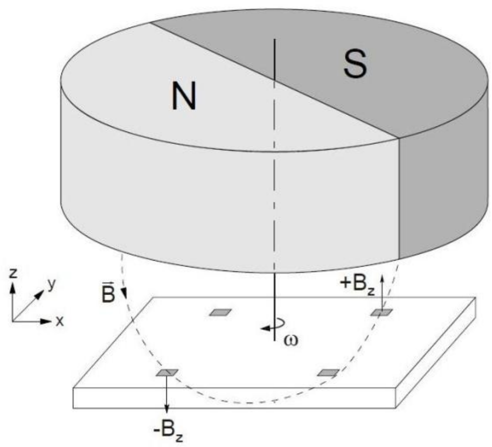


Figure 4-58: Principle of the magnetic field measurement using a Hall sensor [50].

The IC-MA can be configured to operate in various modes and its output form is depended on this configuration. In this project the R-sensor mode with sawtooth output voltage (VSAW) is used. Two separate sensors are used for x and y angle reading. When the COO needs to receive an angle measurement e.g. from the x angle sensor, then it selects the x sensor by activating the respective output of the decoder U4 in the router. These two sensors can be placed in a stationary point of the tracking system and x, y sensing permanent magnets can be placed in the x and y axes respectively. IC-MA works fine in conjunction with neodymium iron boron (MdFeB) or samarium cobalt (SmCo) magnets. A cylindrical magnet of 4mm in diameter is a good solution.

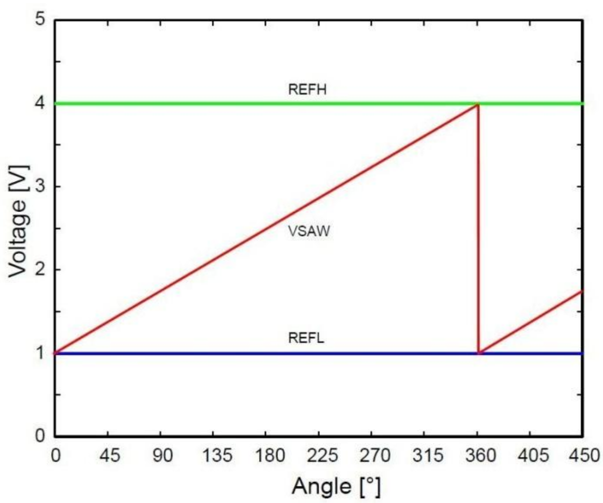


Figure 4-59: Output voltage versus measured angle [50].

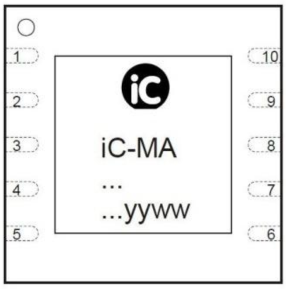


Figure 4-60: IC-MA pinout [50].

As shown in figure 4-59 the output voltage is proportional to the sensing angle. The angle dependable output voltage is applied to input 3 (pin 1) of the ADC0808CCN analog to digital converter in the router upper PCB. (see schematic diagram figures 4-49, 4-50). The IC-MA comes in a QFN-10 package (Figure 4-60).

4.9.2.10 The current sensor

The current sensor can monitor the output current of the PV module. Currents up to 30Amps can be measured. The current sensor (U2 in the schematic diagram) can be shown in figure 4-49. It is actually the same ACS0713ELKTR30A hall sensor with that used for the battery charge current sensor of chapter 4.8.2.6. Diode D1 protects the circuit from reverse polarity. Further details about the operation of the ACS0713 can be found in chapter 4.8.2.6.

The output of the sensor is connected to pin 3 of connector J13A. J13A on main PCB is connected with connector J13B on the upper PCB. Pin 3 of connector J13B is connected to pin 27 (input 1) of the ADC0808CCN. The selection of this input is defined by the software. The software (when necessary) causes the ETRX2 to control address select inputs (pins 24 and 25) of ADC0808CCN. For e.g. when the software needs to have a current measurement from PV panel 1, then the COO ZigBee module in the COO board selects device No1.

4.9.2.11 The voltage sensor

The voltage sensor can measure the output voltage of the PV module. This sensor is actually nothing more than a voltage divider that is formed by resistors R1 (18KΩ) and R2 (2KΩ) schematic diagram (Figure 4-49). This resistance value combination has a division ratio of 10. The output of the voltage sensor is connected to pin 4 of connector J13A. J13 on main PCB is connected with connector J13B on upper PCB. Pin 4 of connector J13B is connected to pin 26 (input 0) of the ADC0808CCN. The selection of this input is defined by the software. The software (when necessary) causes the ETRX2 to control address select inputs (pins 24 and 25) of ADC0808CCN.

4.9.2.12 The relay outputs

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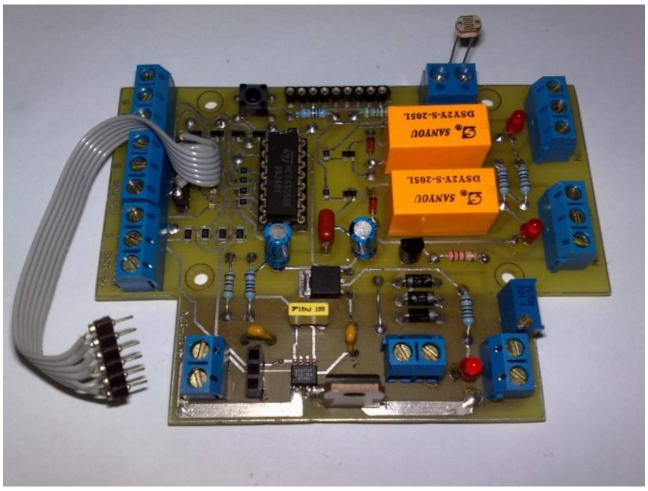

Figure 4-61: View of routers main PCB.

The output relays are shown in figure 4-56. As shown in the schematic diagram (Figure 4-49), each DPST relay is activated through a NPN transistor (Q5 and Q6). Each transistor is controlled by pins 1 and 11 (I/O9 and I/O8 of ETRX2). The relay outputs are connected to connectors J10 and J11

4.9.2.13 The UPS

It is obvious that during night hours the output of the PV panel is 0Volt. For that reason a UPS circuit is used. This circuit is the same with that of the COO board. Further details can be found on chapter 4.7.2.10.

4.9.2.14 SMPS

It is well known that the output voltage of a PV panel is not constant but it varies during the day. For example, the output can be low in the morning, when the sun light is at low levels. From the other hand, it can reach a maximum value during the peak hours. These variations can have a range from 3Volts to 18Volts for a 12Volts PV module. As with the COO board circuitry, the routers circuitry requires 3.3Volts and 5Volts to operate. In the first design, an LM7805 [52] linear regulator was used. Unfortunately, the major problem with this regulator was the high dropout voltage that is approximately 2Volts. That means that the regulator needs a voltage higher than 7Volts to its input to operate normally, providing a 5Volts output. It is obvious that with the LM7805, the output voltage could not be regulated when the PV voltage drops below 7Volts. As an alternative solution, the L4940 very low drop regulator [36] was used instead of 7805. With a dropout voltage of 0.5Volt, the system was able to run when the PV module voltage exceed 5.5Volts. Even this solution was not efficient. In order to obtain a constant 5Volt output for a 2-18Volts input a switch mode regulator had to be used. This regulator is the TPIC74100 buck/boost switch mode regulator [55] from Texas Instruments [24].

The TPIC74100-Q1 is a switch-mode regulator with integrated switches for voltage-mode control. With the aid of external components (LC combination), the device regulates the output to 5 V ±3% for a wide input-voltage range. The TPIC74100-Q1 offers a reset function to detect and indicate when the 5V output rail is outside of the specified tolerance. This reset delay is programmable using an external timing capacitor on the REST terminal. Additionally, an alarm (A_{OUT}) feature is activated when the input supply rail V_{driver} is below a prescaled specified value (set by the A_{IN} terminal). The TPIC74100-Q1 has a frequency-modulation scheme to minimize EMI. The clock modulator permits a modulation of the switching frequency to reduce interference energy in the frequency band. The TPIC74100-Q1 is a buck/boost switch-mode regulator that operates in a power-supply concept to ensure a stable output voltage with input voltage excursions and specified load range.

The device provides an alarm indicator and reset output to interface with systems that require supervisory function. The switching regulator offers a clock modulator and a current-mode slew-rate control for the internal switching transistor (Q1) to minimize EMI. An internal low-$r_{DS(on)}$ switch has a current-limit feature to prevent inadvertent reset when turning on the 5Vg output [53]. Figure 4-62 shows the block diagram of the TPIC74000.

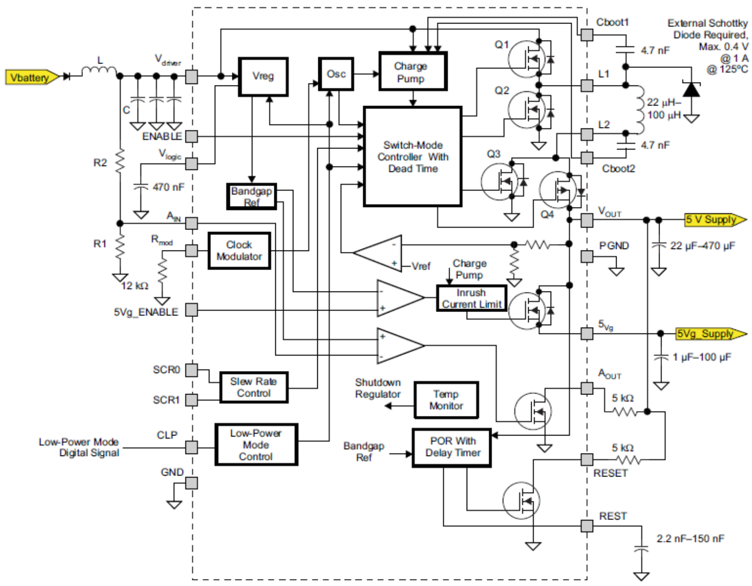

Figure 4-62: TPIC74000 block diagram [53].

The TPIC7400 measures continuously the level of the input voltage. Depending on this voltage level, the internal controller decides when the system will operate in a buck or in a boost mode. In buck mode, (Figure 4-63), the duty cycle of transistor Q1 sets the voltage V_{OUT}. The duty cycle of transistor Q1 varies 10% to 99% depending on the input voltage, $V_{(driver)}$. If the peak inductor current (measured by Q1) exceeds 450mA (typical), Q2 is turned on for this cycle (synchronized rectification). Otherwise, the current recirculates through Q2 as a free-wheeling diode. The detection for synchronous or asynchronous mode is done cycle-by-cycle.

To avoid a cross-conduction current between Q1 and Q2, an inherent delay is incorporated when switching Q1 off and Q2 on and vice versa. In buck mode, transistor Q3 is not required and is switched off. Transistor Q4 is switched on to reduce power dissipation. The switch timings for transistors Q3 and Q4 are not considered. In buck mode, the logical control of the transistors does not change [53].

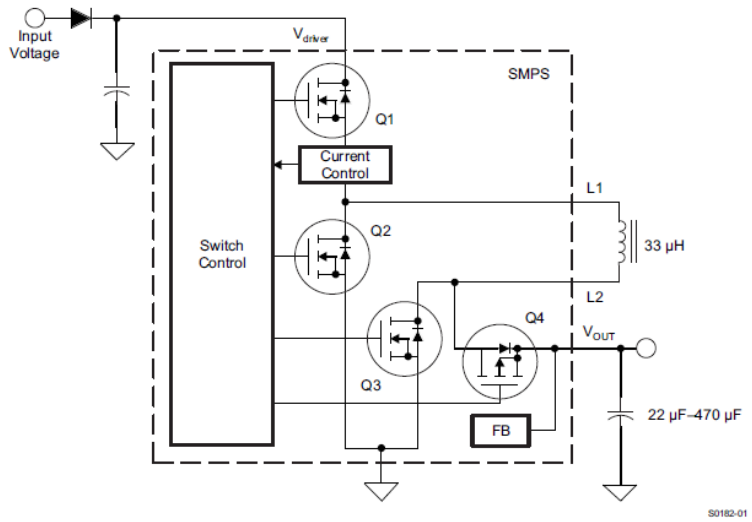

Figure 4-63: Buck/Boost switch mode configuration [53].

In boost mode, (Figure 4-63) (the duty cycle of transistor Q3 controls the output voltage V_{OUT}. The duty cycle is internally adjusted 5% to 85% depending on the internally sensed voltage of the output. Synchronized rectification occurs when $V_{(driver)}$ is below 5 V.

To avoid a discharging of the buffer capacitor, a simultaneous switching on of Q3 and Q4 is not allowed. An inherent delay is incorporated between Q3 switching off and Q4 switching on and vice versa. In boost mode, transistor Q2 is not required and remains off. Transistor Q1, is switched on for the duration of the boost-mode operation (serves as a supply line) [53]. The final schematic circuit of the 5 Volt regulators is shown in figure 4-64.

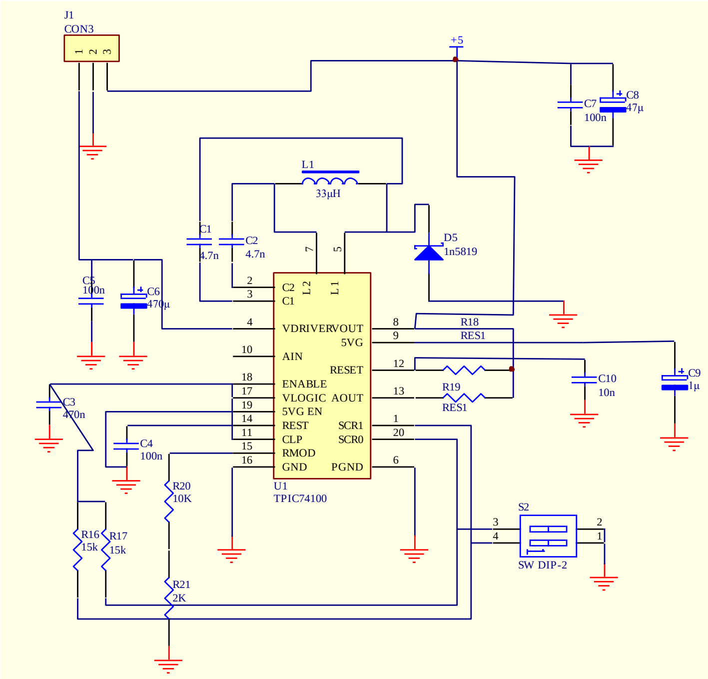

Figure 4-64: Schematic diagram of the 5Volts regulator.

Diode D5 is a 1n5819 Schottky diode [34]. Inductor L1 is a 33μH MSS1278T-333ML coil [54] from coilcraft [41].

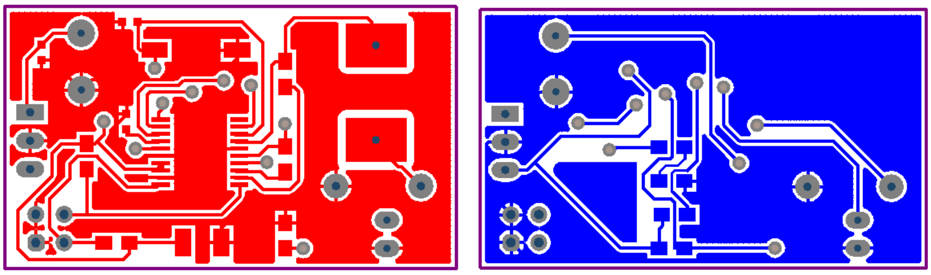

Figure 4-65: Top (red) and bottom (blue) layers of the 5Volts regulator.

The 5Volts regulator is a separate small sized PCB (Figure 4-65) that has the same pinout of a conventional 7805 regulator. The voltage regulator is connected to the place of the 7805 regulator on the routers main PCB.

