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Master Degree Thesis

Design and implementation of a Wireless Sensor and Actuator Network for urban garden irrigation systems

Supervisor

Prof. Giovanni Bracco

Candidate

Asrorbek Eraliev
ID: 264869

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Summary

The implementation of micro-irrigation in urban gardens is being more popular over the years. But, after the initial installation of such micro-irrigation systems, it makes some inconveniences and discomforts in order to control manually. Considering all the aspects of the issue, deployment of wireless sensor and actuator network (WSAN) can be the most optimal and comprehensive solution. Nonetheless, employment of wireless sensor and actuator networks in urban irrigation sector poses different difficult tasks, such as longer battery life, sufficiently long range capability, compact size volume and low cost simultaneously. In the recent past, several different technologies have been used to solve those challenging tasks. In this thesis project, wireless ZigBee network has been studied and analyzed. This work proposes a simple, compact and cost effective design of wireless control nodes specifically to control micro-irrigation of urban gardens. This thesis project presents designs and implementations of hardware and software for the wireless sensor and actuator nodes and coordinator. Moreover, several various state-of-the-art technologies are studied, analyzed and compared to the proposed and designed solution in this thesis paper.

Keywords: drip irrigation; ZigBee; WSAN; low power; valve controller;

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List of Abbreviations

Abbreviation	Phrase
WSAN	Wireless Sensor and Actuator Network
ASK	Amplitude-Shift Keying
FSK	Frequency-Shift Keying
PSK	Phase-Shift Keying
OOK	On-Off Keying
BFSK	Binary Frequency-Shift Keying
MSK	Minimum Shift Keying
GMSK	Gaussian Minimum Shift Keying
GFSK	Gaussian Frequency-Shift Keying
GSM	Global System of Mobile
BPSK	Binary Phase-Shift Keying
AM	Amplitude Modulation
FM	Frequency Modulation
SS	Spread Spectrum
FHSS	Frequency – Hopping Spread Spectrum
DSSS	Direct – Sequence Spread Spectrum
CSS	Chirp Spread Spectrum
CDMA	Code-Division Multiple Access
BOK	Binary Orthogonal Keying
RNF	Receiver Noise Floor

SNR	Signal – to – noise ratio
ANF	Absolute Noise Floor
NR	Noise Ratio
NF	Noise Figure
BER	Bit Error Rate
IEEE	Institute of Electrical and Electronics Engineers
LPWAN	Low Power Wide Area Networks
MAC	Media Access Control Layer
APL	Application Layer
PHY	Physical Layer
ADR	Adaptive Data Rate
SF	Spreading Factor
CRC	Cyclic Redundancy Check
CAD	Channel Activity Detection
WPAN	Wireless Personal Area Network
BLE	Bluetooth Low Energy
AES	Advanced Encryption Standard
MHR	MAC Header
MSDU	MAC Service Data Unit
MFR	MAC Footer
SHR	Synchronization Header
PHY	PHY Header
PSDU	PHY Service Data Unit
IC	Integrated Circuit

CMOS	Complementary Metal Oxide Semiconductor
TSSOP	Thin Shrink Small Outline Package
EMF	Electro Motive Force
SoC	System on Chip
VCO	Voltage Controlled Oscillators
PCB	Printed Circuit Board
UART	Universal – Asynchronous Receiver – Transmitter
SPI	Serial Peripheral Interface
ACK	Acknowledgement

Chapter 1

Introduction

1.1 Basics of micro-irrigation

Micro-irrigation is one of the most optimal approaches to improve gardening quality and to save water. It is a low-pressure, low-flow rate form of irrigation. The term "micro-irrigation" refers to the irrigation systems, which apply water by small devices. These devices pour water on the soil surface very near to the root area of plants. This prevents the plants from pest issues, such as weeds and diseases. Regardless of the topography, micro irrigation can be adapted to a variety of residential or commercial landscapes, urban gardens.

The most popular methods of micro-irrigation are micro-spray irrigation and drip irrigation.

Micro-spray irrigation is a method very similar to natural rainfall. Micro spray systems operate at low pressure using mini spray nozzles to deliver water (Figure 1.1). In micro-spray systems, water is distributed through a network of pipes, tubings and nozzles and it is sprayed to the area of plant root. But, it should not be sprayed directly to the root areas, because of the higher speed of water flow which may make pores on the soil.

Figure 1.1: Micro-spray irrigation

Figure 1.2: Drip irrigation

Micro sprays are designed to throw water over a larger area and are used in locations where drip emitters are not practical, such as large areas of ground cover, flowerbeds or in decorative pots and planters.

Drip irrigation is an efficient method to deliver water to the specific points. As micro-spray systems, water is delivered by the network of pipes, tubings and emitters in drip irrigation systems. In contrast, water is dripped with slow flow, but directly to the root zone of the plant (Figure 1.2). In urban garden irrigation systems, drip irrigation can be more effective compared to micro-spray irrigation due to the following reasons:

- Drip irrigation reduces water loss from evaporation, run-off and wind ;
- Drip irrigation reduces the water usage;
- Drip irrigation minimizes soil erosion;
- Drip irrigation does not make plant foliage wet, thus reduces the potential for foliar diseases;
- Drip irrigation does not irrigate unnecessary soil areas, therefore it prevents the grow of weeds;
- Drip irrigation reduces the damage to irrigation system components due to low flow rate, thus the life-time of the system can reach longer period of time;

Considering these advantages of drip irrigation over micro-spray irrigation, we choose drip irrigation method for this thesis project.
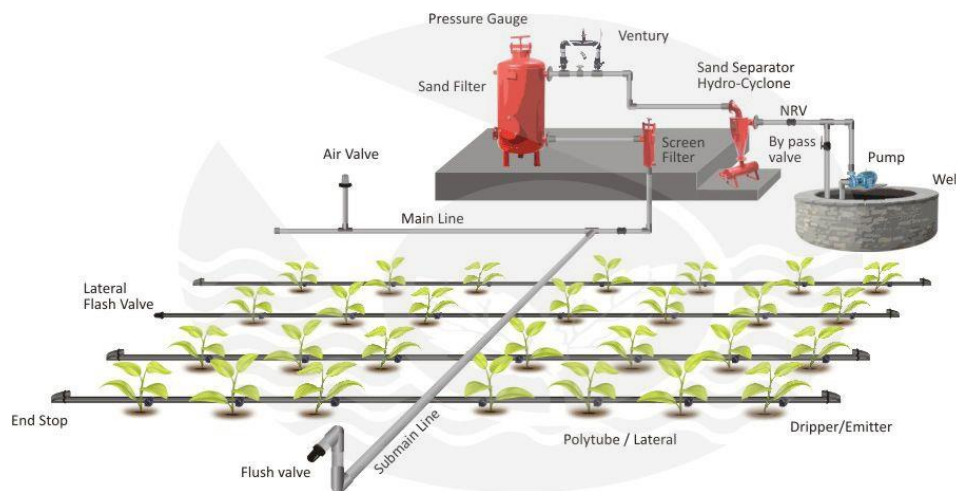
Figure 1.3: Typical layout of drip irrigation system [1]

Figure 1.3 shows a typical drip irrigation system and its main components. Majority of the drip irrigation systems consists of the following main components and operations:

- Pump is used to pump the water from water source to tank storage;
- Filtration unit removes the solid impurities from the water;
- Water is sent to network of pipes which delivers the water from head unit to different areas of the garden;
- Control valves are used to control the water flow in sub-main pipes;
- Emitters drip water to the particular zones of the garden.

Manual control of these operations is labor-required if the system is in large scale. The most appropriate solution is to build remotely controlled and fully automated drip irrigation system. In order to build this system, particular sensors should be installed at the points where the plants need to be irrigated. According to the collected data of the sensors, the system takes automatic decision and gardener can be informed remotely, as well. The most proper approach to establish the intended system is applying WSAN (Wireless Sensor and Actuator Network). However, the issues regarding the power consumption and control algorithms of actuators should be solved.

1.2 Network technologies in gardening

Gardening keeps its significant role in the generation of revenue and a source of food for many people all over the world. Over the past years, gardening sector has experienced tremendous changes and advancement in the different gardening approaches and techniques. Consequently, the application of modern network technologies can give a lot of benefits in gardening. Network technology in gardening can be used in various aspects of gardening, such as irrigation. Over the years, different network technologies have proved to be significantly useful in the gardening sphere. Due to applying those technologies, gardeners are in a position of controlling different processes remotely to raise efficiency and improve productivity. Especially, garden

irrigation issues were in need to be solved by decision support system with the aid of computers, based on the observed and measured data in the garden. One of the most proper approaches for monitoring the field is WSAN (Wireless Sensor and Actuator Network) [2]. Using WSANs gives the opportunity not only collecting measured data but also controlling actuators and even automating whole the irrigation system.

1.3   Related Works

Wireless sensor and actuator network (WSAN) have been being implemented in many different projects, ranging from agriculture to smart cities, medical [3] and even in military applications [4]. Particularly, WSAN oriented for garden irrigation causes difficulties due to the limited energy resources and budget. Nevertheless, the technologies have been developed in recent years can be utilized to set up WSANs with higher efficiency.

In this paper [5], authors implemented wireless low power valve controller for drip irrigation control systems using the JN5139 low power wireless module. Being integrated radio transceiver and the microcontroller inside JN5139 module gave the opportunity of being low cost and compact-sized. It was designed to proceed three months with two alkaline batteries, under different synchronous sleep periods. The activation frequency was assumed as 4-5 times during a week. The valve controller was designed to precisely and accurately control the solenoid valve, collect status information of the solenoid valve, and provide prompt feedback. The field test showed that the controller powered by two alkaline batteries could work continuously at least 3 months.