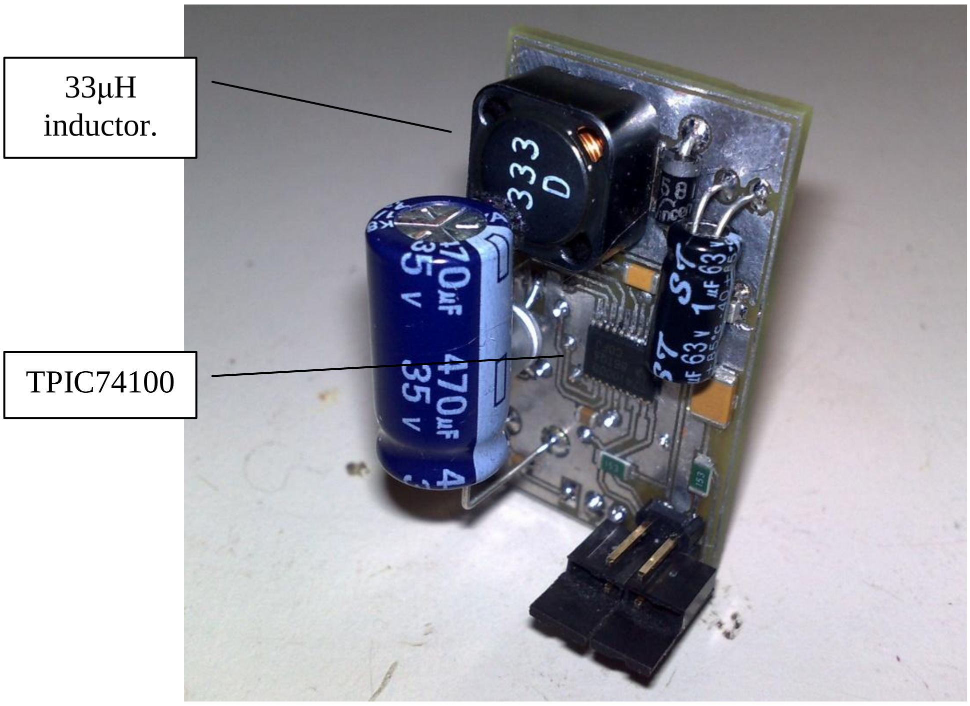

Figure 4-66: Photo of the 5Volts regulator.

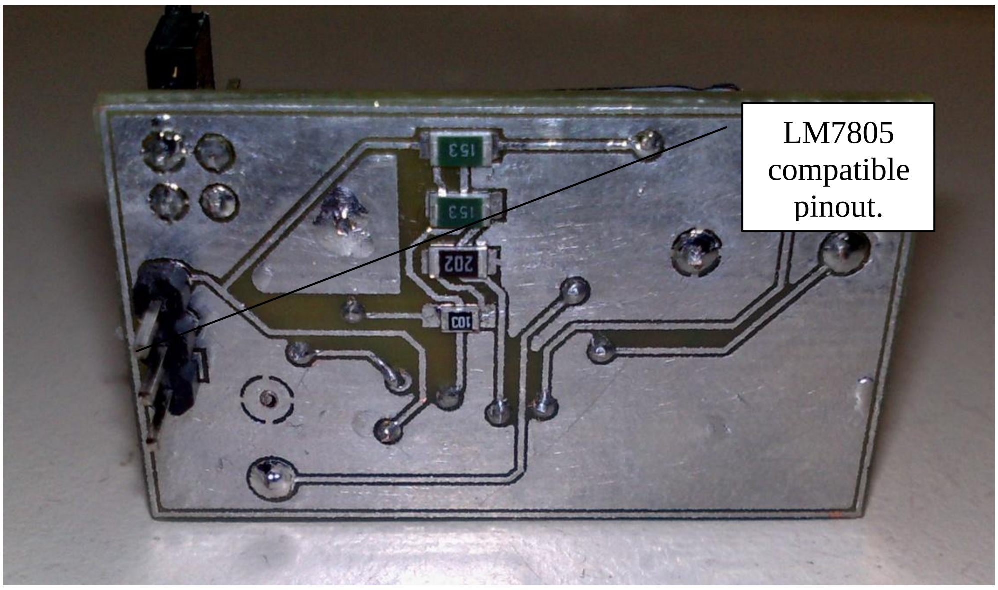

Figure 4-67: Back view of the voltage regulator.

The use of SMT components saved space and also power. The only bulky components are the 470µF capacitor and the 33µH inductor. In figure 4-65 the red and blue regions represents the top and the bottom sides of the PCB.

4.9.2.15 The battery charger

A simple battery charger is formed with the LM317 (U11) adjustable regulator [55] from national semiconductors [22].

The LM317 is an adjustable 3-terminal positive voltage regulator capable of supplying 100mA over a 1.2Volts to 37Volts output range. It is exceptionally easy to use and requires only two external resistors (R8 and P1) to set the output voltage. Further, both line and load regulations are better than standard fixed regulators. The LM35 offers full overload protection. Included on the chip are current limit, thermal overload protection and safe area protection

The regulator is set for 10.5Volts output (adjusting trimmer R8) that is a sufficient voltage to charge the 9.6Volts Ni-MH 8 cell battery pack. The battery charging is done when the PV output voltage is higher than 11Volts. This voltage appears at the PV module output during the daylight.

4.10 Hardware description of an end device

4.10.1 Introduction

The end device is the simplest device on this monitoring system. The parameters that are monitored are the PV modules output voltage, current, and temperature. Figure 4-68 shows the block diagram of the end device. The schematic diagram is shown in figure 4-69.

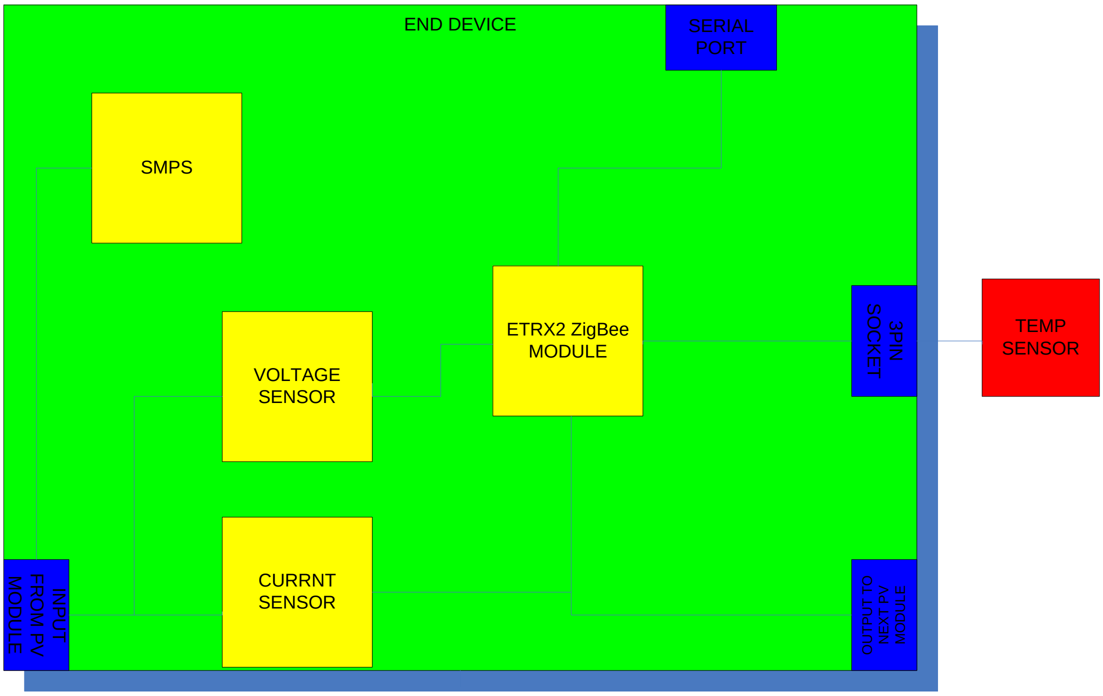

Figure 4-68: End device block diagram.

The block diagram of the end device board is shown in figure 4-68. In yellow blocks, there are main parts of the board. The blue blocks indicate sockets and connectors. The red block is an external temperature sensor that can be glued at the back side of the PV panel.. Back to yellow blocks, the ETRX2 module is connected to an RS-232 port. Through this port the user can update the firmware of the ETRX2 and also can observe monitor parameters to a PC. An SMPS power unit assures that the circuitry will be powered with 5 Volts despite the fact that the voltage of the PV panel may vary.

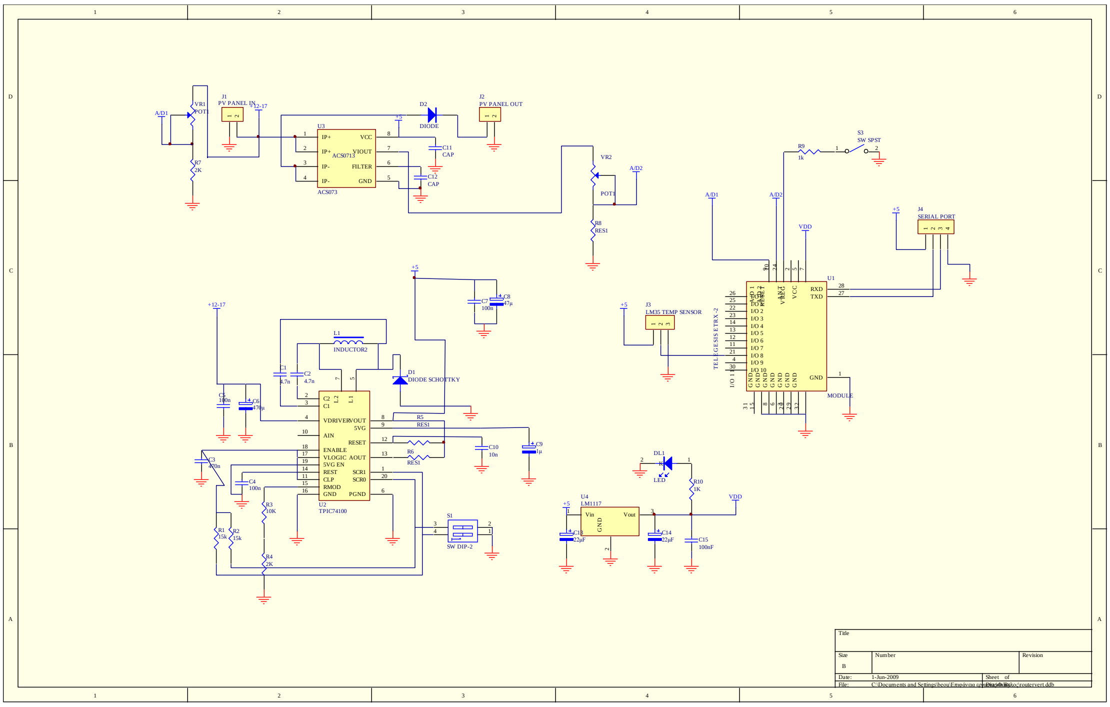

Figure 4-69: Schematic diagram of end device.

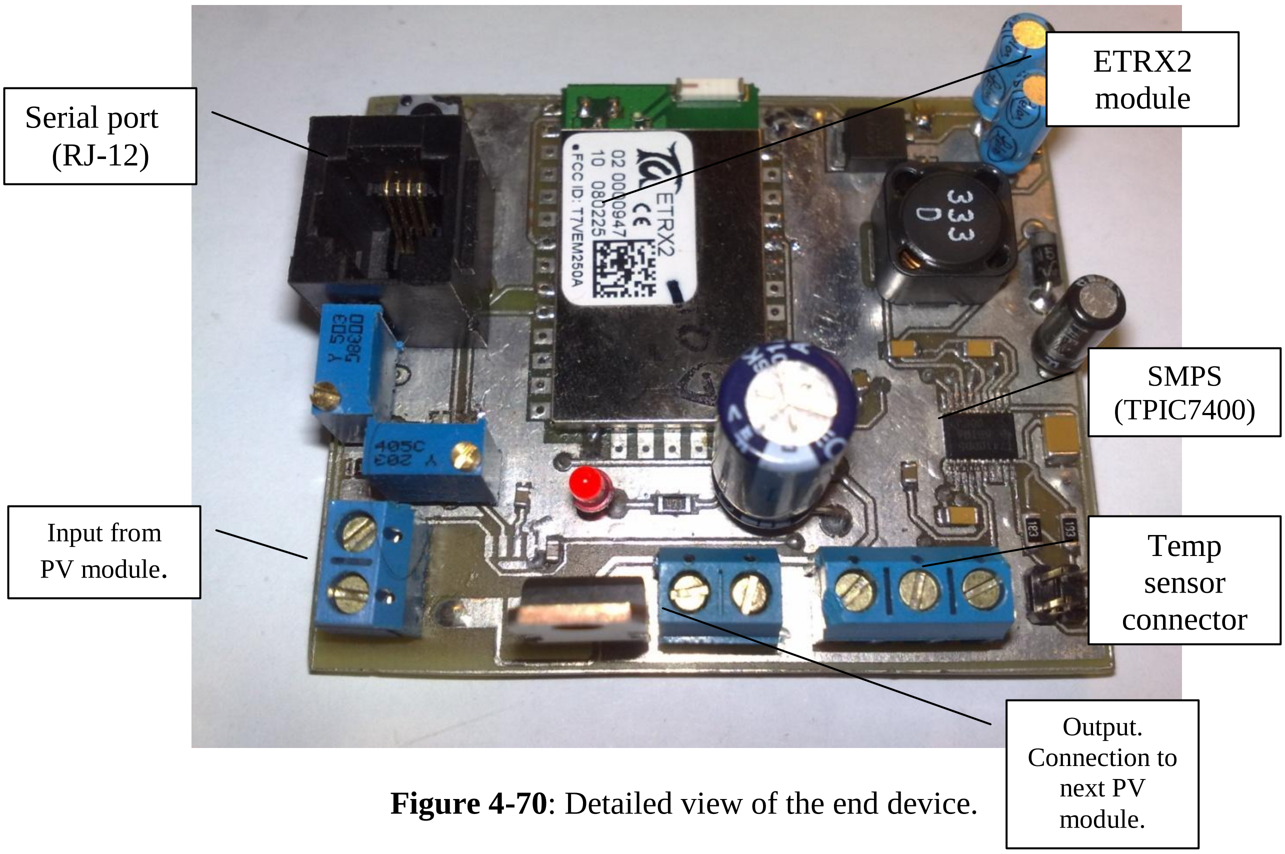

Figure 4-70: Detailed view of the end device.

The SMPS unit of the end device has the same circuitry with that described in 4.9.2.14. The reader can easily see the ETRX2 module, the SMPS components as well as the serial port and connectors from the PV module.

4.10.2 Parts of the end device

The main parts of the end device are:

- The ETRX2 ZigBee module
- The current sensor
- The voltage sensor
- The SMPS

4.10.2.1 The ETRX2 ZigBee module

As with the COO and router boards, the end device uses the same ETRX2 module type. Further details and description of the module are available on chapter 4.5.

4.10.2.2 The current sensor

The current sensor can monitor the output current of the PV module. Currents up to 30Amps can be measured.

The current sensor (U3 in the schematic diagram) can be shown in figure 4-69. It is actually the same ACS0713ELKTR30A hall sensor with that used for the battery charge current sensor of chapter 4.8.2.6. Diode D2 protects the circuit from reverse polarity. The output from the ACS0713 is applied to the input of a voltage divider (resistor R8 and trimmer VR2) and then to pin 10 (A/D2) of the ETRX2 module. This is done because the internal analog to digital converter of the ETRX2 module has a maximum input voltage of 1.2Volts. The voltage divider attenuates the output voltage of the current sensor that can be reach 5Volts in case of 30Amps sensed current.

4.10.2.3 The voltage sensor

As with the router, the end device voltage sensor can measure the output voltage of the PV module.

This sensor is actually nothing more than a voltage divider that is formed by resistor R7 (2KΩ) and trimmerVR1 (50KΩ), see schematic diagram (Figure 4-69). This resistance value combination has a division ratio of 50. The output of the voltage divider is applied to pin 9 (A/D2) of the ETRX2 module.

4.10.2.4 The SMPS

The SMPS circuit is the same with that used in the router. For description of the SMPS refer to chapter 4.9.2.14.

4.11 Serial cable

4.11.1 Introduction

As described, all devices are equipped with a serial port. This serial port is used for communication with a PC (for router and end devices it's usually a laptop). Via this connection the user is able to access the ZigBee module of each device locally and not remotely via the COO of the system.

4.11.2 Construction of the serial cable

The serial port of the ETRX2 module is CMOS compatible. That means that an RS-232 driver/receiver is required to interface the low voltage level side of the ETRX2 serial port (3.2Volts) with the high voltage level side (+/- 10 Volts) of the PC serial port. The design of the serial cable combines the connection of the serial ports with the suitable voltage level interface circuitry. Figure 4-71 shows the schematic diagram of the interface circuit.

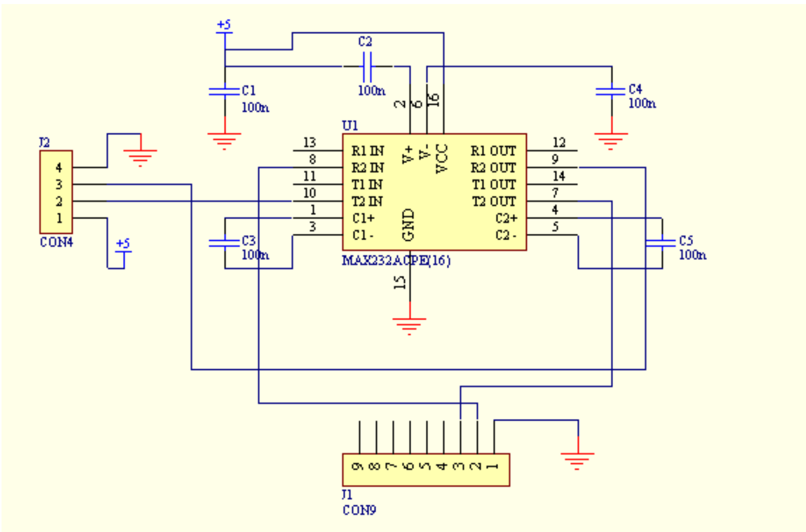

Figure 4-71: Schematic diagram of the RS-232 interface circuit.

The basic component of the serial cable is the MAX232A CMOS driver/receiver [57] from MAXIM [26]. The MAX232A is a two-channel RS-232 line driver/receiver pair designed to operate from a single 5 V power supply. A highly efficient on-chip charge pump design permits RS-232 levels to be developed using charge pump capacitors as small as 0.1 μF. The capacitors are internal to the package on the MAX232A so no external capacitors are required. These converters generate ±10 V RS-232 output levels. Fast driver slew rates permit operation up to120 KB while high drive currents allow for extended cable lengths. An epitaxial BiCMOS construction minimizes power consumption to 10 mW and also guards against latch-up. Overvoltage protection is provided allowing the receiver inputs to withstand continuous voltages in excess of ± 30 V. In addition, all pins contain ESD protection to levels greater than 2 kV [57].

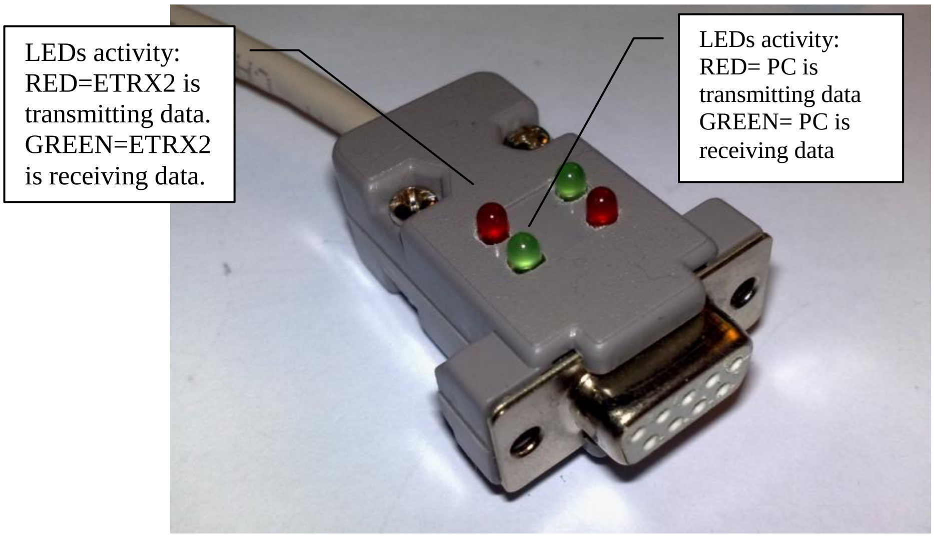

Figure 4-72: The RS-232 male plug with the integrated RS-232 driver/receiver.

The interface circuitry is enclosed in the special RS-232 male plug (Figure above). Four LEDs indicate the connection activity of the receiving and transmitting sides of the two communication sides.

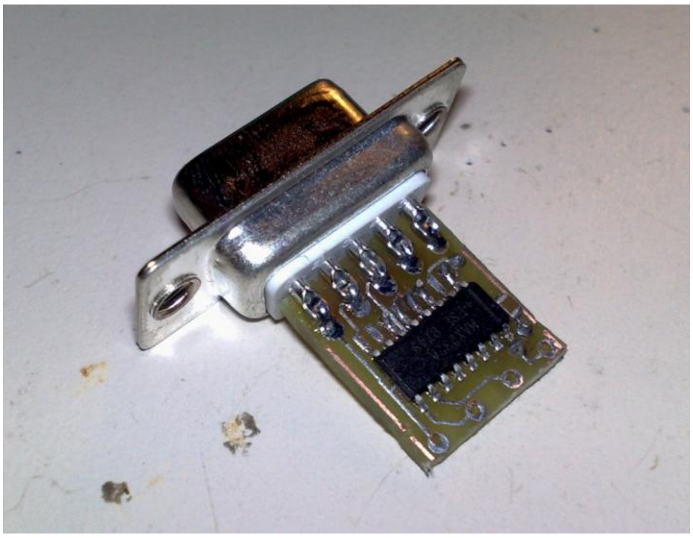

Figure 4-73: The PCB of the interface circuit

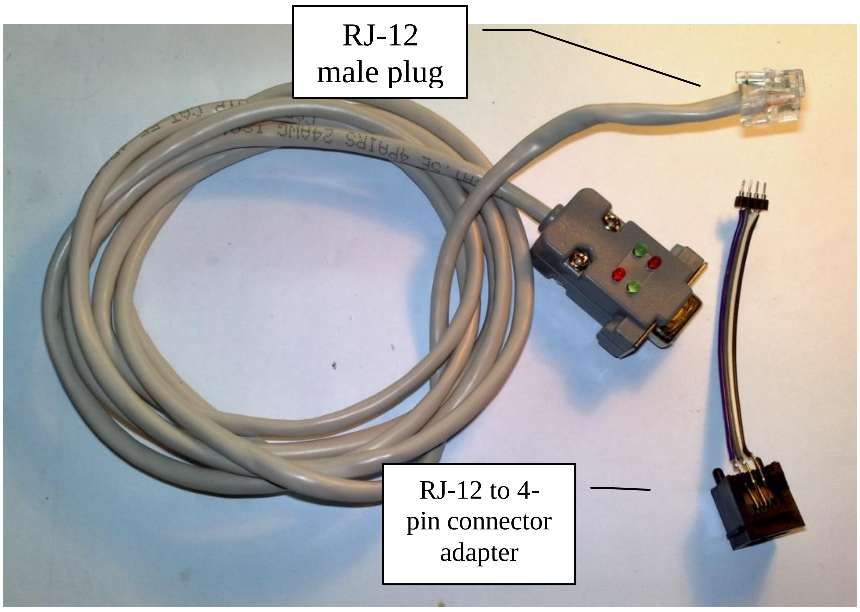

Figure 4-74: The serial cable and the RJ-12 to 4-pin connector adapter.

Figure 4-73 shows how the PCB of the interface circuit is soldered to the RS-232 socket. A male RJ-12 plug is attached on the other end of the serial cable. An extra RJ-12 to 4-pin socket adapter had been designed (Figure 4-74) for connection of the serial cable to the 4-pin connector of the REMB upper PCB and COO board.

4.12 System limitations

In real field applications it can be assumed that the number of PV modules in a large scale PV plant may exceed hundreds in number. Despite the fact that the ZigBee protocol defines that the maximum number of nodes in an existing network can be approximately 65,500 theoretically. Practically a ZigBee network size has limitations. Routers are limited in the number of end devices they can support because they have to store the messages that are sent to the end devices. The network's performance will degrade as more nodes are added because the available bandwidth will become congested with the various network maintenance messages that are passed to and from. The physical layout of the network will therefore affect its possible size, because devices that are far away from each other may not affect each other's radio performance the nature of the traffic flow also has an effect as it will determine the need for repeated messages and route discovery processes. In addition, if every device is sending messages to a central node then its serial port capacity could be exceeded. Ember manufacturer [19], suggest that a practical network size limit may be around 600 nodes but it is not easy to predict. As an alternative solution in the case of larger network size is needed it can be the method of splitting the network itself into two or more. With this implementation, two or more COO boards can exist combining the capabilities of each (sub) network.

4.13 Cost analysis of the hardware

The final cost of a system is a vital issue. The ratio of performance versus price must be a good reason for the engineer to design a well performing work at a minimum cost. Even though a system can operate successfully reliable and has a great number of features, other proposed competitor systems in the market might be tempting. The engineer must keep in mind that an expensive system is not always a better system.

In this work multiple efforts have been done in order to select the most suitable parts that cover the designing needs and simultaneously satisfy the low cost need. Below, a short cost analysis of the system will be presented mainly in the form of tables.

End device				COO board		
Part	Qt.	Cost (Euros)		Part	Qt.	Cost (Euro)
ETRX2 ZigBee module	1	17		ETRX2 ZigBee module	1	17
BYW 81 Diode	1	3		PCB	1	9
PCB	1	5		ADC0808 chip	1	2
SMSP chip TIP74100	1	2		L4940 regulator	1	2.3
Other peripheral parts (resistors, capacitors diodes)	32	4		CP2102 chip	1	3.5
Total		31		SN74LVC4245 chip	1	2.1
Total cost for six end devices	6	186		External 2.4GHz ant	1	6
				Humidity sensor	1	4
ETRX2 ZigBee module	1	17		Other peripheral parts (resistors, capacitors diodes)	38	12
BYW 81 Diode	1	3		12V battery pack1	1	17
SMSP chip TIP74100	1	2		Total COO board cost		71.4
Main PCB	1	5				
Router board	Qt.	Cost (Euro)		REMB	Qt.	Cost (EURO)
Upper PCB	1	4		230V/12V-20mA Transformer	1	3.1
SMPS PCB	1	2		MAX743 chip	1	4
Relays	2	4		UA741 chip	1	1.2
Connecting cables	1	0.5		PCB	1	8
ADC0808 chip	1	5		Ethernet cable	1	3
ACS713 chip	1	2.1		High accuracy resistor trimmers	7	7
ETRX2 module connector	1	0.3		Other peripheral parts (resistors, capacitors diodes)	36	10
HCF4555 chip	1	2		ACS756 current sensor	2	5
Other peripheral parts (resistors, capacitors diodes)	58	14		ACS713 current sensor	1	2.1
Total cost of router board		60.9		LM35 temperature sensor	1	2
				Sensor PCB's	3	8
				Total cost of REMB		53.4
				Total system cost		371.7

Table 4-3: Cost analysis for 6 end devices

As shown in the cost analysis table, the total cost of the system is approximately 378 Euros. The most expensive parts are the ETRX2 ZigBee modules. In the field of ZigBee technology, an engineer can select between two options. The first is a ready ZigBee module with all chipset included in one shielded structure. The manufacturer of a ZigBee module had already designed and engineered for example the RF and power supply circuitry. In addition the product is also tested and certified. The end user has only to program and install the module to his design. This option offers a ready of the self solution but at high cost. The second and much cheaper option is the SoC (System on Chip). The engineer has to design and test himself from the beginning all the circuits. As described, the ETRX2 module includes the EM250 chip. This chip is priced at approximately 3 Euros (for 1000 pieces) if purchased separated. So, it is obvious that if the ETRX2 modules will be replaced with a new design including no ZigBee modules but a SoC solution the cost will drop dramatically.

A good proposal for cost reduction concerning end devices and routers is the possibility to manufacture a SoC ZigBee system onto a film flexible PCB. This will not only reduce the cost but it will make the devices more versatile. Finally, the issue of integrating a ZigBee SoC in each PV module at the manufacturing stage, (of the PV panel) in order to produce ready of-the-shelf PV modules that internally contain a ZigBee monitoring system must be seriously investigated by the PV module manufacturers.

4.14 Summary

Because of the high detailed description of each part of the system, chapter 4 is the largest. Block diagrams, schematics and images presented here in order to give reader a picture of the experimental, designing and development phase of this work. All hardware parts were tested under several conditions and worked reliably. Chapter 5 is dedicated to the software part of the system. Next chapter presents the system testing procedure and some measurement results from the small PV system that is located in the Technical Educational Institute of Crete.

CHAPTER 5

Test and Measurements

5.1 Introduction

In previous chapters a presentation of a theoretical background concerning some widely used wireless protocols including ZigBee and also a detailed presentation of the system hardware and software infrastructure took place. This chapter will provide the results and also some experimentation concerning the PV plant. The present chapter will give an image of the power produced by the 6 PV panels that used in this project through the software. Details of the working status and testing procedure of the hardware are also given.

5.2 PV plant monitoring results, measurements-experiments

Two different experiments were conducted in order to verify the performance and reliability of the ZigBee PV monitoring system.

i. Bad connection experiment

In the first experiment, the case of a bad and of a corrupted connection has been simulated. In case N_o1, we disconnect the positive terminal of a PV module. This disconnection led to a zero current reading (see figure 5-1) of the respective PV module (PV module n_o3) in the GUI application. The absence of current measurement but the presence of a DC value of approximately 16V voltage reading leads to the conclusion that the PV module is disconnected from the DC bus. Such a state can be easily managed by a software application in order to enable an alarm.

In case N_o2, we connected a PV module (PV module n_o4) in the DC bus but in that case corroded connectors used. This situation led to fluctuations of current and voltage readings in the GUI for the specific PV module confirming the bad connection.

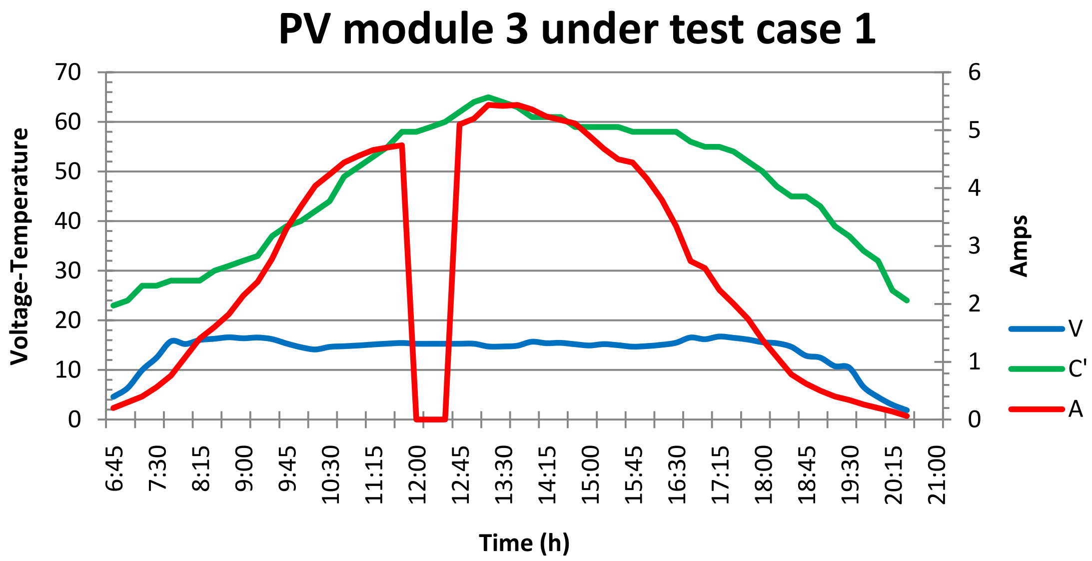

Figure 5-1: Graph of PV 3 during test.