This study [6] proposed solar powered smart irrigation system with Wireless Sensor Nodes (WSN) and Hub Coordinator. Each sensor node was a part of a Zigbee network in a Star topology around a hub concentrator. The designed wireless sensor nodes consisted of 1Watt solar panels to with 9V rechargeable batteries and Xbee S1 modules to communicate with hub in the

range of 300sq feet. Due to the easy interface to standard Wi-Fi shields, USB, I2C and power regulation, Arduino board was utilized in sensor nodes and hub coordinator. Each board was connected to SHT1x sensor to read and collect moisture, temperature and humidity data and send it to hub. Putting sensor nodes into sleep modes frequently, the battery life time was calculated 6 to 9 months. TI CC3300 Wi-Fi shield used in the project sends the data to the cloud. Furthermore, a mobile App was developed to allow users to check the status of the irrigation project online.

Similarly, this irrigation system [7] was performed using wireless Zigbee network. The proposed system consisted of slave nodes and master station. Each slave node was equipped with a temperature sensor, a soil-moister sensor, a water valve, a microcontroller and a Zigbee transceiver. The slave microcontroller reads and frames the surrounding temperature of the garden's grass and trees along with soil moisture. Then, the frame is forwarded to the master station via Zigbee. The master station has an embedded fuzzy logic irrigation algorithm to water the grass and trees based on a set of rules. A home web-server was interfaced with the master station for remote access monitoring and operation. The power consumption characteristics were not highlighted in detail, as the main purpose of the proposed system was allowing the operation through internet and smartphone.

In this experimental study [8], authors developed an energy-efficient wireless sensor mote platform for low data rate applications. Since the drip irrigation system does not require high date rate, this platform can be very useful in drip irrigation purposes. The new platform, which was called DZ50, consisted of ATmega328P microcontroller and RFM12b transceiver. Power consumption of this platform was considerably low and that's why higher energy efficiency can be achieved in long time sleep mode. Experiments showed that DZ50 did better performance compared to TelosB and MicraZ. Energy measurements have been carried out for different network operation states and settings, where the results reveal that the proposed platform allows to multiply the battery lifetime up to7 times compared to MicaZ and TelosB motes in 10s sampling period scenarios.

In this thesis project, we will design and implement wireless control system for the irrigation of urban gardens as the system designed in this paper [6]. However, our system will be more compact, low power, longer battery life and longer operation range compared to the system in the paper [6].

1.4   Objective of the project

The main objective of this thesis project is to design and implement low-cost, low-power controlling system for a drip irrigation in urban gardens. This should be achieved by using WSAN technology and valves to control the water flow according to moisture level of the soil and other several parameters. Since the controlling system will be designed in commercial purposes, the system should be compact and easy to install, reinstall and use. Furthermore, the cost should be kept as low as possible, without negative effecting the performance reliability.

Main tasks of the project:

- Design and implementation of the hardware prototypes for wireless control nodes and coordinator hub;
- Development of firmware for coordinator hub and end devices;

The designed irrigation system should satisfy following requirements:

- Minimum 2 years lasting battery life, assuming each WSAN checks the certain parameters (such as soil moisture, temperature, battery status and rain presence) and activates the solenoid valve at average 4 to 10 times in every 24 hours;

- Minimum 100 meters of communication range between the wireless nodes;

- Low cost, compactness, easy and fast installation & setup;

- No activation during rainy time.

These system requirements demand to select the component types very carefully. Therefore, existing WSAN technologies are studied in the next chapter (chapter 2). The designed project and its implementation is presented thoroughly in chapter 3. Lastly, the thesis project is concluded in chapter 4, including future developments for better performance.

Chapter 2

Wireless Sensor and Actuator Networks Technologies

2.1 Key concepts and technologies

Before selecting or designing any data transmission system some key concepts and properties should be addressed and studied. According to the characteristics of radio waves used to transfer data, different kind of wireless technologies satisfy various application requirements.

2.1.1 Modulation methods

In the early phases of radio systems, only the analog signals were transmitted. But, nowadays, majority of the radio systems transmit digital signals consists of binary bits. The same modulations techniques can be used for both analog and digital signals transmissions. But, today there a different kind of modulation methods have been developed in order to increase radio efficiency in wireless digital communication.

Baseband modulation is usually used for short range transmission systems. This modulation is sometimes called line coding. Square pulse waveform is created utilizing the sequence of the digital symbols. The features of the square pulse waveform represent every signal type without vagueness and consequently they can be re-established during the reception. These features are variations of Pulse Amplitude, Pulse Width and Pulse Position.

Different baseband modulation waveforms are presented in the following figure (Figure 2.1). The first example of baseband modulation shows non-return to zero-level (NRZ-L) modulation. In this representation, positive square pulse with full length T represents a signal 1 and negative square pulse with full length T represents signal 0. The second baseband modulation is the unipolar return to zero (Unipolar RZ) modulation. This modulation uses positive square pulse with half-length of T (T/2) for signal 1. Particularly, it does not use any pulse of waveform for the signal 0. The third example of baseband modulation is called Manchester or biphase level (Bi-Φ-L). This modulation employs the waveform including the first-half T positive and second-half negative pulses for the representation of signal 1. For the signal 0, the exactly reverse waveform is used.
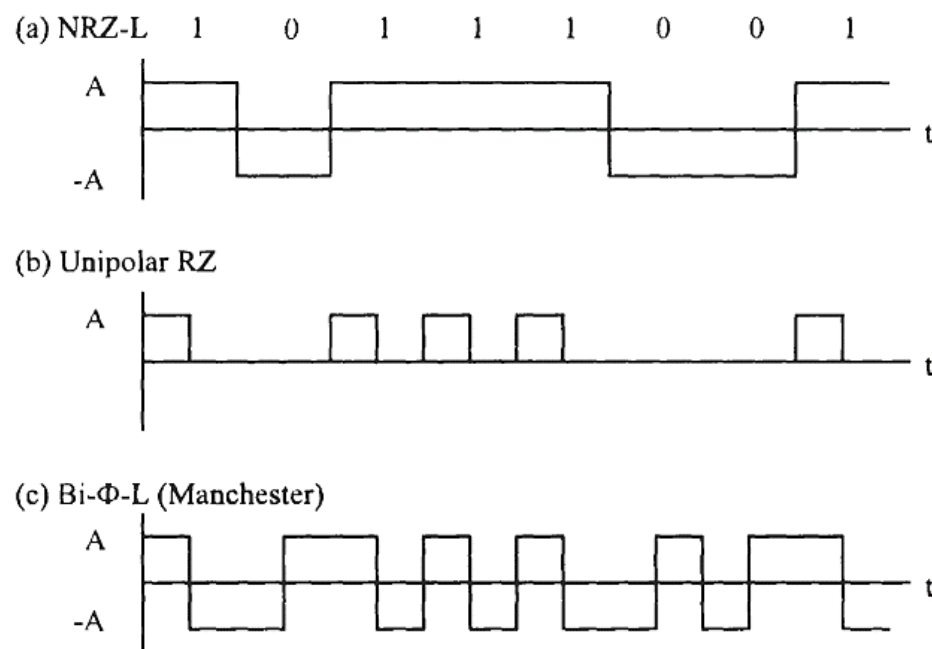
Figure 2.1:   Baseband digital modulation examples [9]

Bandpass modulation is usually used for long range and/or wireless transmission systems. This modulation is named carrier modulation, as well. In order to vary the parameters of a high-frequency sinusoidal signal, the sequence of digital symbols are utilized. Obviously, the sinusoidal signal

possesses three parameters: amplitude, frequency and phase. This is the reason why the three basic modulation methods are Amplitude Modulation (AM), Frequency Modulation (FM) and Phase Modulation (PM). Those three basic carrier modulations are shown in Figure 2.2. Their digital representations are known as Amplitude shift keying (ASK), Frequency shift keying (FSK) and Phase shift keying (PSK) [9], [10]. Those modulation methods are the most common type digital modulation schemes. Different types of modulation methods can be generated by the combination of those three basic techniques. For example, quadrature phase shift keying (QPSK) modulation scheme can be derived by the combination of two binary phase shift keying (BPSK) signals with orthogonal carriers. Besides that, a new scheme called quadrature amplitude modulation (QAM) can be generated by the amplitude and phase modulation together.
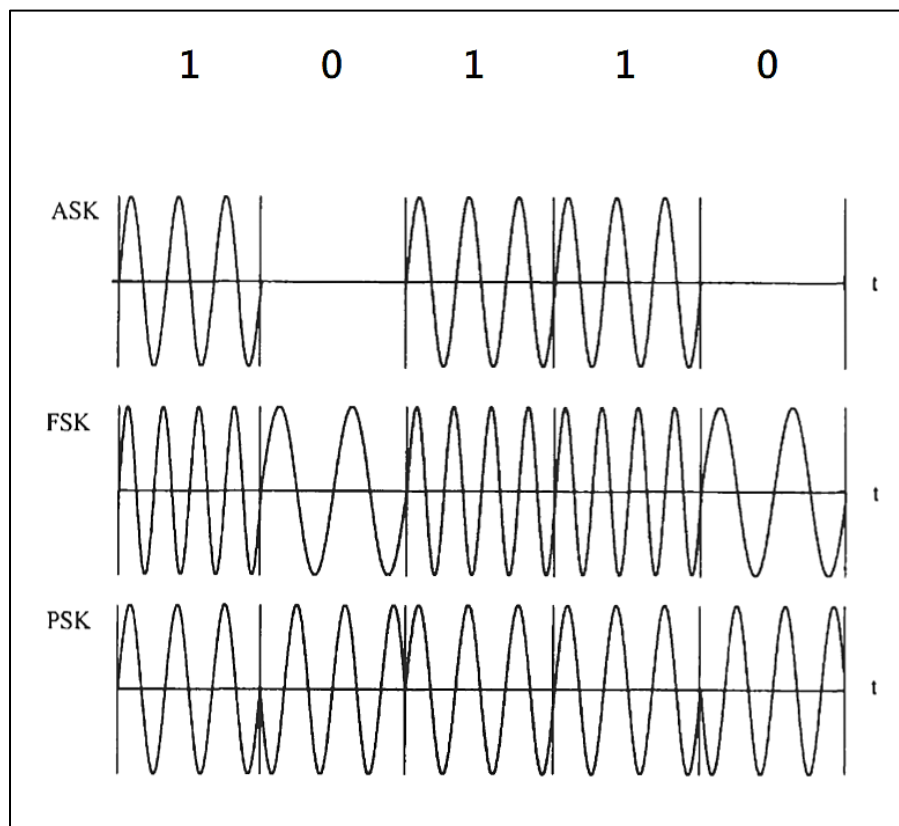
Figure 2.2:   Three basic bandpass modulation schemes: ASK, FSK and PSK [10]

ASK – Amplitude shift keying is one of the amplitude modulation forms, which represents digital data as the carrier wave amplitude alternations. The digital message is mapped only to the amplitude variations of the carrier wave. ASK is based on the keying. One particular case of amplitude shift keying is called On-off keying (OOK). In the OOK, carrier is switched on and switched off through the binary signals. The following figure shows the general ASK and two amplitude levels with OOK (Figure 2.3). Although ASK has the drawback of inclination to noise, it possesses the main superiority of simplicity at modulation and, at the same time at the demodulation. ASK modulated radio channel occupies twice the maximum frequency of the modulated signal. However, 2 binary bits (i.e. 1 and 0) can be represented in one period of modulated signal (Figure 2.3). To put it simply, 1 Hz of bandwidth is demanded for every bit per second. For instance, 10 kHz bandwidth is needed around the carrier signal frequency for the purpose of achieving transfer digital data at 10000 bits per second using OOK or ASK modulation.
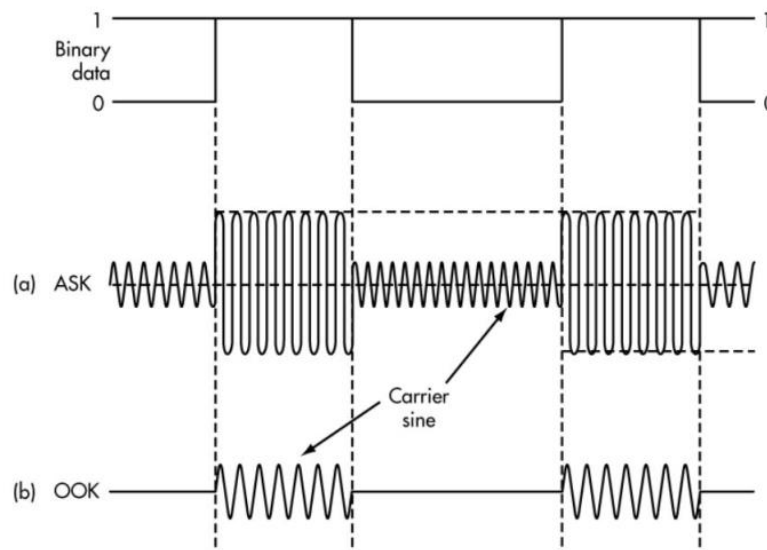
Figure 2.3:   ASK modulation producing two amplitude levels and OOK modulation [9]

General model of OOK modulation is demonstrated in the Figure 2.4, below.
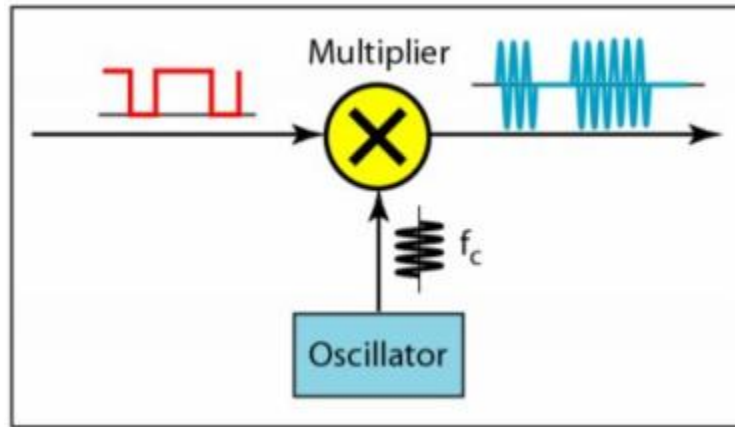
Figure 2.4: General OOK modulation model [10]

FSK – Frequency shift keying is a frequency modulation scheme in which digital information is transmitted via discrete frequency changes of a carrier wave. The simplest version of FSK is called binary FSK or BFSK. In order to transmit binary data (0s and 1s) BFSK employs pair of discrete frequencies. In the Figure 2.5, frequency modulating of a carrier wave with binary information producing FSK. As it is seen from the figure, when the modulating signal is a binary 0, the carrier frequency is the center frequency value and when the modulating signal is a binary 1, the carrier frequency suddenly varies to a higher frequency level. The amount of the shift depends on amplitude of the binary signal.
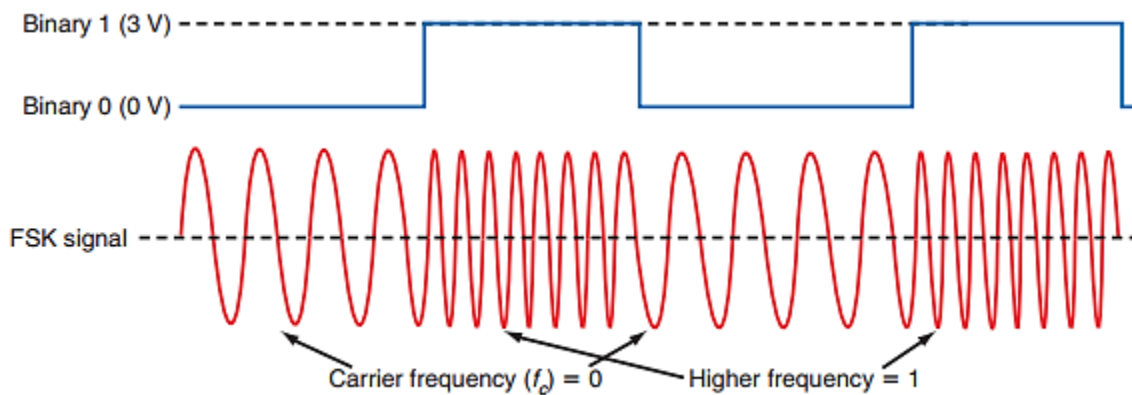
Figure 2.5: FSK modulation [10]

In the FSK, the receiver waits only for the specific frequency variations over the number of intervals. That's why, FSK is less susceptible to noise than ASK. However, FSK modulation method has some disadvantages, such as higher spectrum requirements and bandwidth requirements. FSK modulation produces sidebands which are spread out on either side of the carrier wave. This may interfere with the neighboring channels. Minimum Shift Keying (MSK) is employed in order to achieve the reduction of the sidebands. MSK is spectrally efficient form of FSK. Besides that, in order to smooth the transitions of frequencies, Gaussian frequency-shift keying (GFSK) can be utilized. GFSK is based on the applying Gaussian filter to the binary information transitions. Another modulation method which is called Gaussian minimum shift keying (GMSK) is employed in GSM mobile phone standards. The main reason to be used GMSK in GSM mobile phone standards is that achieving lower sideband power and less out-of-band interference. GMSK modulation is generated by the combination of MSK and GFSK modulating.

PSK – Phase-shift keying modulation is the digital modulation method which conveys data by changing the phase of carrier wave. The most importantly, the frequency and amplitude of the carrier signal remain the same. The simplest version of PSK is Binary phase-shift keying (BPSK). BPSK is used as a robust modulation scheme in many applications. In 802.11 wireless local area networks, although various modulation schemes are utilized depending on the transmission rate, the header of each frame is always transmitted by the BPSK in order to ensure its successful reception. BPSK shifts the carrier signal 180º for each variation of binary state. In the BPSK modulation, phase transition happens at zero points. According to the noise interference point of view, PSK has the advantage of less susceptibility to noise over ASK, yet it needs the same bandwidth with the ASK modulating scheme. The demodulator of PSK requires the signal to be compared to a sine carrier of the same phase and therefore PSK demodulator is more complex. This is the main drawback of the PSK modulation.
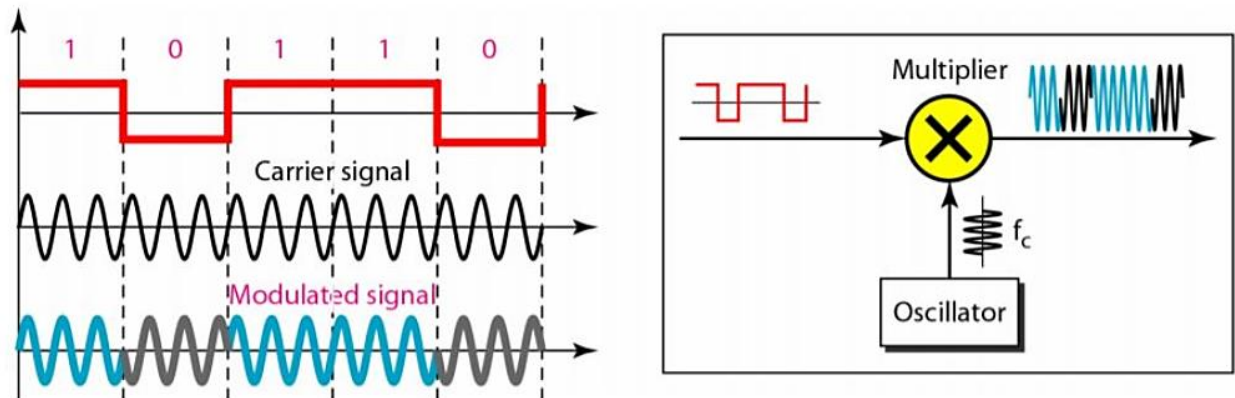
Figure 2.6: PSK (BPSK) modulation [10]

There are some versions of PSK modulation, such as Quadrature phase-shift keying (QPSK), 8-PSK, 16-PSK and M-PSK. All of those modulation schemes employs the same principle, the only thing to differ them is that phases' shifts get smaller and therefore more bits are transmitted at the same carrier frequency.