In the graph of figure, there is current drop to zero from 12:00 to 12:30 caused by the disconnection of module 3 from the DC bus. Note that the voltage reading is normal and this is because the end device module reads the voltage of the DC bus that is connected with the other PV modules.

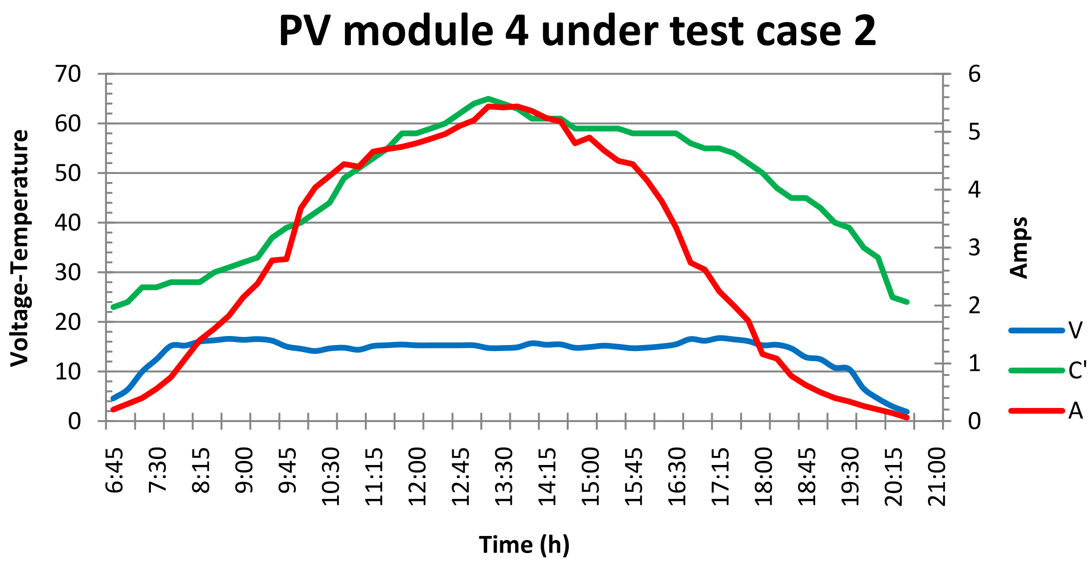

Figure 5-2: Graph of module 4 during test.

In the graph of figure 5-2, note the fluctuations of current at 9:45, 11:00, 14:45 and 18:00. The fluctuation of the voltage is very small (almost negligible) and cannot be displayed in this graph.

ii. Low performance of a PV module

In this experiment, the case of a low performance caused by dirt or dust in the transparent surface of the module had been investigated. A mixture of fine sand and water had been sprayed to the glass surface of PV N_o4 simulating the red rain effect caused from the African dust, that is a very common phenomenon in the area of Crete. The PV monitor displayed a slight lower current reading in comparison to the mean value of the rest PV modules. The dust sensor discussed previously can alert for high air dust concentration. Depending on the software extra reading can be extracted like power (W) and energy (Joules).

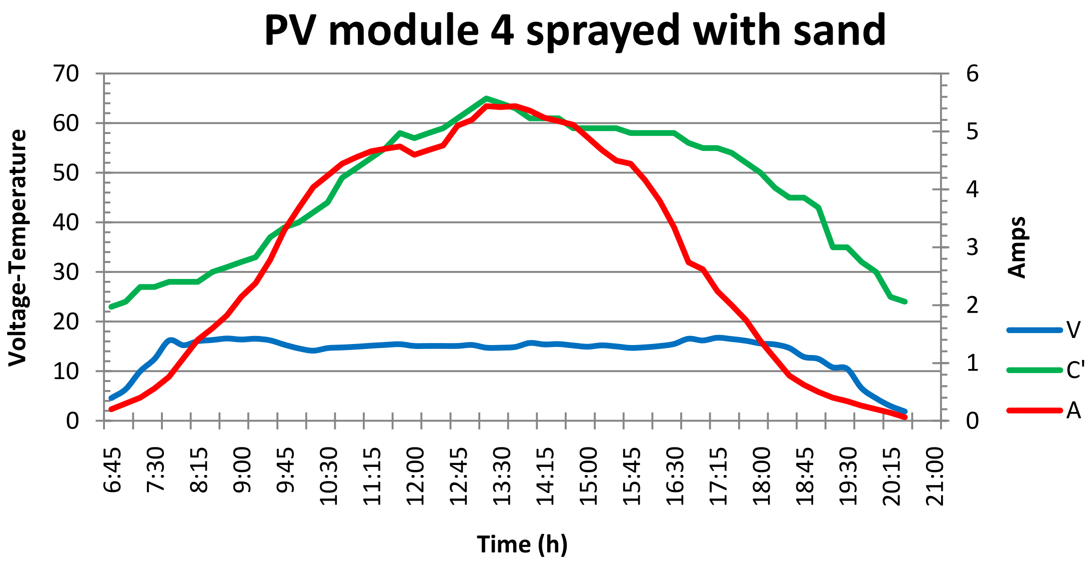

Figure 5-3: Graph of PV module 4 during test.

In the graph above, there is a low current performance caused from a dirt surface. From 12:00 to 13:00 the current reading shows a little lower current output. At the same time the temperature of the PV module is slightly reduced.

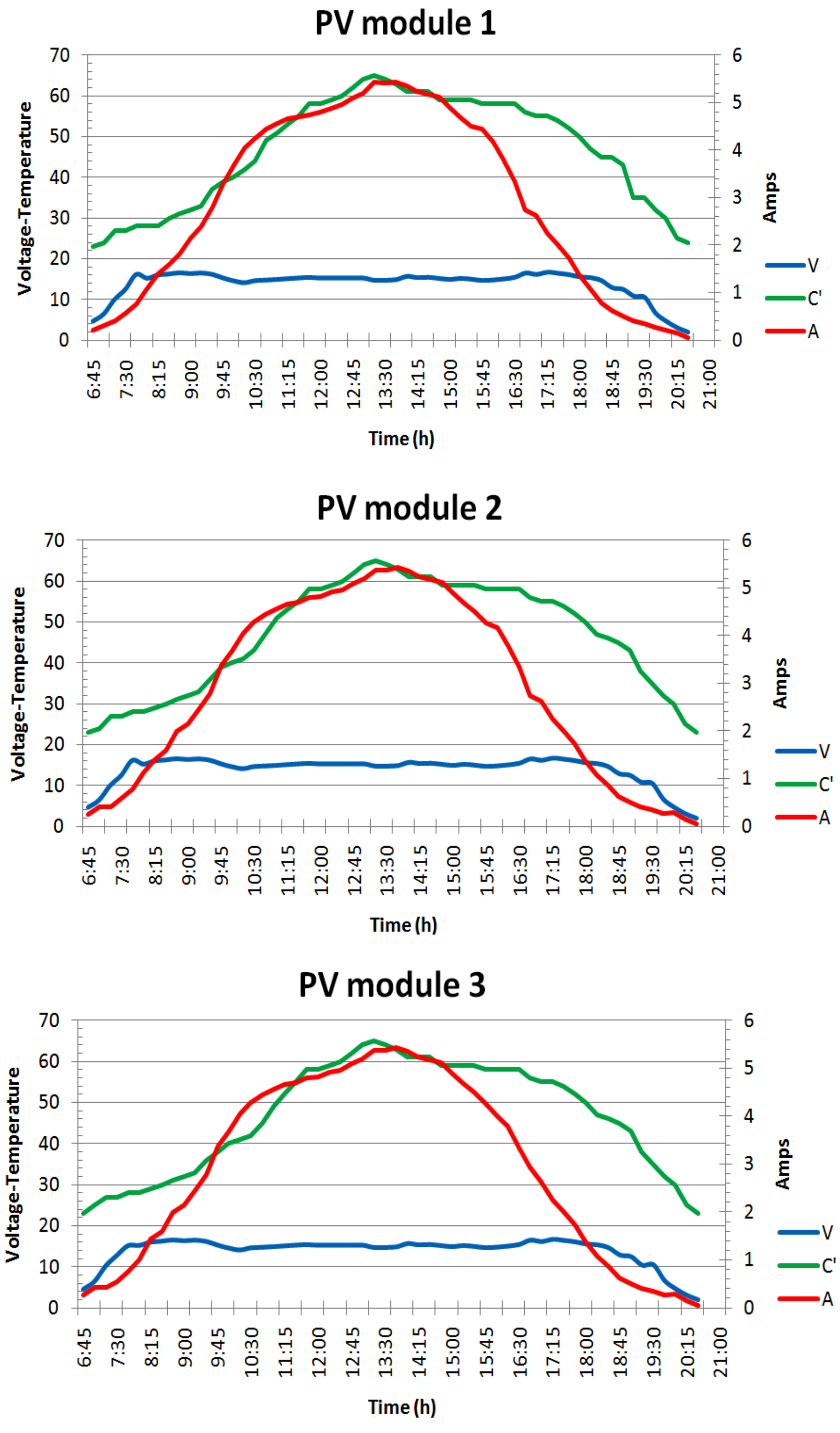

Figure 5-4: Graphs of PV modules 1, 2 and 3 for a specific day.

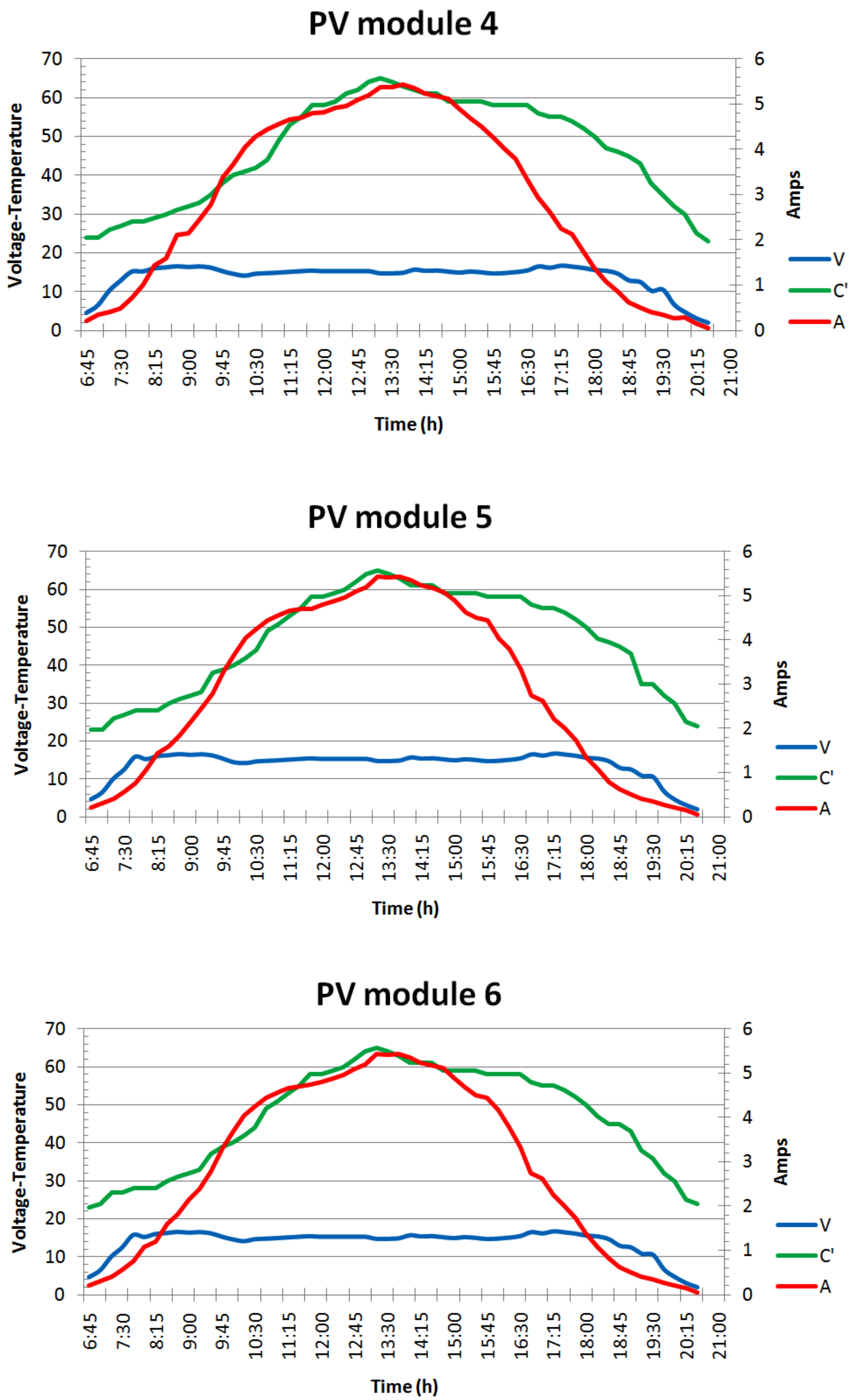

Figure 5-5: Graphs of PV modules 4, 5 and 6 for a specific day.

In Figures 5-4 and 5-5, a number of graphs are shown representing the measurements corresponding to a specific day for each PV panel separately. The small differences between the graphs are mostly sensor errors. Another reason of these variations can be the fact that none of the PV module outputs the same amount of energy for a specified sun illumination Below, a table with the electrical parameters of the PV plant as well as the day characteristic of it is given. Figure 5-6 shows a graph of the PV plant total current. Figures 5-7 and 5-8 show the output voltage and power respectively.

	V [V]	I [A]	P (w)			V [V]	I [A]	P (w)
6:45	4.60	1.2	5.52		**14:00**	15.49	32.16	498.16
7:00	6.50	1.8	11.70		**14:15**	15.41	31.44	484.49
7:15	9.20	2.4	22.08		**14:30**	15.48	31.08	481.12
7:30	12.25	3.36	41.16		**14:45**	15.44	30.72	474.32
7:45	16.20	4.56	73.87		**15:00**	15.20	29.4	446.88
8:00	15.28	6.48	99.01		**15:15**	15.22	28.08	427.38
8:15	16.06	8.4	134.90		**15:30**	15.10	27	407.70
8:30	16.30	9.6	156.48		**15:45**	15.00	26.64	399.60
8:45	16.60	10.92	181.27		**16:00**	14.83	24.96	370.16
9:00	16.38	12.84	210.32		**16:15**	15.08	22.8	343.82
9:15	16.51	14.28	235.76		**16:30**	15.50	20.04	310.62
9:30	16.19	16.68	270.05		**16:45**	16.55	16.44	272.08
9:45	15.35	19.8	303.93		**17:00**	16.21	15.72	254.82
10:00	15.40	22.08	340.03		**17:15**	16.75	13.44	225.12
10:15	15.30	24.24	370.87		**17:30**	16.49	12	197.88
10:30	15.35	25.44	390.50		**17:45**	16.14	10.44	168.50
10:45	15.36	26.64	409.19		**18:00**	15.81	8.28	130.91
11:00	15.20	27.36	415.87		**18:15**	15.62	6.48	101.22
11:15	15.15	27.96	423.59		**18:30**	14.60	4.68	68.33
11:30	15.32	28.2	432.02		**18:45**	12.63	3.72	46.98
11:45	15.38	28.44	437.41		**19:00**	11.67	3	35.01
12:00	15.59	28.8	448.99		**19:15**	10.66	2.4	25.58
12:15	15.60	29.28	456.77		**19:30**	9.62	2.04	19.62
12:30	15.84	29.76	471.40		**19:45**	6.06	1.56	9.45
12:45	15.69	30.6	480.11		**20:00**	4.57	1.2	5.48
13:00	15.83	31.2	493.90		**20:15**	3.00	0.84	2.52
13:15	15.70	32.64	512.45		**20:30**	1.60	0.36	0.58
13:30	15.50	32.52	504.06		**20:45**		32.16	498.16
13:45	15.30	32.64	499.39		**21:00**		31.44	484.49

Table 5-1: Table of main electrical parameters during a specific day.