Majority of the modulation methods are developed to be spectrally efficient that is as high transmission value of bits/Hz as possible. The aim is the fastest transmission speed in the given bandwidth. On the other hand, another class of modulation techniques are developed which employ more bandwidth. The bandwidth used by transmitted radio signal is many times greater than the bandwidth of the information. Special advantages derive from such wideband modulation methods. The two most commonly used modulation techniques are spread-spectrum and orthogonal frequency – division multiplexing [10].

Spread Spectrum (SS) – is a modulation and multiplexing method which distributes a signal and its sidebands over a very wide bandwidth. The widespread types of the SS are frequency-hopping spread spectrum (FHSS), direct-sequence spread spectrum (DSSS), chirp spread spectrum (CSS) and other different combinations of those techniques.

In frequency – hopping SS, the frequency of the transmitter's carrier is varied correspondingly the predetermined sequence. This sequence is called pseudorandom. In FHSS, the changing rate of the frequency of the transmitter's carrier is higher than the changing rate of the serial binary signal modulating the carrier. During frequency hopping the FSK modulation scheme is applied, usually. In the Figure 2.7, the block diagram of FHSS transmitter is demonstrated, below.
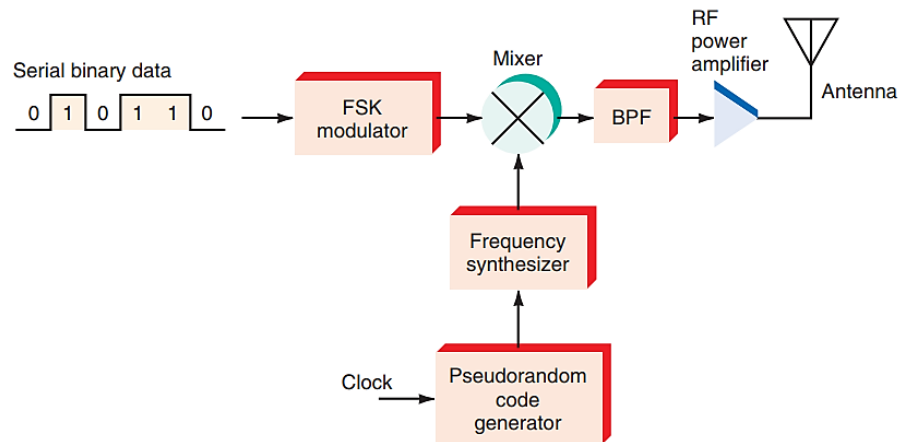
Figure 2.7:   The block diagram of FHSS transmitter [10]

Figure 2.8 shows an example for switching pseudorandom frequency-hop sequence. As the frequency intensively fluctuates, the signal is spread all over the bandwidth, effectively. So, a signal that occupies only few kilohertz of spectrum can reach many times and even several thousand times greater of its previous bandwidth wide. Therefore, any traditional radio signal on any of the hopping frequency cannot interfere with this signal. Due to the frequencies are hopped at various sequence at different times, several transmitters of various pseudorandom codes can employ the same bandwidth and they never interfere. Furthermore, it is known as a secure method owing to no chance of the catching and reading possibility of the radio signal by unknown receivers. If any receiver catches the radio signal, it is impossible to extract the data without the pseudorandom code.

In direct-sequence SS, the serial binary data and a serial pseudorandom code are mixed through an X-OR logic gate. The pseudorandom code occurs faster than the binary signal. One radio-pulse duration for one pseudorandom code is called a chip and code rate is referred as the chipping rate. Usually, the chipping rate is higher than the rate of data.
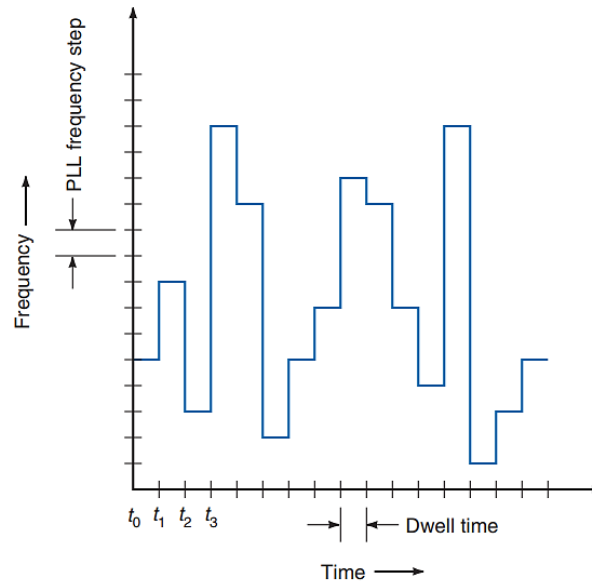
Figure 2.8:   A pseudorandom frequency – hop sequence [10]

The generated signal at the output of the X-OR gate is then directed to a PSK modulator, typically BPSK. The modulated signal occupies great deal of the spectrum, because the chip rate is higher compared to the data rate. Thus, the resulting signal seems wideband noise to a conventional narrowband receiver due to the randomness of the signal. In the following figures, the DSSS transmitter block diagram (Figure 2.9) and an example for pseudorandom code application to serial data are demonstrated (Figure 2.10).

DSSS method is called Code-Division Multiple Access (CDMA), too. CDMA is utilized in satellite systems due to its capability of using multiple signals on the same communication channel. In the satellite systems, many users can take advantage of the same transponder. Besides that, the CDMA technique is very widely used in mobile phone systems.
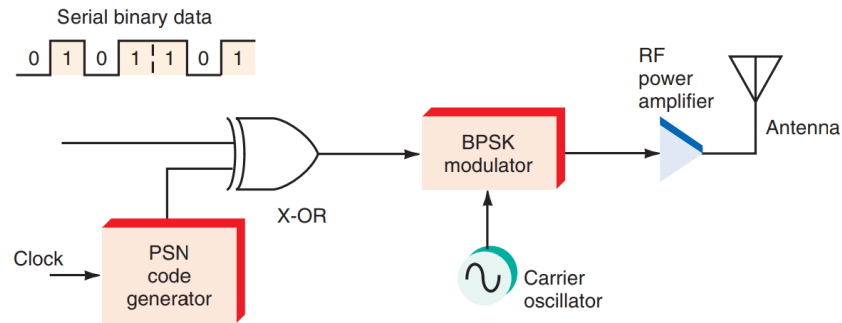
Figure 2.9: DSSS transmitter block diagram [10]
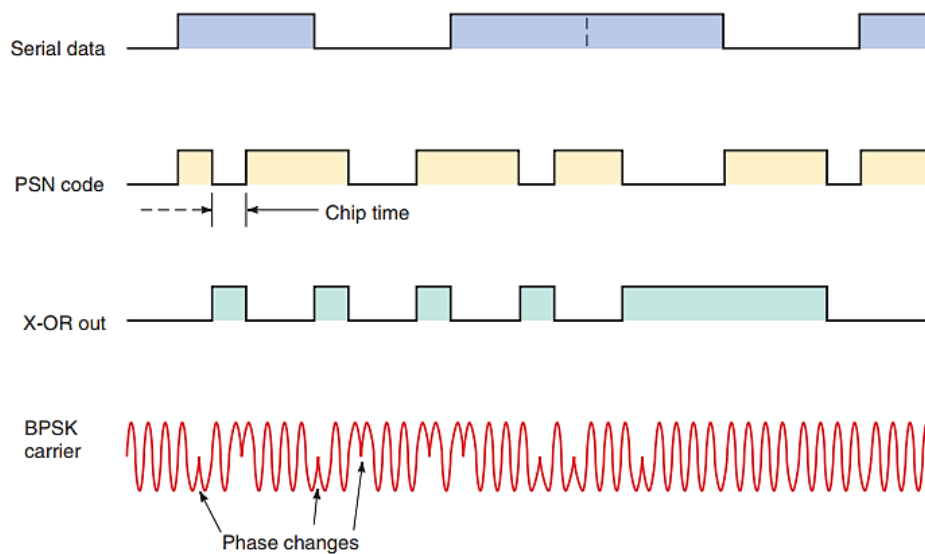
Figure 2.10:   Applying pseudorandom code to serial data in DSSS [10]

In Chirp Spread Spectrum (CSS) method, encoding data is implemented by the use of chirp pulses. Chirp is sinusoidal signal wave and its frequency changes as the time passes. Increment or decrement of the signal frequency can be linear or non-linear. One use of CSS technique is Binary Orthogonal Keying (BOK) method. In BOK, binary data is encoded through the linear chirps. 1s are encoded as up-chirps and 0s are down-chirps as the signal frequency varies over time (Figure 2.11). The linear up-chirp (and down-chirp) signal increases (and decreases) its instantaneous frequencies. In the Figure 2.12, the time-

frequency characteristics of the linear chirps and their real output waveforms are demonstrated.
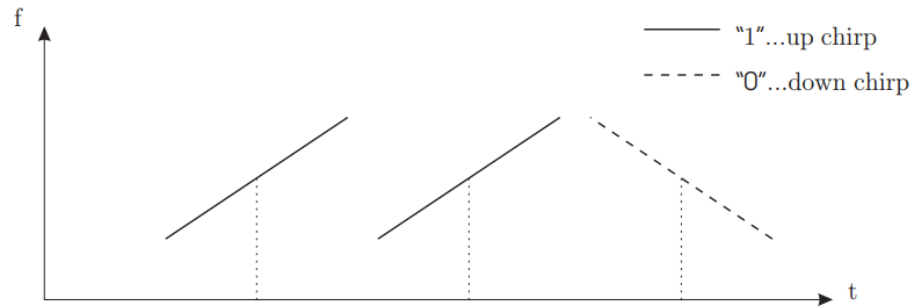
Figure 2.11:   CSS – binary orthogonal keying (BOK) scheme [11]

CSS technique is perfect choice if the using application requires low power and low data rates. Another important advantage of CSS method is its resistant feature for Doppler Effect. Doppler Effect occurs when the devices move with the respect to each other.
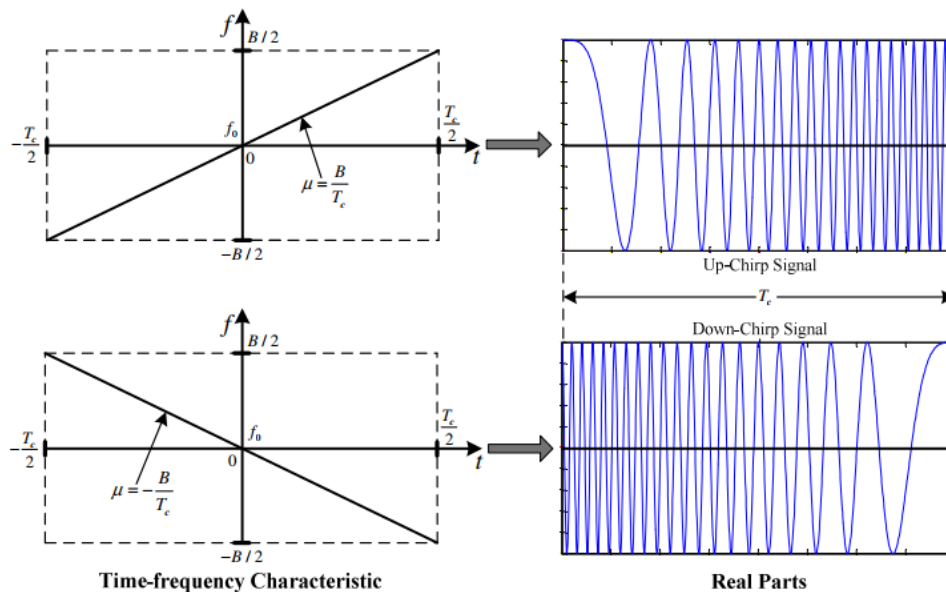
Figure 2.12:   Linear chirps and their corresponding real parts [12]

Generally, Spread Spectrum (SS) is being widely employed in many different data communication applications due to its advantages given below:

- Security – any unauthorized receiver cannot listen the SS signal due to unknown pseudorandom code and the type of modulation.

- Resistance to jamming and interference – jamming signals are restricted to one single frequency, and jamming one frequency and the spread spectrum signal cannot interfere. Furthermore, any interference of a signal using the same band is greatly restricted. In most cases, those interferences are virtually eliminated.

- Band sharing – multiple users can take advantage a single band without little or no interference.

- Resistance to fading and multipath propagation – owing to the reflections and other phenomena during propagation spread spectrum abolishes signal strength variations.

- Precise timing – beginning and end of transmission can be determined with high accuracy due to pseudorandom code employed in spread spectrum.

2.1.2   Frequency and bandwidth

It is very important to choose the bandwidth and the frequency of carrier wave. Because, regulatory agencies have licensed many frequency bands all over the world. However, it is still possible to find some license-free bands which are internationally accepted. These frequency bands referred as ISM bands because, they usually intended for Industrial, Scientific and Medical applications. The most common ISM frequencies are 315 MHz, 433.92 MHz, 868 MHz (in Europe) and 915 MHz. However, in different countries,

regulatory details may differ. As it is known from the modulation methods part, the channel bandwidth around the carrier wave frequency is necessary to consider. There are different technologies have been developed in order to minimize the channel bandwidth. Minimizing channel bandwidth gives the opportunity to fit many channels into the allocated frequency range. On the other hand, the narrow bandwidth decreases the produced data. Therefore, according to the application scenario, the devices are developed considering those factors.

Nonetheless, thanks to Shannon's Channel Capacity Theorem (Equation 2.1), maximum channel capacity can be calculated using given the bandwidth and the signal strength.

$$C = B * log_2(1 + \frac{S}{N}) \qquad\qquad (2.1)$$

where:

C – channel capacity – [bit per second];

B – channel bandwidth – [Hz];

S – signal strength – [Watts];

N – noise power – [Watts].

The ratio of the transmitted signal strength to the noise strength is called signal-to-noise ratio (SNR) and it is expressed as:

$$SNR = \frac{S}{N} \qquad\qquad (2.2)$$

Considering Equation 2.2, we can rewrite the Shannon's Channel Capacity Theorem as:

$$C = B * log_2(1 + SNR) \qquad\qquad (2.3)$$

2.1.3   Power and Sensitivity

Every radio device possesses certain transmission power and usually it is measured in Watts [W] or milliwatts [mW]. However, employing decibel (dBm) is more popular and convenient in wireless transmission sphere. Power ratio in dBm can be calculated as in Equation 2.4.

$$P = 10 * log_{10} \frac{Power}{1mW} \quad [\text{dBm}] \tag{2.4}$$

It is clear that communication distance and power consumption are really depend on transmission power. Increasing dBm causes more power consumption and longer communication range. But, unlicensed applications need to be powered less than 100mW transmission power according to the regulations. Fortunately, communication range, data rate and power consumption can be determined by the key factors which are modulation method and the receiver sensitivity.

Receiver sensitivity, or capability to catch weak signals, is the minimum detectable signal energy (or power) in order to receive data correctly. Receivers see white noise if the coming signal power is smaller than the minimum detectable value. Thus, receiver with lower minimum detectable value can receive the signal from longer distance. We can determine the receiver sensitivity through the receiver noise floor (RNF) and required SNR (Equation 2.5). The value of required SNR is specified by the given bandwidth and data rate of the application.

$$P_{rx}^{min} = RNF + SNR \quad [dBm] \tag{2.5}$$

For instance, the given receiver noise floor is -108 dBm and the required SNR is 8 dBm. In that case, the minimum receiver sensitivity should be $P_{rx}^{min} = 100$dBm. With 100dBm power level, the receiver can interpret the coming signal data at the specified rate in the given bandwidth. Modulation

method and the bandwidth can affect the sensitivity. Increasing the bandwidth causes the increment of noise level.

2.1.4 Channel noise

Channel noise completely depends on bandwidth in all communication systems. Any object that emits heat from itself, radiates radiofrequency energy in the form of random Gaussian noise. This noise is named as thermal noise. The amount of the power emitted as radiation can be calculated by the following equation:

$$NP = k * T * B \qquad\qquad (2.6)$$

where:

NP – noise power [Watts];

k – Boltzman's constant ($1,38 * 10^{-23}$) [J/K];

T – system temperature, usually token as 290 K [Kelvin];

B – bandwidth of the channel [Hz].

Expressing noise power in dB means *Noise floor*. Using the equation 2.6, *Absolute noise floor* (ANF) can be calculated, considering the temperature is 209K and the channel capacity is 1 bit/Hz:

$$ANF = 10 * log_{10}(k * 290K * B * 1000) \quad [dBm]$$

or

$$ANF = -174dBm + 10 * log_{10}(B) \quad [dBm] \qquad (2.7)$$

Where 1000 is simply scaling coefficient to convert from Watts to milliWatts.

The *noise factor* is the ratio of the SNR at the input to the SNR at the output. The noise factor or *noise ratio* (NR) can be stated as

$$NR = \frac{SNR_{input}}{SNR_{output}} \qquad (2.8)$$

where:

SNR$_{input}$ – SNR ratio of the coming signal to receiver;

SNR$_{output}$ – SNR ration of the output signal

If the noise factor is stated in decibels, it is usually named the *Noise figure* (NF) (Equation 2.9). NF is a measure of the noise amount produced by receiver itself.

$$NF = 10 * log_{10}(NR) \qquad (2.9)$$

Usually, commercial radio receivers operate with higher than 3 dB noise figure. In case of smaller than 2 dB noise figure, the radio receiver is referred as excellent. Noise figure of ideal receiver would be 0 dB, however in reality it is impossible to achieve this noise figure. In general, the SNR of the overall communication link can be reduced by NF. This gives possibility of calculating the particular *receiver noise floor* [13]:

$$Receiver\ noise\ floor = ANF + NF \qquad (2.10)$$

where:

ANF – absolute noise floor because of the thermal radio frequency noise;

NF – noise figure.