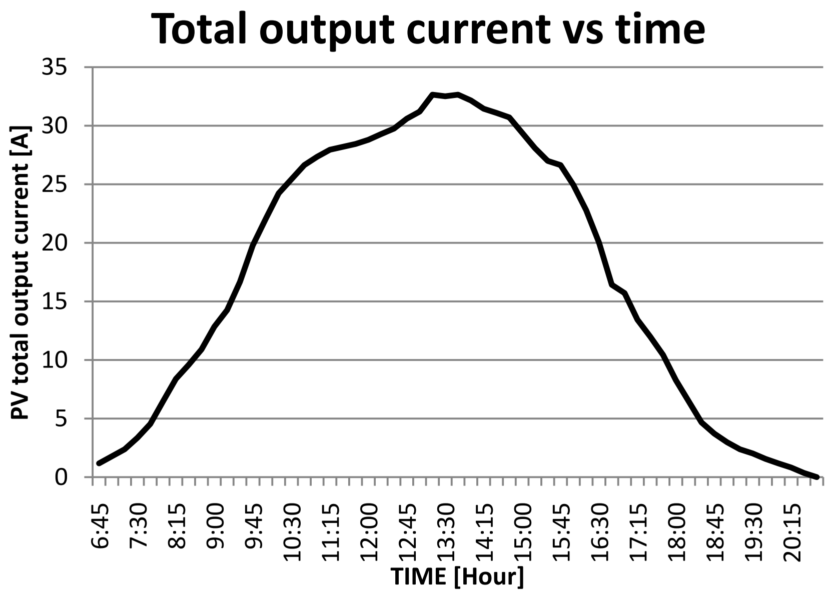

Figure 5-6: PV total output current vs. time.

As shown in graph of figure, the maximum current of the PV array is achieved from 13:30 until 14:30. This is because the sun illumination at this time is at maximum.

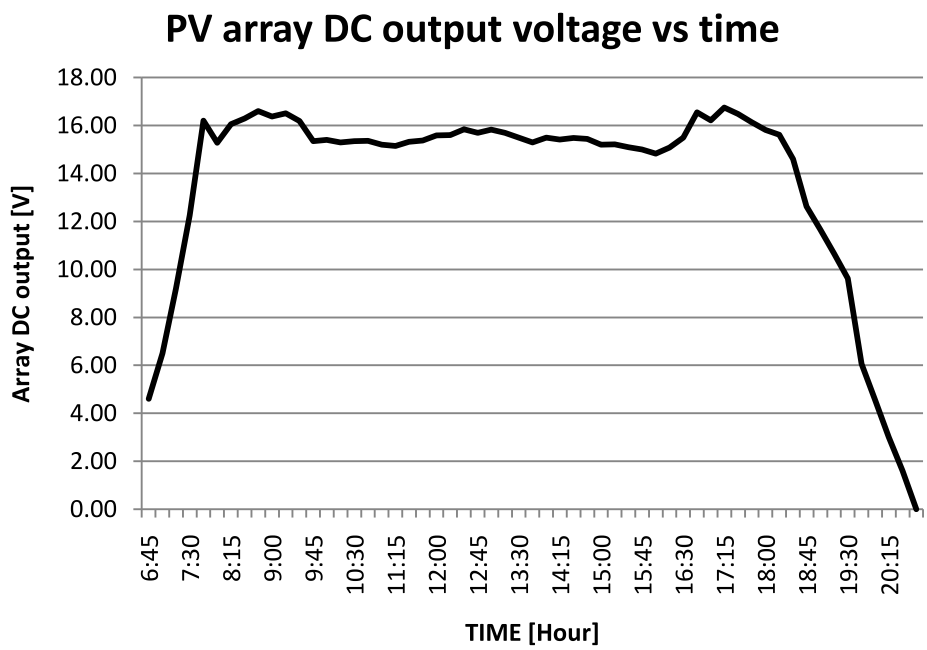

Figure 5-7: PV plant output voltage vs. time.

The voltage of the PV system varies from 15.8 Volts to 16.2 Volts. These variations are mostly sensor errors. Note that the voltage output is the same even though at times where the current is low. This is a natural behavior of PV modules.

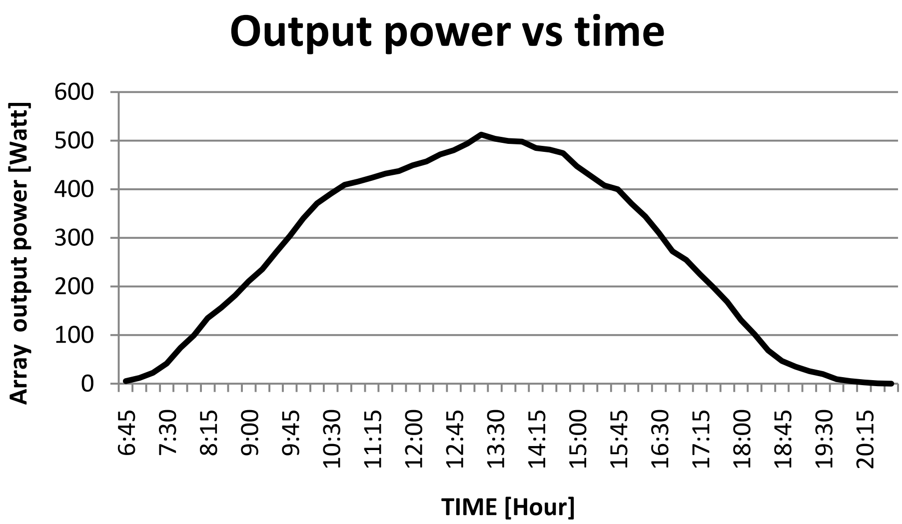

Figure 5-8: PV plant output power vs. time.

Figure shows the overall output power of the PV system. The maximum power is achieved from 13:30 until 14:30.

5.3 Functionality tests

In this chapter a description of the hardware healthy working testing will be given.

5.3.1 Testing of the COO

All hardware systems of the COO board were tested for good working operation. The ZigBee module of the COO board was tested as below:

- Checking if the ZigBee module transmits and receives data from other modules. (For this reason a separate ZigBee module used).
  Result: ZigBee RF module operates normally.

- To test if the ZigBee module receives correctly signals from the ADC a 5Volt signal applied to the input of the ADC. A digital multimeter showed a 5Volt signal at each the 8-bit bus. Similarly a 0Volt signal applied to the input of the ADC. A check at the register S11 confirmed the correct operation.

- To test the functionality of the serial port of the ZigBee module, some AT commands were sending and received to the Telegesis Terminal. The module answered on each command.
  Result: Test passed.

- The ZigBee module also tested for current consumption. The average current consumption was 30mA.
  Result: Current consumption in acceptable levels.

- The clock source of the ADC checked for stability and also for noise.
  Result: Pure square wave with no noise.

- Logic level translator
  Result: Passed

- RS-232 to USB interface
  Result: Passed

- The relative humidity sensor tested for its reliability. For that reason, an analog RH instrument used. During the test, the analog instrument gave a 50% RH. The output of the RH sensor (HIH-4031) was 2.3Volts. This output corresponds to an approximately RH 51%
  Result: Passed

- All temperature sensors were tested and compared with the built-in thermometer of a digital multimeter (Fluke 116). All sensors worked fine with minimum tolerance.

- The UPS of the COO board tested too. After unplugging the mains power, the UPS worked as expected with the COO board running on batteries.
  Result: Passed, autonomy approximately 6 hours.

5.3.2 Testing of the REMB

All the hardware of the REMB was tested for healthy operation. The connection with the COO board was tested too and also some calibrations took place.

- Precision rectifier. Testing of the PR was easy. A low 1Volt AC voltage applied to the input of the PR. The output of the PR gave 1Volt DC.
  Result: Passed

- Testing of the DC-DC converter.
  The DC-DC converter worked fine. Applying a 5Volt DC input the outputs were +15Volts and -15Volts.
  Result: Passed.

- Testing connection to the COO board.
  All signals from REMB were transferred successfully to the COO board. (Green LED on).
  Result: Passed

- The DC attenuator was calibrated by simply adjusting trimmers R1 and R3 to provide a 10 division ratio.

- Also the AC voltage attenuator was calibrated by adjusting trimmers R5 and R7 to provide a attenuation ratio of 100
  Result: Passed.

- Testing the PV total current sensor.
  The DC current sensor tested for reliability of its output. To test the sensor (ACS756) a 10Amp 12Volts DC power supply and a 12Volt 55W automotive bulb used. The output of the ASC756 was then 90mV corresponding to a current of 4.55Amps. This measurement was successfully compared with a digital multimeter
  Result: Passed.

- Testing the battery charging current sensor.

This test was the same with the previous. A 10 Amp 12Volts power supply and a 10W automotive bulb were used. The output of the ACS713 was 110mV corresponding to 0.8Amp.

Result: Passed.

- Testing the inverter output sensor.

  In this test a 220Volts 100W bulb and a digital multimeter were used. The output of the ACS754 was 82mV corresponding to a current of 2.1Amps.

5.3.3 Testing of the router

The router board is a very important device of this ZigBee network because of being the relay device for all end devices to the coo. Its reliability influences the performance and good working status of the whole system.

- Checking if the ZigBee module transmits and receives data from other modules. (For this reason a separate ZigBee module used).

  Result: ZigBee RF module works fine.

- To test if the ZigBee module receives correctly signals from the ADC a 5Volt signal applied to the input of the ADC. A digital multimeter showed a 5Volt signal at each the 8-bit bus. Similarly a 0Volt signal applied to the input of the ADC.

- To test the functionality of the serial port of the ZigBee module some AT commands war send an received to the Telegesis Terminal

  Result: Test passed.

- The ZigBee module also tested for current consumption. The average current consumption was 28mA.

  Result: Current consumption in acceptable levels.

- The clock of the ADC checked for stability and also for noise.

  Result: Pure square wave with no noise.

- Logic level translator
  Result: Passed

- RS-232 to USB interface
  Result: Passed

- The voltage divider was calibrated to provide an attenuation factor of 10 by selecting the right values of resistors R1 and R2.Its output voltage compared with a digital multimeter.
  Result: Passed

- The SMPS voltage regulator tested for reliability. A variable 0-32Volts 5Amps DC power supply was used for that purpose. The output of the SMPS voltage regulator was 5Volts for input voltages in the range of 2.5Volts – 32Volts. That was a simulation of the router board working in low light (low voltage) or overvoltage conditions.
  Result: Passed.

- The UPS of the router board tested too. When the input voltage in the router board dropped below 3Volts, the system run successfully on battery.
  Result: Passed, autonomy approximately 5 hours.

- Testing the current sensor (ACS713) of the router board.
  This test had been done by shorting the output terminals of the router board. With the board connected to a PV panel, the sensor output measured 1.8Volt corresponding to the maximum short circuit current of the PV panel that is 5.6Amps at full lighting conditions. The output of ACS713 measured with a digital multimeter too.
  Result: Passed.

- Each relay of the router board checked for good working through the Telegesis Terminal. Through the use of the terminal, AT commands for open-close operation was used successfully.
  Result: Passed.

5.3.4 Testing of the end devices

All 5 end devices tested for reliability.

- Checking if the ZigBee module transmits and receives data from other modules. (For this reason a separate ZigBee module used).

- Result: ZigBee RF module works fine.

- To test the functionality of the serial port of the ZigBee module some AT commands war send an received to the Telegesis Terminal
- Result: Test passed.
- The ZigBee module also tested for current consumption. The average current consumption was 28mA.
- Result: Current consumption in acceptable levels
- The voltage divider was calibrated to provide an attenuation factor of 10 by adjusting P2. Its output voltage compared with a digital multimeter.
- Result: Passed
- The SMPS voltage regulator tested for reliability. A variable DC 5Amp 0-32Volts power supply was used for that purpose. The output of the SMPS voltage regulator was 5Volts regulated for input in the range of 2.5Volts – 32Volts. That was a simulation of the end device working in low light (low voltage) or overvoltage conditions.
- Result: Passed
- Testing the current sensor (ACS713) of the router board.

  This test had been done by shorting the output terminals of the end device. With the board connected to a PV panel the sensor output measured 1.8Volt corresponding to the maximum short circuit current of the PV panel that is 5.6Amps at full lighting conditions. The output of ACS713 measured with a digital multimeter too.
- Result: Passed.
- The output of the temperature sensor compared with that of a digital multimeter. The output measured 33 degrees Celsius.

5.3.5 Testing wireless connectivity and networking

All boards including a ZigBee module tested for connection with the COO. All devices including end devices as well as the router were successfully connected to the COO.

5.3.6 Functional testing

The final test of the system included a full day time period monitoring of the 6 PV panels. (Hours from 21:00 to 06:30 are not shown due to sun absence). The monitoring parameters such as current, voltage and temperature had been compared every 1hour (during the time period 7:00 – 20:00) with the readings of a digital multimeter (Fluke 114). The readings of the GUI were too close to the readings of the digital multimeter including a small error that is probably caused by the current sensors and voltage attenuators-dividers and of course by the ADC accuracy of the system. During night, the router board was running on batteries and was communicating continuously with the COO board for at least 4hours. When the first light of the day came on, and when the output voltage of the PV panels exceeded the voltage of 2.5Volts, all end devices and router board started to operate, then scanning for the predefined PAN, and finally joined the network. To observe this, the COO board was connected to a laptop PC running the Telegesis Terminal application. One by one the end devices was connecting and communicating with the COO via the router. The laptop PC connected also to the router board to observe the connection of the router itself and also connection of end devices to the COO board. The batteries of the router board were starting to charge when the output voltage of the PV panel exceeded the voltage of 8Volts.

RF Channel, as well as the PAN ID is predefined at the COO board. All end devices and router board are not allowed to join any other PAN. At the same way no device that is new to this PAN is allowed to join in. The PAN is code protected.

5.4 Summary

The crucial procedure of system testing took part in this chapter. The reliability, accuracy and healthy operation of hardware and software presented. In addition, measurements originated from the PV system were also available. The next and final chapter presents the conclusions along with some thoughts about the future utilization of this system.

CHAPTER 6

Conclusion and further work

6.1 Conclusion

In this Thesis a wireless monitoring and controlling system for PV systems had been presented. A short reference to other short range wireless and WSN technologies also took place as well as a short general presentation of the most common PV systems components. One of these wireless technologies, known as ZigBee had been further investigated and analyzed. In order to examine, test and evaluate the functionality of the ZigBee technology in the area of PV monitoring, the design of hardware equipment from the beginning had been characterized as a vital issue. So, all major components of a ZigBee network (COO, FFD, and RFD) and also a set of sensors constructed. The hardware construction phase of this work required a lot of research and experimentation in the field of design and development in order to achieve a healthy and reliable system. The software part in this work based on a Visual Basic platform is also of great importance for the system.

The system has been successfully tested on a low powered (600Wp) PV system consisting of (6) Photovoltaic modules (100Wp each). The system provided accurate and also real time information about not only the overall PV plant behavior but also for any PV module alone. The main advantage compared to other monitoring systems is that failures as well as disoperation of any component that consist the PV system can be identified immediately leading to the result of energy saving.

During the designing and development phase of this work, it seemed from the beginning that ZigBee is going to be an appropriate technology for PV monitoring and controlling not only for its simplicity, but for its low cost, low power and reliability as well. ZigBee has all the features to participate in the designing of a PV monitoring system.