Clearly, the higher the noise amount makes greater the number of bit errors. The number of errors that occurs in one second interval of data transmission is called *bit error rate* (BER). For example, if 6 errors happen in 1 second in a 12 Mbps data transmission, the BER can be calculated as

$$BER = \frac{6}{12} * 10^6 = 5 * 10^{-7}$$

Different modulation techniques have different level of immune to the noise. The dependence of $\frac{E_b}{N_0}$ on BER is represented for several modulation

methods in the Figure 2.13. Basically, E_b is the energy required per bit of information and N_0 is thermal noise in 1 Hz of bandwidth. The given graph in Figure 2.13 demonstrates the data independent from the data rate and the system bandwidth. The Equation 2.11 helps to convert from $\dfrac{E_b}{N_0}$ into SNR taking into account the bandwidth and data rate.

$$ SNR = \frac{E_b}{N_0} * \frac{R}{B_T} \tag{2.11} $$

In the equation above, R – data rate [bits per second] and B_T – channel bandwidth [Hz].
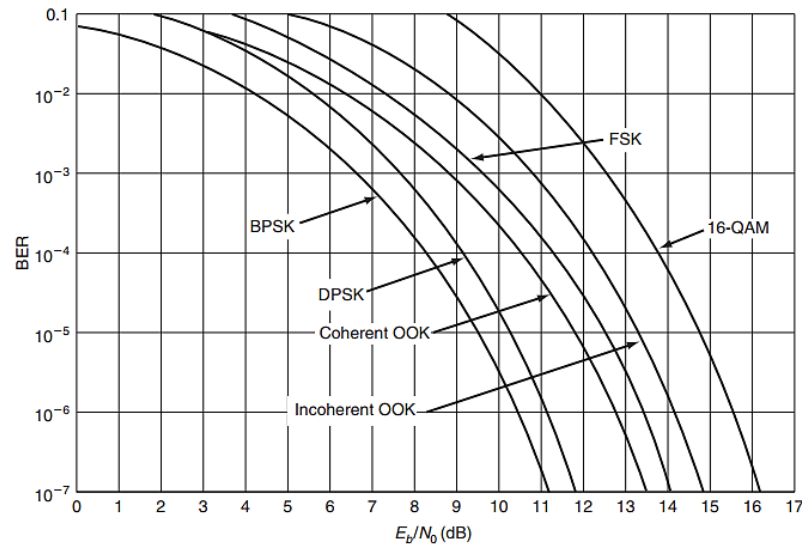
Figure 2.13:   BER vs $\dfrac{E_b}{N_0}$ for different modulation schemes [10]

2.1.5   Path Loss and Fade Margin

As radio signals propagate in free space, the signal power reduces down proportionally for the square of range. The *path loss* calculation in ideal free space is stated in the Equation 2.12.

$$PL = 10 * log_{10}(\frac{4*\pi*D}{\lambda})^2 \qquad (2.12)$$

In the equation above, PL – path loss because of the propagation [dB];

λ – wavelength of the carrier wave frequency [m]. It is calculated by ratio of light speed ($3*10^8$) and frequency: $\frac{c}{f}$;

D – distance between transmitter and receiver [m].

Path loss and transmission distance can be affected by the frequency of carrier wave. Therefore, owing to propagation, radio signals with low frequency have lower path loss. But, the Equation 2.12 depicts only the line-of-sight or free space propagation loss. Due to different obstacles such as ceilings, walls and furniture indoor applications have higher path losses. Experiences [13] have proved that propagation losses of indoor applications can increase up to 30 dB for every 30 meters distance in the dense office environments.

In the wireless transmission applications, there is another factor called *Multipath*, which happens when transmitter sends signal waves along a different path and interfere destructively with each other (Figure 2.14).
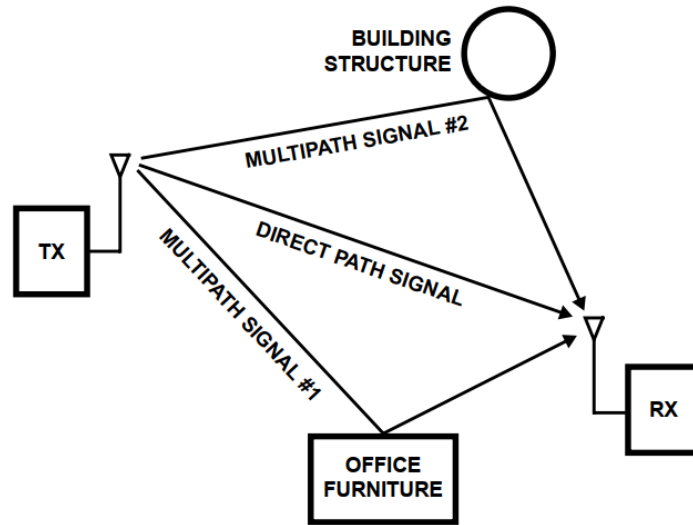
Figure 2.14:   Multipath [13]

As a result, this phenomenon causes the signal fading. Indeed, over 30dB of signal reduction can be occurred as the consequence of multipath fading. This issue can be solved by raising up the power of transmission and providing the receiver with enough sensitivity. The amount of additional radio frequency power to overcome multipath issue is called *Fade margin.* According to the desired link reliability, the amount of fade margin can be added, but the pragmatic value is between 20 dB to 30 dB.

Other method to overcome multipath phenomenon is antenna diversity. Due to the effects of multipath fading depends on the geometry of radio wave paths, employing 2 or multiple antennas positioned by half of the wavelength distance from each other can solve the problem. The scenario is that the receiver checks all the antennas and chooses the one which gives the better signal quality. The main drawback of this approach is requirement of more antennas and the complication in designing the receiver device.

2.1.6   Wireless Link Budget Analysis

In order to design reliable wireless communication system, it is really necessary to calculate the radio link budget. Principally, link budget is the summary of all the gains and losses in the transmission system, so the link budget enables to calculate strength of the received radio signal. This analysis gives the possibility to determine whether power and gain values are enough, higher or lower and then perform the necessary action in order to insure the system will work satisfactorily. Link budget styled calculations are also employed in wireless applications. To provide the required link quality, these calculations take into account the power levels, antennas and required receiver sensitivity measures. The equation form of link budget can be expressed as below (Equation 2.13):

$$P_{RX} = P_{TX} + Gains - Losses - M \quad [dBm] \quad (2.13)$$

where:

P_{RX} – Receiving signal power [dBm];

P_{TX} – Transmitted signal power [dBm];

M – Fading margin [dB].

In the equation above, gains are the system gains which are generated by directional antennas, processing gains of modulation schemes and etc. Furthermore, the losses in the equation are path loss and the losses associated with the system. For example, the given system's receiver and transmitter are positioned 1.6 km away from each other, and the following system parameters are given: transmitted power is +15dBm, system gain is +4dB, path loss is 0dBm, fade margin is 25dB and the frequency of carrier wave is 2.4GHz (or wavelength is 0.125m). In this example, the expected power of received signal can be calculated as:

$$Path\ Loss = 10 * log_{10}(\frac{4*\pi*D}{\lambda})^2 = 10 * log_{10}(\frac{4\pi*1600m}{0.125m})^2 = 104\ dB$$

$$P_{RX} = 15dBm + 4dB - 104dB - 25dB = -110dBm$$

The calculation above tells us that minimum sensitivity of receiver should be below -110 dBm for the reliable reception of the transmitted signal from 1.6 km distance and the correct demodulation. Note that the calculation above is for line-of-sight reception.

In order to design and implement wireless communication link following the rules of regulations and avoiding too much expenses, the link budget analysis is very important. Besides, it enables to determine the suitable technology for the requirements of application.

2.2 Standards of Wireless Sensor and Actuator Networks

Wireless Sensor and Actuator Network (WSAN) is the network that includes multiple nodes and those nodes sense and control the associated

actuator, and enables those nodes to interact with the users or computers. WSANs may be developed for ground, underground and/or underwater applications. Development of better WSAN demands to take into account following key factors:

- Reliability – the wireless nodes may work in critical conditions, therefore it is necessary to deploy reliable WSAN in order to avoid unexpected errors;
- Low energy – in most of the cases, the WSAN nodes are needed to operate by limited energy source, usually using batteries and required to have long battery life.
- Low cost – owing to the high number of WSAN nodes, small additional cost in one node causes very large extra expenditure on the overall cost of the system.

For the better deployment quality of WSANs, there are a lot of wireless communication standards have been developed. These developed standards indicate the required protocols and functions for wireless nodes to interact with different networks. Majority of them defined by IEEE 802.15[1]. Particularly, IEEE 802.15.4 defines low-data rate wireless personal area network (LR-WPANs) operations. It specifies the physical layer and media access control for LR-WPANs and is the basis for different wireless technologies, such as Zigbee, MiWi, 6LoWPAN and other specifications. Each of them can be further extends the standard by the development of upper layers which are not defined in IEEE 802.15.4 [14].

According to the operating range, WSAN technologies are classified in two categories: long range and short range. Both WSAN groups should meet the requirements of low cost and low power. Deploying the suitable network topology can give the opportunity of achieving longer distance of communication. Generally, two types of network topologies, Star and Mesh topologies are employed.

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[1] IEEE 802.15 is a working group of the Institute of Electrical and Electronics Engineers IEEE 802 standards committee which specifies wireless personal area network (WPAN) standards

2.3 Long Range WSAN Technologies

Long range wireless technologies are required to be deployed for the applications, such as military, farming and other different fields. However, implementation of long range communication without raising the power up is challenging and requires higher cost and lower the data rate. Besides, transmitting power is limited by the regulations. Therefore, one solution is to achieve longer communication range is to raise up the sensitivity of receiver.

The most commonly-used long range communication technology has been already provided by cellular networks. Using the GSM modules, very costly WSAN systems can be built. But, there are several drawbacks of using cellular networks in WSAN applications, since it is not free to use and consumes more power. Furthermore, this method does not guarantee to be operated in rural areas.

In this section, we overview three of the most prominent long range WSAN technologies, namely SigFox, Ingenu and LoRa. Generally, those technologies are referred as the standards of Low Power Wide Area Networks (LPWAN).

2.3.1 SigFox

SigFox is narrowband based communication technology. Its physical layer employs ultra-narrow band wireless modulation. This technology uses binary phase shift keying modulation scheme. Operating on very narrowband of spectrum enables to reduce down the level of noise. Usually, the end-point radio devices are not costly in SigFox, however managing the network demands more sophisticated gateways. Particularly, the antennas of SigFox are built on towers as the antennas of cell phone companies. The data transmissions are implemented through the unlicensed frequency bands, generally sub-GHz category. This technology suits well for the applications

which used infrequently and requires small data exchanges because SigFox transmits very small quantity of data (12 bytes) at low transmission rate (100 – 600 bits per second). SigFox works in 200 kHz of public band to transmit data and each message takes 100 Hz wide bandwidth. About the network layer of SigFox, there is no documentations that are publicly available. On the first release of SigFox, only the unidirectional uplink communication was supported, but now, it supports bi-directional communication, too. It is claimed by the SigFox that each gateway is able to handle up to a million connected nodes and can cover the area of 30 – 50 km in rural areas and 3 – 10 km in urban areas [16]. Due to the proprietary of SigFox protocols, we cannot review thoroughly the system's security aspects [15].

2.3.2   Ingenu – RPMA technology

Another different wireless network technology called Random Phase Multiple Access (RPMA) is designed and owned by Ingenu. It is the most suitable one for worldwide usage due to its 2.4GHz operating band. Because, the only 2.4GHz band is recognized all the world as the unlicensed ISM band, so designing a system with RPMA fits all the regulations of all the countries. This wireless technology can work over long distance ranges due to its robust development of physical layer. According to the claims of Ingenu, RPMA is the best suitable technology for LPWANs. The comparisons between RPMA and other several wireless technologies and advantages of RPMA are stated in this e-book [16]. Even though RPMA employs the bandwidth (2.4 GHz) higher than most of the LPWAN technologies, it still can cover wider than 200 km area. Its access point is able to receive about five hundred thousand 32-byte messages in an hour, in comparison with SigFox (about 500 messages per hour) and LoRa (2600 messages per hour). Furthermore, it is claimed by Ingenu that the performance of downlink and uplink communications are the same, which is not exist in other LPWAN technologies. It employs DSSS along with differential BPSK modulation method and can obtain very nice processing gain ~ 39dB.

RPMA technology offers the following six modern security guarantees:

- Mutual authentication;

- Message integrity and replay protection;

- Message confidentiality;

- Device anonymity;

- Authentic firmware upgrades;

- Secure multicasts.

The main shortcomings of RPMA technology are the deficiency of widespread availability and being restricted to only one single network type. In comparison with any narrowband system which works at unlicensed sub – GHz categories, radio – hardware cannot be employed for customized systems, such as point to point applications among low number of nodes. Every nodes can be accessed only by the gateways and cloud platforms which Ingenu offers.

2.3.3 LoRa and LoRaWAN

LoRa is spread spectrum based modulation scheme for LPWAN technologies, designed and developed by Semtech, whereas LoRaWAN is the communication protocol and system architecture for the network, developed by "Lora Alliance" and it is kept as an open-standard. LoRa is offered by the radio-chipsets of only Semtech, such as SX1272 and SX1278. It is employed as a physical layer in general Open System Interconnection (OSI) model. On the other side, LoRaWAN provides MAC (Media Access Control) functionalities. It is also referred as data-link layer.

LoRaWAN

The protocol and network architecture deployed in the system manipulates the network capacity, the service quality and security and the battery lifetime of the wireless node. The main reason to be developed LoRaWAN as MAC protocol is to meet the system requirements of low-power and long range. A lot of existing networks use a mesh network architecture. Mesh network enables to raise up the network range through forwarding the messages by intermediate wireless nodes. But, it reduces the lifetime of batteries and increases the complexity and cost. So, LoRaWAN utilizes the star architecture, because it provides long range communication capability and makes huge impact on battery preservation. As depicted in the Figure 2.15, LoRaWAN consists of the end-devices, gateways (base-stations) and network servers.
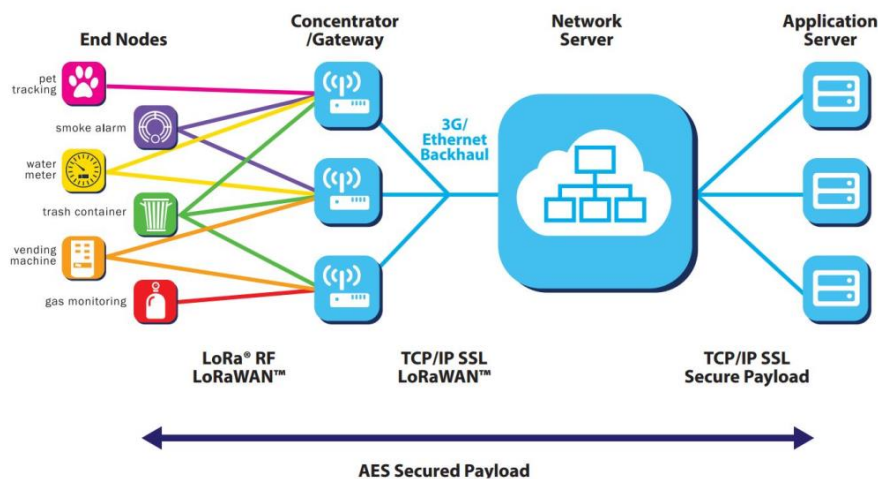
Figure 2.15:   LoRaWAN network architecture [17]

End devices control and measure sensors and transmit the gained data through the gateways. The transmitted data is usually received by multiple gateways, so any end device should not be associated with a specific gateway.

Gateways receive the data coming from end devices and transmit it to a network server. This transmission is performed over some backhaul such as, Wi-Fi, cellular or Ethernet. Despite the multiple gateways receive the same

packet from end devices, the network server selects only one gateway to transmit the reply data to the specific end-device.

Network server decrypts the transmitted packets through multiple gateways, deletes duplicate ones, and generates response packets by the appropriate gateway. It also runs an Adaptive Data Rate (ADR) scheme to control the data rates of individual nodes to save even more energy [17]. Consequently, if the end device node is mobile or in motion, there is no need for handover from one base-station to another, which allows LoRaWAN to be used for asset tracking applications.

LoRaWAN nodes operate as asynchronous. Those nodes communicate only when data is ready to be transmitted according to the schedule or event-driven. Usually, this sort of protocol is referred to as the Aloha technique. The wireless nodes in a mesh network should leave sleep mode and wake up frequently for the synchronization with the network and check for upcoming messages. This synchronization spends much more energy and reduces battery life – time.

For building a long range star network feasible, the gateway should have high capacity in order to receive packets from a high number of wireless nodes. LoRaWAN can give an opportunity to achieve high network capacity by using adaptive data rate and multichannel multi-modem transceiver in the concentrator. That's why, messages can be accepted on multiple channels, at the same time. If the wireless node is near to the gateway and have a nice link, the available spectrum longer than required should not be wasted by utilization of the lowest data rate. Time – on – air can be reduced in order to open larger potential space for another nodes to send by shifting higher the data rate. Besides, lifetime of battery is optimized with adaptive data rate, as well. The link from end device to gateway (uplink) and the link from gateway to end device (downlink) have to be symmetrical to make adaptive data rate operate as expected. In case of higher capacity is demanded, extra additional gateways can be deployed, making the data rates up, and decrease the overhearing to another gateways. It enables to scale the system up by 6 to 8 times.

All the nodes are not created equally. End devices in various applications have different specific requirements. So, there are three different device classes

offered by LoRaWAN for various application profiles, tradeoff battery life-time and network downlink latency. The downlink latency is a necessary factor in control applications, in which actuators are required to be controlled wirelessly [17].

In *Class A,* every uplink transmission is followed by 2 downlink receiving windows as depicted in Figure 2.16 (a). Due to being active only when certain conditions are met, Class A devices can have low energy consumption. But, its main drawback is that any downlink data from the server should wait till the next scheduled uplink, and this causes a big downlink latency.

In *Class B,* devices open additional receive windows periodically during scheduled times as shown in Figure 2.16 (b). Time synchronized beacons are transmitted from gateway to end device in a periodic manner, in order to synchronize receive windows slots. This enables the server to be informed when the end device is receiving data and reduces the latency of downlink. But, owing to the periodic windows, energy consumption of Class B devices is high.
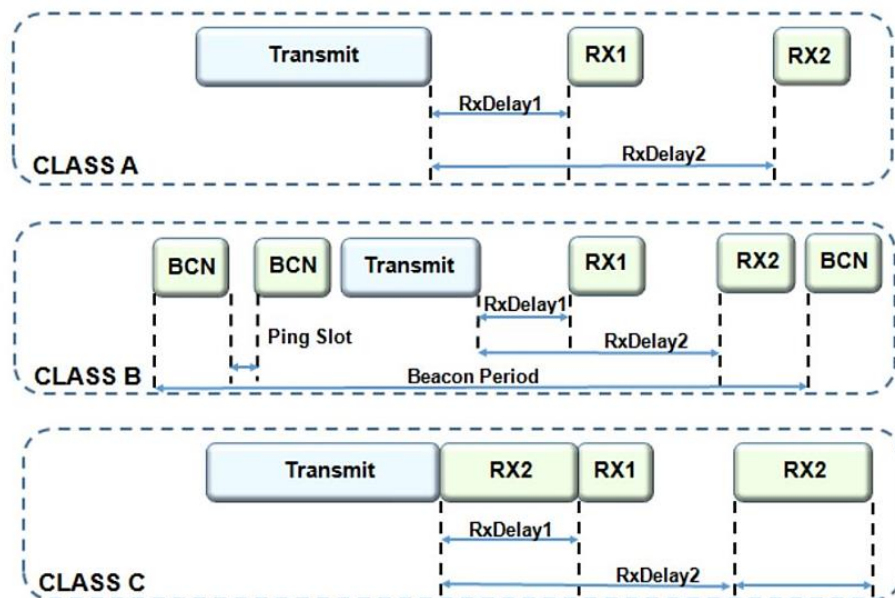

Figure 2.16:   Three device classes offered by LoRaWAN [18]

In *Class C,* the receive windows of end device is almost continuous, except the time when it transmits data, as described in Figure 2.16 (c). It has the lowest downlink latency, but the power consumption is the highest among those three classes. Generally, this class devices are powered by the power resources without energy limits.

Due to not frequent controlling of actuators in drip irrigation, LoRaWAN class A or class B devices may be suitable to build wireless network. But, for the deployment of LoRaWAN, multi-channel gateway devices and multi modem capabilities have to be employed. Besides that, in order to increase the range the number of gateways should be increased and this makes the system cost more expensive.