As ZigBee is a very fast growing technology tending to be a global standard and enters uninterruptedly in applications where only fantasy can limit, it can be safely told that there will be surprises in the next years as ZigBee enters the technological arena.

6.2 Further work

This section describes some improvements which can upgrade the system that are not covered by this thesis, and will be covered in future.

They can be summarized in the following points:

- More sophisticated GUI software can be designed in order to add further flexibility and higher performance to the system. Extra parameters can be extracted with the addition of new software routines.

- Testing of the system in a large PV plant. In case of monitoring a large scale PV plant, the possibility of employing ZigBee networks together could be investigated.

- In a future work, a simulation of a ZigBee network in a PV plant will provide interesting and useful information.

- Connection to the internet can be easily established with the addition of a wireless GSM modem (where an internet connection is not available)

Appendix

Firmware and Software

A.1Introduction

In this appendix a description of the firmware and software will be given. The firmware of the ETRX2 module is preloaded from Telegesis. This firmware is a ZigBee platform designed by Ember [19]. The preloaded ZigBee platform is the EmberZNet meshing self-healing ZigBee stack. A preloaded AT-style command interface firmware that is based on the EmberZNet meshing stack is also included. Despite the fact that the user is able to develop a custom firmware, in this thesis the preloaded firmware used.

In appendix A, the reader will be able to understand the basic structure of the software part. Also, a short description of the firmware that the ETRX2 modules use is given. Furthermore, the GUI (Graphical User Interface) is explained.

A.2 The EmberZNet protocol stack

EmberZNet is a complete ZigBee protocol software package containing all the elements required for robust and reliable mesh networking applications on Ember's silicon platforms. EmberZNet PRO includes the industry's ZigBee stack based on the ZigBee feature Set, enhanced with unique Ember innovations, providing "professional grade" networking for the most challenging applications such Advanced Metering Infrastructure (AMI), Home Automation, and Building Automation systems [58], [59]. In addition the Telegesis firmware also allows low-level access to physical parameters such as channel and power level.

Parameters that define the functionality of the ETRX2 module and also allow standalone functionality are saved in non-volatile memory organized in so-called S-Registers. The SPI and I2C buses are not supported by the current firmware release, but can be used with custom firmware. Further description of the EmberZNet software is out of the scope of this thesis. For further details and full documentation please refer to Embers website.

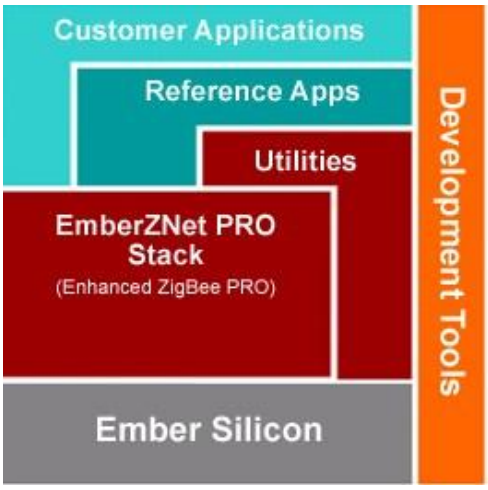

Figure A-1: The EmberZNet protocol stack [58].

The EmberZNet stack is shown above. The lower block of the stack is the hardware platform. The hardware platform includes the microcontroller and the transceiver circuits. The firmware of the stack includes the ZNet that contains the ZigBee stack. User applications are placed at higher levels. With the use of development tools the programmer is able to configure the firmware and also the hardware.

A.3 The AT commands interface

Introduction

For simplicity of programming the ETRX2 module comes with a preloaded AT command interface. Thanks to it, there is not necessity from the user side to develop a complex software part. In this section a description of the AT command set will follow. In this system the COO board is connected to the host computer. The ETRX2 module of the COO board sends and receives commands and data (in AT-style form) through its UART to the host computer using ASCII strings. A software tool like Hyper Terminal can be used to send and receive commands. A similar software tool, the Telegesis Terminal is available from Telegesis. The Telegesis Terminal will be described below.

A.4 The Telegesis Terminal software

The Telegesis Terminal (Figure A-2) is not a GUI (Graphic User Interface). This software is simply an AT command editor. When the user enters a command, the Telegesis Terminal sends it to the UART in ASCII string format. The command is then received by the ETRX module. Similarly, when the module wants to sent a prompt or a response to the host computer the opposite process occurs. When a user wishes to develop a custom software, it must be kept in mind that this software should send and receive data as formatted in the AT command set dictionary of Telegesis.

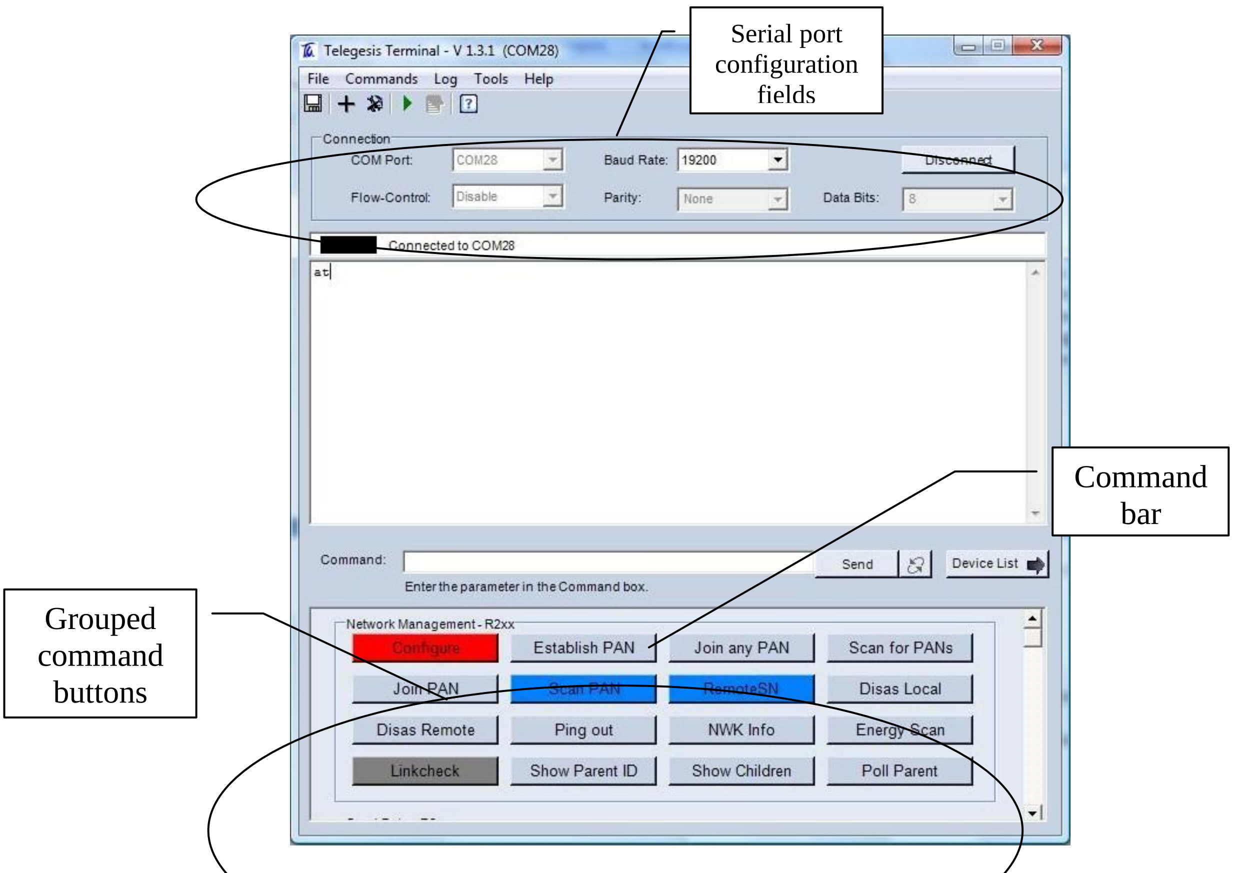

Figure A-2: The Telegesis Terminal.

All of the commands are pre-defined and conveniently grouped at the bottom of the terminal window (Figure A-2). Pressing a button (where no parameters are required) causes the corresponding command to be issued instantly. Where a parameter is required the command is shown in the Command bar and the required parameter can be entered manually. Every EUI64 number reporting in is listed in a separate window which can be opened or closed by clicking on the button labeled '**Device List**'. If a device ID is required as a parameter in the command bar, a double click on an entry in the device list and its EUI64 will be automatically transferred to the current cursor position of the command bar.

To allow for easier identification, the EUI64 IDs in the device list can be named. When right clicking on any EUI64 ID a name can be associated with the respective ID. The application software also allows to add custom command buttons and/or edit existing command buttons. New groups of commands can be created and command buttons can be moved between groups.

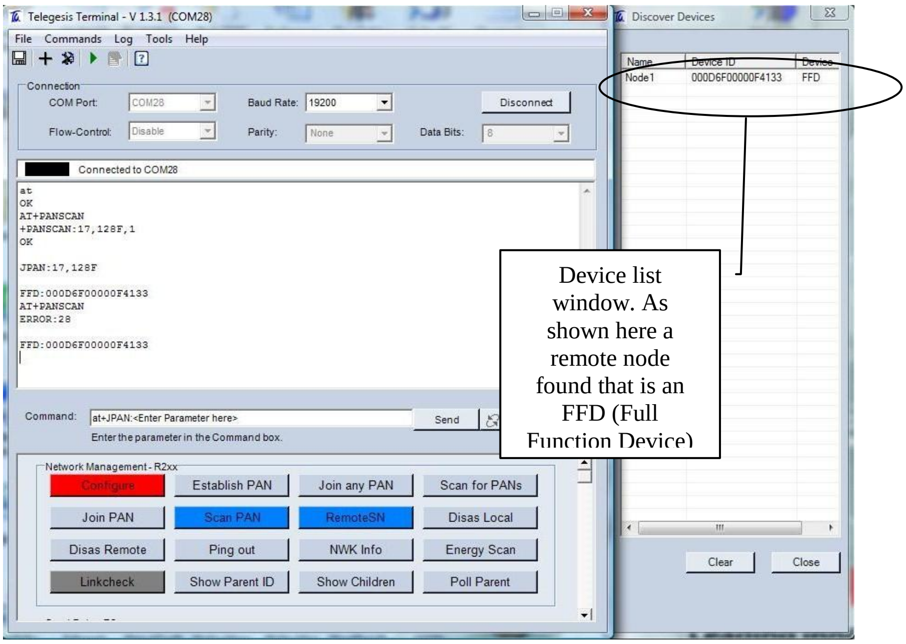

Figure A-3: An FFD as it is displayed in the device list window.

Figure A-3 shows an example of communication between two ZigBee devices. The devices that part the WPAN (Wireless Personal Area Network) are shown in the device list window.

A.5 At commands set

The AT command set that is used here is a version similar with the industry Haynes modem control language. The AT command language can be found on modems, faxes and cell phones. It is a practical way of programming that simplifies the communication between devices. Just to take a flavor, table A-1 gives a quick reference of all commands available.

Command Overview	
ATI	Display product identification information
ATZ	Software reset
AT&F	Restore factory settings
AT+BLOAD	Enter the bootloader menu
AT+CLONE	Clone the local node's firmware to a remote node
AT+RECOVER	Recover from a failed clone attempt (ETRX2 only)
AT+PASSTHROUGH	Enter pass-through bootloading mode (ETRX1 only)
ATS	S-Register access
ATSALL	Write all remote S-Registers
AT+TOKDUMP	Display all local S-registers
ATSREM	Remote S-register access
AT+ESCAN	Scan the energy of all channels
AT+EN	Establish PAN
AT+JN	Join next best network
AT+PANSCAN	Scan for active PANs
AT+JPAN	Join specific PAN
AT+DASSL	Disassociate local device from PAN
AT+DASSR	Disassociate remote device from PAN
AT+NTABLE	Show the neighbour table
AT+N	Display network parameters
AT+CTABLE	Display list of local children
AT+PARENT	Display Parent's ID
AT+POLL	Poll Parent for data
AT+SN	Scan network for other nodes
AT+REMSN	Scan for remote device's direct neighbours
AT+LINKCHECK	Check link parameters with a neighbour
AT+PING	Indicate presence in the network
AT+BCAST	Transmit a broadcast
AT+BCASTB	Transmit a broadcast of binary data
AT+UCAST	Transmit a unicast
AT+UCASTB	Transmit a unicast of binary data
AT+SCAST	Transmit data to the Sink
AT+SCASTB	Transmit binary data to the sink
AT+SSINK	Search for a sink
AT+SINK	Display the local Node's sink
AT+OPCHAN	Opens a channel to a remote node
+++	Close channel
AT+OPLCHAN	Opens a limited channel to a remote node
AT+ACKCHAN	Accept channel
AT+RDATAB	Send binary raw data
AT+IDENT	Play a tune on remote devboard

Table A-1: AT commands overview [61].

Each command is entered with the “AT” or “at” prefix. A command is terminated with “enter”. A command example follows:

ATS03=? < This command asks the value of the S03 register of the ETRX2 module >
S03:00FF < In this line the response of the module is shown. The value of register S03 is 00FF >
OK < An OK prompt indicates the end of response >

The module might prompt an “error” if there is a mistake in the command syntax.

During the operation of the ETRX2 module the following prompts can show up.

Prompt Overview	
JPAN: CC,PPPP	The Node has joined a PAN on channel CC with PAN ID PPPP
LeftPAN	The node has left the PAN
UCAST:<EUI64>=<data>[,<length>]	Reception of a Unicast
BCAST:<EUI64>=<data>[,<length>]	Reception of a Broadcast
RAW:<data>	Reception of raw data
SCAST:<EUI64>=<data>[,<length>]	Reception of a Scast (Data sent to the sink)
ACK:nn	Receipt for successful acknowledgement of a message
NACK:nn	Notification of missing acknowledgement
CHAN:<EUI64>	A request to open a channel
OPEN	A channel has been opened
CLOSE	A channel has been closed
NEWNODE:<EUI64>	A new node has joined the network
SINK:<EUI64>	A new sink was found and stored
[REM]SED:<EUI64>	A sleepy end device has been found
[REM]MED:<EUI64>	A mobile sleepy end device has been found
[REM]FFD:<EUI64>	A router has been found
[REM]COO:<EUI64>	A coordinator has been found
COUNT:<EUI64>,XX,<ioread>,<A/D1>,<A/D2>	Triggered by action 2000 (see section 5)
NDATA:<EUI4>,XX,<ioread>,<A/D1>,<A/D2>	Triggered by actions 0110 - 0113 (see section 5)
SDATA:<EUI64>,<ioread>,<A/D1>,<A/D2>	Triggered by actions 0100 - 0103 (see section 5)
<plaintext>	Message prompted on the sink (see section 5, functionality 0108 – 010B)
Snn[x]:<data>:<EUI64>	Remote S-Register reading
NAK:<EUI64>	A request to a remote node with EUI64 was not acknowledged.
PWRCHANGE:nn	Indicates a change of power mode caused by an action

Table A-2: Prompt overview [61].

A.5.1 Short description of the AT commands (app)

In the following lines a short description of each AT command will be given.

- **ATI** < This command returns the current firmware of the ETRX2 module (in this project the firmware version is R212X)>.

- **ATZ** < The Telegesis Terminal forces the module to perform a software reset>.

- **AT&F** < The Telegesis terminal forces the module to perform a factory reset>.

- **AT+BLOAD** < The device leaves the AT command line and enters the Ember bootloader menu. A new firmware version can be installed>.
- **AT+CLONE:<EUI64>,cccccccc** < This command clones the current firmware of the local module to remote module where its address is defined by the EUI64 number.(where cccccccc is the security password) >.

- **AT+RECOVER** < This command clones the current firmware of the local module to a remote module which is already in the bootloader >.

- **ATS** < This command returns the value of an S-register>. E.g. ATS05?
  The module will return the value of its S05 register in hex format. E.g. ATS05=00ff.

- **ATSALLnn=<data>** < This command allows to write the S-registers of all remote modules of the PAN. The number of the register to be written is defined by letters nn. > E.g. ATSALL06=<00ff> , S-registers06 of all remote modules will have the value 00ff.

- **ATSREMnn:<EUI64>?** < This command forces the local module to display the content of the S-register defined by letter nn of a remote module that is defined by the EUI63 number.>

- **AT+TOKDUMP** < This command forces the module to display the values osf all S-registers>.

- **AT+ESCAN** < The module performs an energy scan of all available channels>.

- **AT+EN** < This command forces the local mode to became a COO>.

- **AT+JN** < The local module scans all channels and joins the PAN with the highest RSSI (Receive Strength Signal Indicator)>.

- **AT+PANSCAN** < The local module scans all PANs and displays a list of all available PANs>.

- **AT+JPAN:CC,PPPP** < The local module joins a particular PAN on channel CC and PANID PPPP>.

- **AT+DASSL** < This command forces the module to leave the PAN>

- **AT+DASSR** < This command forces a remote module to leave the PAN>.

- **AT+TABLE?** < This command displays the local device's neighbor table>.

- **AT+N** < This command displays the network information>

- **AT+POLL** < Polls the parent device for new data>.

- **AT+PARENT?** < Displays the device's parent EUI64>.

- **AT+CTABLE?** < Displays the device's children EUI64>.

- **AT+LINKCHECK:<EUI64>** < This command returns the RSSI and LQI (Link Quality Indicator) of the link between the local and a remote module>.

- **AT+PING** < The ping command will display a prompt on all modules>.
- **AT+BCAST:nn,<data>** < This command forces the local module to broadcast data to all remote modules>.

- **AT+UCAST:<EUI64>**,<data> < This command broadcasts data to a remote module that is defined by the EUI64 number>.

- **AT+OPCHAN:<EUI64>** < This command forces the local and a remote module to operate as a wireless RS-232 serial port>.

- **AT+RDATAB:xx** < This command allows the broadcast of raw data>

Below there is a list of error codes that a module might return.

01	Too many characters have been entered on the command line
02	Unknown command
04	Invalid S-Register
05	Invalid parameter
06	Unicast could not be sent
07	Message was not acknowledged
08	No sink known
0E	Channel is unavailable
0F	Fatal error initialising the network
10	Error bootloading
12	Fatal error initialising the stack
14	Binding problem
15	Channel failed
16	Error trying to acknowledge a channel, which has not been requested recently
17	Only allowed on end devices
18	Out of buffers
19	Trying to write read-only register
20	Invalid password
23	PWM not in use (ETRX1 only)
24	Error Polling from Parent
25	Cannot form network
26	Cannot join network
27	No network found
28	Operation cannot be completed if node is part of a PAN
29	Local device is sink
2A	Error during energy scan
2B	No free Bindings
2C	Error leaving the PAN
2D	Error scanning for PANs
2F	Polling parent unsuccessful
30	Trying to clone or passthrough to an incompatible hardware platform
33	No response from the remote bootloader (ETRX2)
34	Target did not respond during cloning (ETRX2)
35	Timeout occurred during xCASTB
40	UART RX Frame error
41	UART RX Parity error
42	UART TX software buffer overflow
43	UART RX software buffer overflow
44	UART RX hardware buffer overflow
6C	Invalid binding table index
72	the maximum number of in flight messages has been exceeded
74	Payload too long
91	Operation only possible if joined to a PAN
A1	Network overload

Table A-3: List of possible errors [61].

S-registers

The user is able to access the modules volatile as well as non-volatile registers. A description of the modules s-registers follows.

S-Register Overview		Local R/W	Remote R/W
S00	Channel Mask	(•/•)	(•/•)
S01	Preferred PAN ID	(•/•)	(•/•)
S02	Transmit Power Level	(•/•)	(•/•)
S03	Encryption key[1]	(-/•)	(-/•)
S04	User Definable name	(•/•)	(•/•)
S05	OEM Word[1]	(•/•)	(•/•)
S06	Main Function[1]	(•/•)	(•/•)
S07	Extended Function1	(•/•)	(•/•)
S08	Extended Function2	(•/•)	(•/•)
S09	Password[1]	(-/•)	(-/•)
S0A	Revision Number	(•/•)	(•/•)
S0B	UART Setup	(•/•)	(•/•)
S0C	ETRX2: Pull-up enable ETRX1: Reserved	(•/•)	(•/•)
S0D	Data Direction of I/O Port (DDR) **(volatile)**	(•/•)	(•/•)
S0E	Initial value of S0D	(•/•)	(•/•)
S0F	Output Buffer of I/O Port (PORT) **(volatile)**	(•/•)	(•/•)
S10	Initial value of S0F	(•/•)	(•/•)
S11	Input Buffer of I/O Port (PIN) **(volatile)**	(•/-)	(•/-)
S12	A/D1	(•/-)	(•/-)
S13	A/D2	(•/-)	(•/-)
S14	ETRX2: A/D3 (Reserved) ETRX1: Reserved	(•/-)	(•/-)
S15	Immediate functionality at IRQ0	(•/•)	(•/•)
S16	Immediate functionality at IRQ1	(•/•)	(•/•)
S17	Timer/Counter 0	(•/•)	(•/•)
S18	Functionality for Timer/Counter 0	(•/•)	(•/•)
S19	Timer/Counter 1	(•/•)	(•/•)
S1A	Functionality for Timer/Counter 1	(•/•)	(•/•)
S1B	Timer/Counter 2	(•/•)	(•/•)
S1C	Functionality for Timer/Counter 2	(•/•)	(•/•)
S1D	Timer/Counter 3	(•/•)	(•/•)
S1E	Functionality for Timer/Counter 3	(•/•)	(•/•)
S1F	Timer/Counter 4	(•/•)	(•/•)
S20	Functionality for Timer/Counter 4	(•/•)	(•/•)
S21	Timer/Counter 5	(•/•)	(•/•)
S22	Functionality for Timer/Counter 5	(•/•)	(•/•)
S23	Timer/Counter 6	(•/•)	(•/•)
S24	Functionality for Timer/Counter 6 **(volatile)**	(•/•)	(•/•)

S25	Initial Functionality for Timer/Counter 6	(•/•)	(•/•)
S26	Timer/Counter 7	(•/•)	(•/•)
S27	Functionality for Timer/Counter 7 **(volatile)**	(•/•)	(•/•)
S28	Initial Functionality for Timer/Counter 7	(•/•)	(•/•)
S29	Power mode **(volatile)**	(•/•)	(•/•)
S2A	Initial Power Mode	(•/•)	(•/•)
S2B	Start-up Functionality Plaintext A	(•/•)	(•/•)
S2C	Start-up Functionality Plaintext B	(•/•)	(•/•)
S2D	Parent's EUI	(•/-)	(•/-)
S2E	Device Specific	(•/•)	(•/•)
S2F	Special Function Pin 1 **(volatile)**	(•/•)	(•/•)
S30	Initial value of S2F	(•/•)	(•/•)
S31	Special Function Pin 2 **(volatile)** (ETRX2 only)	(•/•)	(•/•)
S32	Initial value of S31 (ETRX2 only)	(•/•)	(•/•)
S33	Supply Voltage (ETRX2 only)	(•/-)	(•/-)

Table A-4: List of S-registers [61].

- **S00** < Setting this register with a value in the range 0001-ffff the user is able to define which channel will be scanned automatically>.

- **S01** < The value of this register defines the PANID>.

- **S02** < The value of this register defines the module's transmit power level in dBm>

- **S03** < In this register an 128-bit AES encryption key is kept>.

- **S04** < This register contains a user defined name for module identification>.

- **S05** < This register contains a 16-bit hex number that can be written by the OEM>.

- **S06** < This register defines the behavior of the module. (For more details please refer to ETRX2 AT commands manual) [62])>.

- **S07** < This register defines the behavior of the module>.

- **S08** < This register defines the behavior of the module>.

- **S09** < The value of this register contains the modules password>.

- **S0A** < The value of this register represents the firmware revision number>.

- **S0B** < The value of this register defines the RS-232 port behavior. (For more details please refer to ETRX2 AT commands manual) [62]>.

- **S0C** < The content of this register enables the built in pull up resistors of the EM250 [21]>.

- **S0D** < This register defines the data direction of the I/Os (input or output) >.

- **S0E** < This register contains the initial value of register S0D (Register S0D will have the content of S0E after a boot-up, soft or hard reset)>.

- **S0F** < This register contains the output buffer of the module I/O port>.
- **S10** < This register contains the initial value of register S0F (Register S0F will have the content of S10 after a boot-up, soft or hard reset)>.
- **S11** < The content of this register represents the current values of the modules I/O pins>.
- **S12** < This register represents the reading of the A/D1 port in mV hex>.
- **S13** < This register represents the reading of the A/D2 port in mV hex>.
- **S14** < This register represents the reading of the A/D3 port in mV hex>.
- **S15** < This register describes the immediate action taken on IRQ0>.
- **S16** < This register describes the immediate action taken on IRQ1>.
- **S17** < This is a timer-counter register. Its functionality defined by S18>.
- **S18** < This register defines the functionality of S17>.
- **S19** < This is a timer-counter register. Its functionality defined by S1A>.
- **S1A** < This register defines the functionality of S19>.
- **S1B** < This is a timer-counter register. Its functionality defined by S1C >.
- **S1C** < This register defines the functionality of S1B>.
- **S1D** < This is a timer-counter register. Its functionality defined by S1E>.
- **S1E** < This register defines the functionality of S1D >.
- **S1F** < This is a timer-counter register. Its functionality defined by S20 >.
- **S20** < This register defines the functionality of S1F >.
- **S21** < This is a timer-counter register. Its functionality defined by S22 >.
- **S22** < This register defines the functionality of S21>.
- **S23** < This is a timer-counter register. Its functionality defined by S24>.
- **S24** < This register defines the functionality of S23>.
- **S25** < This is a timer-counter register. Its functionality defined by S26>.
- **S26** < This register defines the functionality of S25>.
- **S27** < This is a timer-counter register. Its functionality defined by S28>.

- **S28** < This register defines the functionality of S27>.
- **S29** < The value of this register defines the power mode of the module> .
- **S2A** < The value of this register defines the power mode of the module after start up and reset>.
- **S2B** < This register contains text which is used by some built in actions>.
- **S2C** < This register contains text which is used by some built in actions>.
- **S2D** < This register contains text which is used by some built in actions>.
- **S2E** < This register defines the behavior of the module. (For more details please refer to ETRX2 AT commands manual) [62]>.
- **S2F** < This register contains the mode of operation of the special function pin 1 of the module>.
- **S30** < This register contains the initial value of register S2F>.
- **S31** < This register contains the mode of operation of the special function pin 2 of the module >.
- **S32** < This register contains the initial value of register S31>.
- **S33** < The content of this register represents the module's supply voltage in mV hex>.

The EmberZNet platform offers a plenty of built in functionalities. These functions can be triggered either by the two external interrupts IRQ1, IRQ2 or by the 8 individually programmable timers-counters S17, S19, S1B, S1D, S1F, S21, S23, and S26. Below, a table of all available built in functions is given.

Overview of Actions	
0000	No operation of the corresponding interrupt/timer/counter
0001	Change to power mode 0. In case this was triggered by a timer, the timer will stop.
0002	Change to power mode 1. In case this was triggered by a timer, the timer will stop.
0003	Change to power mode 2. In case this was triggered by a timer, the timer will stop.
0004	Change to power mode 3. In case this was triggered by a timer, the timer will stop.
0005	Change to power mode 0. In case this was triggered by a timer, the timer will restart.
0006	Change to power mode 1. In case this was triggered by a timer, the timer will restart.
0007	Change to power mode 2. In case this was triggered by a timer, the timer will restart.
0008	Change to power mode 3. In case this was triggered by a timer, the timer will restart.
…	Reserved
0010	If I am a Mobile/Sleepy end device Poll Parent for data and stop timer (if applicable)
0011	If I am a Mobile/Sleepy end device Poll Parent for data and restart timer (if applicable)
0012	If I am a Sink advertise and stop timer (if applicable)
0013	If I am a Sink advertise and restart timer (if applicable)
0014	Check for neighbours in local neighbour table. If no neighbours are present for 5 consecutive times leave the PAN. Note: It takes about 80 seconds for a neighbour to age out of the neighbour table.
0015	In case I am not joined to a network scan for and join the next best network and stop the timer (if applicable)
0016	In case I am not joined to a network scan for and join the next best network and restart the timer (if applicable)
0017	Allow joining for 60 Seconds (in case it is disabled in S06) and stop timer (if applicable)
0018	Copy local inputs to remote outputs: Read the local S11 and if changed since the previous time, write the reading to the remote S0F, whose address is given in S2B. If applicable the timer will stop.
0019	Same as 0018, but if applicable the timer will restart.
001A	Copy remote inputs to local outputs: Read the remote unit's S11, whose address is given in S2C and write the reading to the local S0F. If applicable the timer will stop.
001B	Same as 001A, but if applicable the timer will restart.
…	Reserved
002x	Toggle I/Ox and stop timer (if applicable)
003x	Toggle I/Ox and restart timer (if applicable)
004x	Flash I/Ox (pull low) for 250ms and restart timer afterwards
…	Reserved
0100	Sends the reading of the I/O and the two analogue ports to the network's sink and if no sink is known the unit will search for a sink instead. After 3 unsuccessful transmissions the sink is assumed unavailable and a new sink is searched. If applicable the timer will stop.
0101	Sends the reading of the I/O and the two analogue ports to the network's sink and if no sink is known the unit will search for a sink instead. After 3 unsuccessful transmissions the sink is assumed unavailable and a new sink is searched. If applicable the timer will restart.
0102	Same as 0100, but to charge an external RC timer I/O7 is pulled high whilst sending the data and left high impedance the rest of the time.
0103	Same as 0101, but to charge an external RC timer I/O7 is pulled high whilst sending the data and left high impedance the rest of the time.
0108	The unit sends the contents of S2B to the networks sink. If applicable the timer will stop.
0109	The unit sends the contents of S2B to the networks sink. If applicable the timer will restart.
010A	The unit sends the contents of S2C to the networks sink. If applicable the timer will stop.
010B	The unit sends the contents of S2C to the networks sink. If applicable the timer will restart.
…	Reserved
0110	Sends the reading of the I/O and the two analogue ports as well as an 8-bit transmission counter which increments with every transmission to the network's sink and if no sink is known the unit will search for a sink instead. After 3 unsuccessful transmissions the sink is assumed unavailable and a new sink is searched. If applicable the timer will stop.

0111	Sends the reading of the I/O and the two analogue ports as well as an 8-bit transmission counter which increments with every transmission to the network's sink and if no sink is known the unit will search for a sink instead. After 3 unsuccessful transmissions the sink is assumed unavailable and a new sink is searched. If applicable the timer will restart.
0112	Same as 0110, but to charge an external RC timer I/O7 is pulled high whilst sending the data and left high impedance the rest of the time.
0113	Same as 0111, but to charge an external RC timer I/O7 is pulled high whilst sending the data and left high impedance the rest of the time.
0120	Sends the contents of S2B as a RAW transmission. If applicable the timer will stop.
0121	Same as 0120, but if applicable the timer will restart.
0122	Sends the contents of S2C as a RAW transmission. If applicable the timer will stop.
0123	Same as 0122, but if applicable the timer will restart.
…	Reserved
0200	Show status on I/O10. LED on (pin driven low) = no connection. Blinking fast = Auto-searching for PAN. Blinking slow = connected to PAN. The accompanying counter register defines the update interval. Note: I/O10 must be defined to be an output in S0D/S0E.
0201	Show AT Command line's error status on I/O11. LED off no error. LED blinking = error. Reset by 'OK' prompt. The accompanying counter register defines the update interval. Note: I/O11 must be defined to be an output in S0D/S0E.
…	Reserved
2000	When triggered the number of times listed in the accompanying counter a message is sent to the sink containing a transmission counter and the reading of the analogue and digital inputs. Note: Can only be triggered by setting S15 or S16 to 400x.
2001	When enabling this action the command line is disabled and as soon as a number of bytes in excess of the number N specified in the accompanying timer/counter register is received on the serial port, a SCAST containing these characters is sent to the network's sink. If no sink is known a sink is searched instead. After 3 unsuccessful transmissions the sink is assume unavailable and a new sink is searched. **Notes:** This event is triggered by receiving a character on the serial port. $N \leq 64$.
…	Reserved
3000	The contents of S2B is sent to the local command line[2] followed by carriage return. If applicable the timer will stop. Note: No AT-Prefix required!
3001	The contents of S2B is sent to the local command line[1] followed by carriage return. If applicable the timer will restart. Note: No AT-Prefix required!
3002	The contents of S2C is sent to the local command line[1] followed by carriage return. If applicable the timer will stop. Note: No AT-Prefix required!
3003	The contents of S2C is sent to the local command line[1] followed by carriage return. If applicable the timer will restart. Note: No AT-Prefix required!
…	Reserved
400x	Start timer x. If applicable the timer will stop.
401x	Start timer x. If applicable the timer will restart.
402x	Toggle timer x. If applicable the timer will stop.
403x	Toggle timer x. If applicable the timer will restart.
404x	Stop timer x. If applicable the timer will stop.
405x	Stop timer x. If applicable the timer will restart.
…	Reserved
8xxx	Change I/O port to the LSBs and if applicable the timer will stop.
9xxx	Change I/O port to the LSBs and if applicable the timer will restart.
Axxx	Change data direction of the I/O port to the LSBs and if applicable the timer will stop.
Bxxx	Change data direction of the I/O port to the LSBs and if applicable the timer will restart.
…	Reserved

Table A-5: List of built in functions [61].

A.6 Examples of system operation

Let's assume that the GUI needs to know some monitoring parameters from a specific PV module in the PVAS (PV Area Sector). In this example the desired PV module is equipped with the router (ROUT) of the system. The procedure is as follows:

- a) The GUI sends an AT command to the COO module (located in the COO board see chapter 4).
- b) The COO module accepts this command and rebroadcasts it to the target module that in this case is the router. (Also see chapter 4). The router module receives the command and sends back its data to the COO module.
- c) The COO module receives data from the router module and sends back to the GUI.
- d) The GUI displays the received data (PV temp, current, voltage) and stores it in the database.

The actual AT command program for the above procedure is: (request for current, voltage, temperature, dust, light and angle values measurements are shown below).

- ATSREM0F:00765fbdc0009=0800 (*1)
- OK
- ATSREM11:00765fbdc0009? (*2)
- OK
- S11:004b: 00765fbdc0009 (*3)
- OK

Commands for current measurement

-(*1) With this command, the GUI instructs the COO module to alter the value of register S0F (new value is 0800hex) of remote module with EUI64 address 00765fbdc0009 that in this case is the router module.

As shown in the schematic diagram of the router, (Figure 4-49 and 4-50) the current sensor is connected to input 1 (pin27) of the ADC0808CCN A/D converter. In order to select input 1, logic levels must applied to inputs ADD A (pin25) and ADD B (pin26) of the internal 8 to1 decoder of the ADC0808CCN. These pins are connected to pins I/011 and I/O10 of ETRX2 module respectively. Referring to table 1 of ADC0808CCN datasheet [24], input 1 is selected by setting input ADD A to a high logic level and input ADD B to a low logic level. By altering the content of register S0F with value 0800hex, pins I/O11 and I/O10 of router module are driven high and low respectively. By doing this, the A/D converter is ready to read the current measurement. (Further details on S11 register operation are given in the ETRX2 AT commands manual)

- (*2) With this command, the COO asks the value of the content of register S11 of remote module with EUI64 address 00765fbdc0009 that in this case is the router module.
The content of register S11 represents the logic level of each I/O pin of ETRX2 module. I/O pins 0-7 are connected to the 8-bit output of the A/D converter. (Further details on S11 register operation are given in the ETRX2 AT commands manual).
- (*3) This line is the response of the remote module. Assuming that the current sensor (ACS713 see schematic diagram in figure 4-49) measures 5Amps, the output voltage on its output will be 1.5Volts (Figure 4-36). This voltage is applied to the input of the A/D converter and results in a binary output of 004b(hex). The GUI reads this result and correspond this voltage value to the equivalent current value.

Similarly, the commands for reading the PV modules voltage are:

- ATSREM0F:00765fbdc0009=0000 (*1)
- OK
- ATSREM11:00765fbdc0009? (*2)
- OK
- S11:004b: 00765fbdc0009 (*3)
- OK

Program for voltage measurement

- (*1) The GUI forces the COO to alter the value of register S0F. As shown in the schematic diagrams of router, (Figure 4-49, 4-50) the voltage sensor is connected to input 0 (pin26) of the A/D converter. Altering the value of register S0F to value 0000hex, the A/D converter is ready to read the voltage measurement.

- (*2) COO asks for the state of the remote module.

- (*3) The remote module responses and data are sending back to COO.

Similarly the GUI sends a command for temperature, dust, light and angle when it is necessary.

A.7 The GUI software (Graphic User Interface)

For the system to be practical, user friendly and reliable, a software platform had to be designed first. This software is based on the VB.net platform offers an easy implementation of a user graphic interface (GUI).

Because the data of the ETRX2 module are send in hex format, (see A.3) it is difficult for the user to read them as is. The VB software will interface the ETRX2 output data in such a way that all monitored parameters are going to be displayed in a graphic environment.

Below, a description of how the GUI will operate and an example of a command is given.

A.7.1 Description of the GUI

Figure A-5 shows the main GUI window. By double clicking the PVAS (PV Area Sector) button the PVS window opens (see figure A-6). The user is able to see the monitoring parameters of each PV panel separately in real time. The GUI also lets the user to add or remove a panel in case of a system upgrade. At the right bottom corner of the PVS window, the user can see the extra monitored parameters of the routers PV module. Air dust concentration (mg/m^3), sun illumination (%), x and y angle (degrees) in case of a tracking system used.

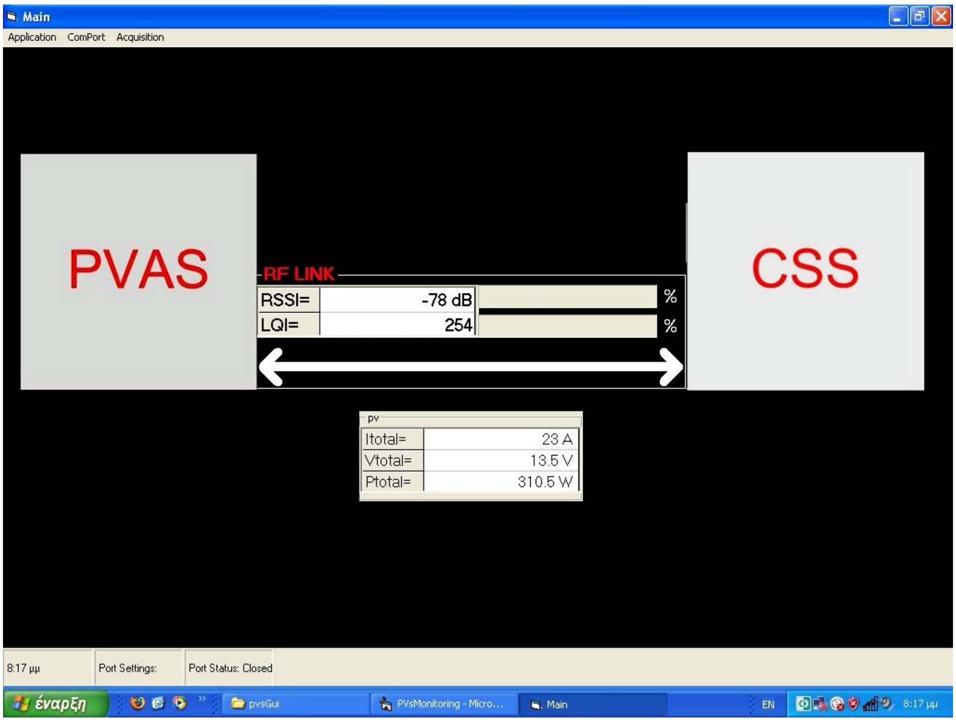

Figure A-5: The GUIs main window

By pressing the charts module button of the tool bar (see upper part of figure A-6), the chart window opens. In this window the monitored parameters of each PV module are given in a graphical format. Pressing the select source button of the tool bar, two options are given. By selecting the option “from file” the user is able to see previous values that are stored in an automatically generated file.

By pressing the real time button, parameters are monitored in real time.

At the center of main window, a real time RF link strength monitor is shown. This monitor shows the RSSI (Received Signal Strength Indicator) in dB and also the LQI (Link Quality Indicator) factor. Two graphical bars at the right of each parameter give an “analog” view of the signal strength. The RF link indicator represents the connection between the COO and the router.

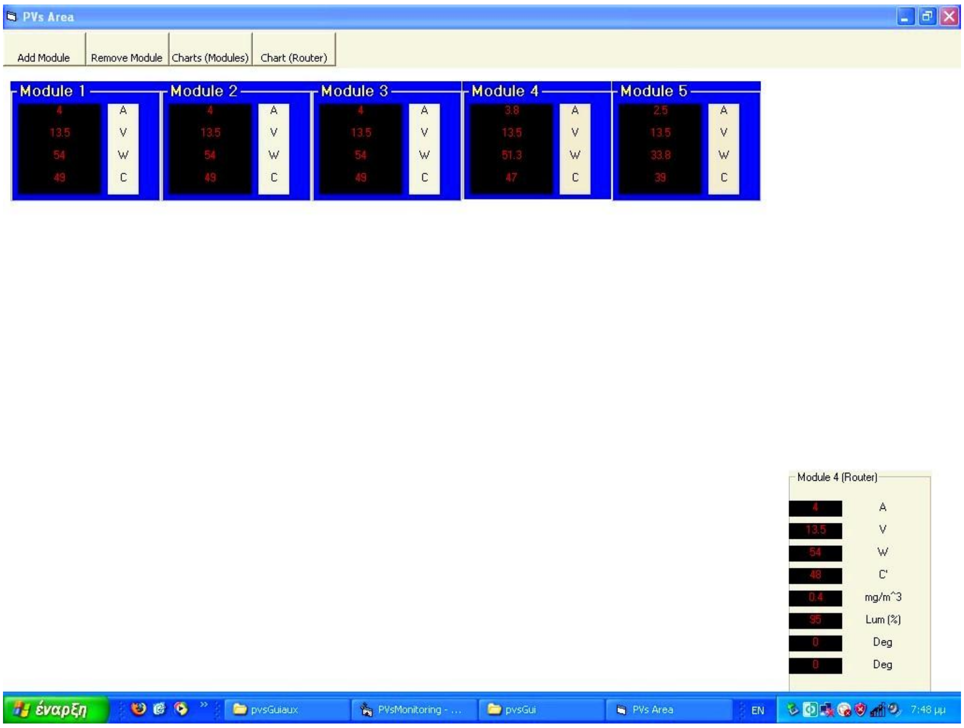

Figure A-6: PVS window

Back to main window (see figure A-5), by double click the CSS (Central Station Sector) button, the CSS window opens and the user is able to see the monitoring parameters that exist at the control station. As figure A-7 shows these parameters are:

- The total plant current, voltage and power
- The battery (where used) charging, voltage and temperature

- The Inverters output current, voltage and temperature
- The ambient temperature and also the relative humidity (RH%) of the control room.

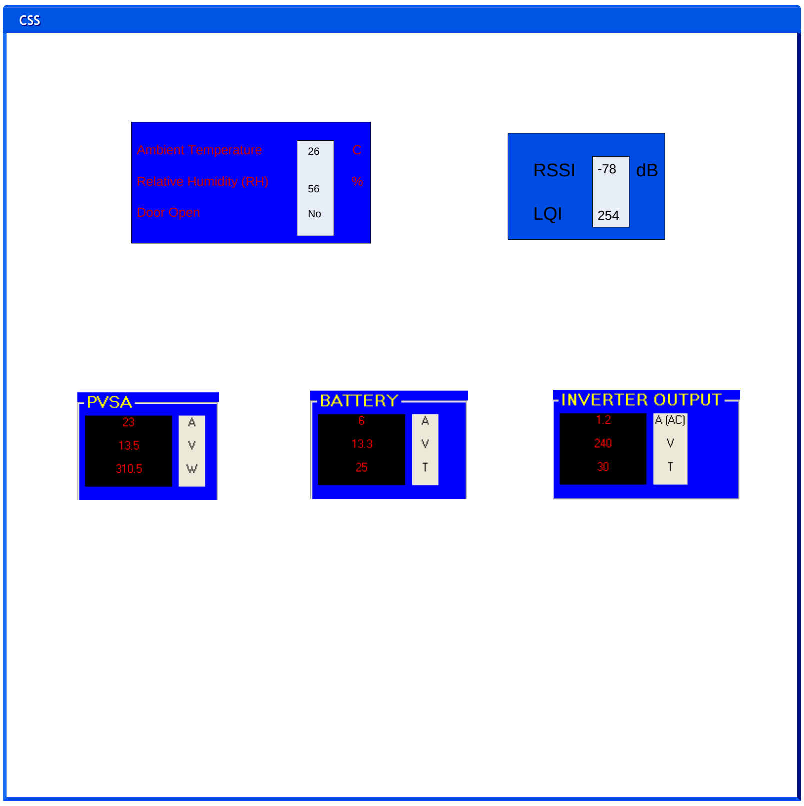

Figure A-7: The CSS window.

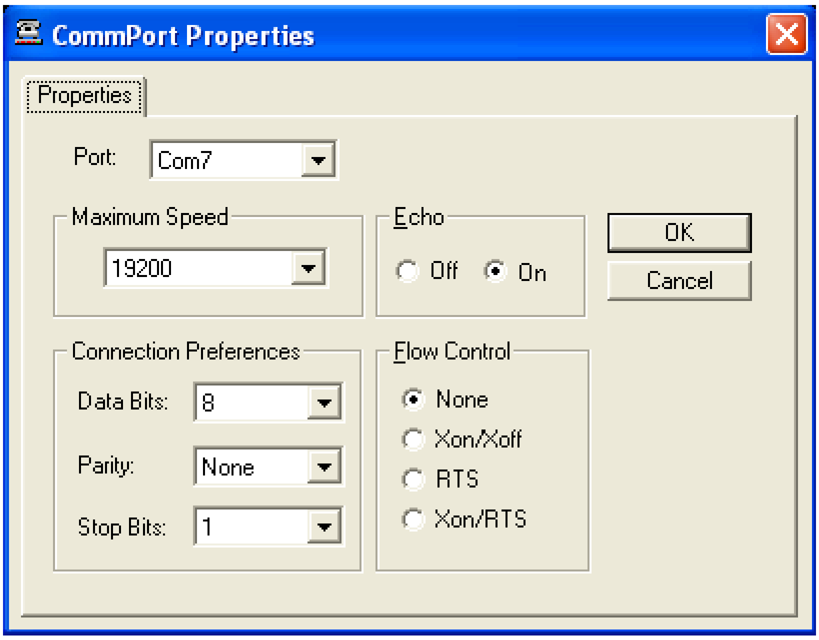

Figure A-8: Com port properties window.

Com port button on the main window tool bar opens the serial port setup window (see figure A-8). Even though in this work the PC is connected with the COO board through a USB port, setup of the serial port is essential. This is because the Visual Basic GUI allows a virtual serial port to the system in order to communicate with the USB port. The system automatically assigns a virtual COM port (Com7 in this case). As shown in the Com port properties window, the maximum connection speed is set to 19200Kbps that is actually the maximum speed of the ETRX2 module of the COO board.

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