LoRa

LoRa is a spread spectrum modulation technique, which is based on CSS. LoRa is designed by Semtech [19]. LoRa modems operate at unlicensed frequency bands (sub-GHz category). LoRa modulation employs frequency chirps that the frequency varies linearly over time in order to encode data spreading over wider bandwidth (Figure 2.17).

A chirp is defined as a signal. Its frequency varies with the fixed rate which may be constant rate or exponential. A symbol is generated by the instantaneous variance of chirp frequency. Multiple bits of data are encoded into each symbol. The *Spreading Factor* (SF) refers to the number of encoded bits per symbol, and it can range between 7 : 12. The first order derivative of chirp's frequency variance over time is referred to as the *Chirp Rate,* and it is a function of spreading factor and bandwidth of channel, as depicted in the Equation 2.14.

$$Chirp\ Rate = \frac{df}{dt} = \frac{Bandwidth}{2^{SF}} \qquad (2.14)$$

The rate of data may be varied in a constant bandwidth through adjusting spreading factor (SF), which permit the performance of network to be optimized in fixed channel bandwidth, trading the rate of data for range or power [20]. Because of being chirp pulses linear, the frequency offsets between transmitter and receiver are equivalent to the timing offsets, so that they are cleared very easily in the decoder.
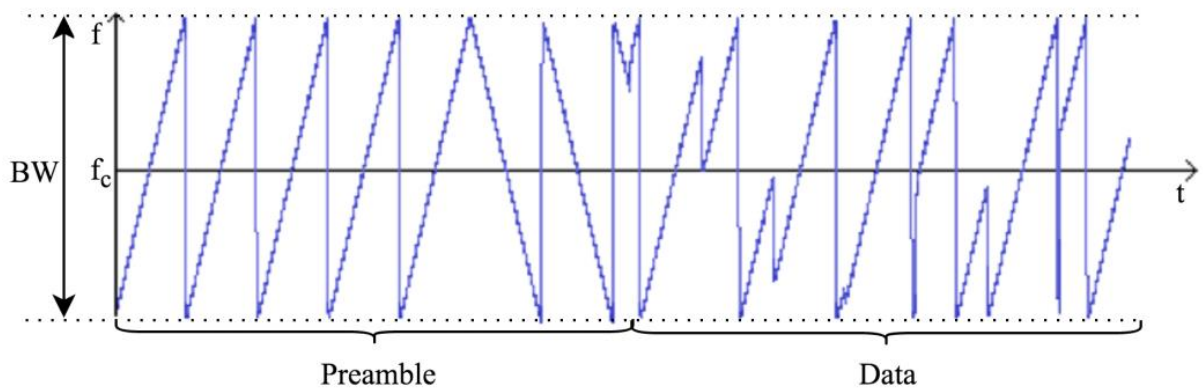
Figure 2.17:   Spectrogram pattern of a Lora chirp;
BW – bandwidth;
f_c – central frequency of the channel;

The communication data rate is dependent on the selected parameters. The final transmission rate is effected by the spreading factor, bandwidth and employed coding. The bitrate of LoRa modulation is defined as the equation 2.15 [19].

$$BR = SF * \frac{\frac{4}{4+CR}}{\frac{2^{SF}}{BW}} \ bits/second \qquad (2.15)$$

in the equation above:

BR – bit rate;

SF – spreading factor (7 : 12);

BW – bandwidth (Hz);

CR – coding rate (1 : 4).

In the LoRa modules of Semtech, all these parameters can be adjusted.

Every frames of LoRa starts with preamble. The preamble begins with a constant up-chirps' sequence which cover the entire frequency band. The last couple of the up-chirps encode the sync word. The sync word is 1 byte value and it is employed to differentiate the LoRa networks with the same frequency bands. If the decoded sync word does not match its configuration, the device stops to listen to the transmission. As depicted in Figure 2.17, the sync word is followed by 2 and a quarter down-chirps, for a duration of 2.25 symbols. The preamble can be configured between 10.25 to 65539.25 symbols [20].

After the preamble, optional header is transmitted with a 4/8 code rate. It indicates the payload size (in bytes), employed code rate, and if the 16 cyclic redundancy check (CRC) bits exist at the end of the frame or not. Besides that, the header itself includes its CRC in order to permit the receiver to discard the packet if the header is invalid. Maximum payload size limitation is 255 bytes. The header is optional to permit disabling it in cases when it is not necessary, for example, when coding rate, payload length and CRC presence are known beforehand.

The payload should be transmitted after the header. There may be an optional CRC at the end of the frame. Figure 2.18 shows a schematic summarizing the frame format.

Preamble	Header (optional)	Payload	Payload CRC (optional)
	CR = 4/8	CR = 4 / (4+n)	

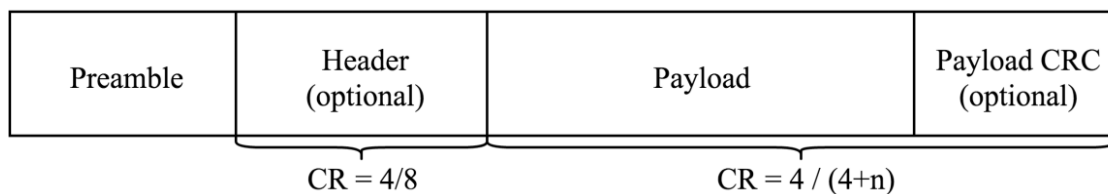Figure 2.18:   Typical LoRa frame structure. $n \in \{1..4\}$ [20].

For the applications scenarios requiring low energy consumption, Channel Activity Detection (CAD) mode of LoRa modem can configure duty cycled reception. In CAD mode the associated microcontroller is alerted as soon as the modem detects the presence of packet preamble. Figure 2.19 shows flow chart of one CAD cycle.

Figure 2.19:   LoRa CAD flow [21]

2.4   Short Range WSAN Technologies

Short range wireless technologies are used broadly in the industrial and home automation with a dense sensor networks and near field monitoring [14]. They are designed to operate with low power consumption and low data rate, enabling operation on a single battery over many years. Short – range wireless technologies can be applied for the applications, such as the one developed in this thesis project – irrigation control system for urban gardens. But,

The objective of this project requires to have 100 meters of communication range, therefore it is preferred to use short – range wireless technology for the project. Because of the lower energy consumption, higher data rate and having sufficient communication distance, short – range wireless technologies are preferred over the long – range wireless technologies.

Although there are many different short – range wireless technologies, two of the most popular and the best suitable for WSANs are discussed in this section: Bluetooth Low Energy and ZigBee based WSANs.

2.4.1   Bluetooth Low Energy based wireless sensor

Bluetooth is based on the IEEE 802.15.1 standard and it is short – range wireless radio system developed for the devices to replace cables for the peripherals of computers, such as printers, joysticks, mice and keyboards. Bluetooth was first invented in 1994, by the telecom vendor "Ericson". The applications range is known as Wireless Personal Area Network (WPAN). Bluetooth operates in the 2400 – 2483.5 MHz frequency range within the ISM 2.4 GHz band. There are 79 designated Bluetooth channels each of which have 1 MHz in bandwidth. The data packets are exchanged through those 79 channels. Originally, Bluetooth was developed for continuous and streaming

data applications. Thus, it could not meet the requirements of low power applications which demands several years of battery life. *Bluetooth Low Energy* (BLE) was introduced in 2011 as Bluetooth 4. The main difference between BLE and classic Bluetooth is power consumption. The devices with BLE can operate on a small battery for many hours. It is not ideal for constant streaming of data, however it is really vital for the applications which only requires to exchange small data periodically. BLE works with 2.4 to 2.483 GHz ISM band as Bluetooth classic. However, it employs a different frequency – hopping spread spectrum scheme. Bluetooth classic hops at 1600 hops/second rate over 79 channels. BLE FHSS employs 40 channels with 2 MHz wide in order to provide better reliability over longer range. But, BLE stays in sleep mode continuously except when connection is initiated. Actually, its connection duration is only few milliseconds, while this duration is about 100 milliseconds for classic Bluetooth. BLE cannot exchange data with classic Bluetooth, therefore most vendors deploy both technologies into one device to be more efficient and flexible. In those devices each technologies operate separately, but not at the same time. And they can share the same antenna. The Table 2.1 shows the main differences between BLE and Bluetooth classic, below. BLE is very suitable for sensor level technology, public transportation applications and health and fitness monitoring devices. In comparison, BLE consumes low power and costs less.

Another characteristics of BLE are a power output of 0 dBm (1 mW) and a typical maximum range of 50 meters. Security is 128 bit Advanced Encryption Standard (AES). Link reliability is improved using an adaptive frequency hopping technique which avoids interference. The most used network configurations are P2P or star. Latency is only 6 ms [10].

Specification	Bluetooth classic	BLE
Range	10 m	> 10 m
Over the air data rate	1-3 Mbps	125 kbps - 1 Mbps - 2 Mbps
Application throughput	0.7 - 2.1 Mbps	0.27 Mbps
Robustness	Adaptive fast frequency hopping, FEC, fast ACK	Adaptive frequency hopping, Lazy Acknowledgement, 24-bit CRC, 32-bit Message Integrity Check
Latency (from a non-connected state)	Typically 100 ms	6 ms
Minimum total time to send data (det. battery life)	100 ms	3 ms
Voice capable	Yes	No
Peak current consumption	<30 mA	<15 mA

Table 2.1: Comparison of BLE and Bluetooth classic [22]

There are different projects have been proposed to deploy wireless sensor networks by the use of BLE. In this article [23], BLE and other short – range technologies are compared, and presented the advantages of BLE for optimizing power consumption. Besides, two types of network topologies are suggested to deploy low power WSAN. As presented in Figure 2.20, BLE enables to design Piconet by the use of one star topology, or more complex scatter nets can be designed using several interconnected piconets.
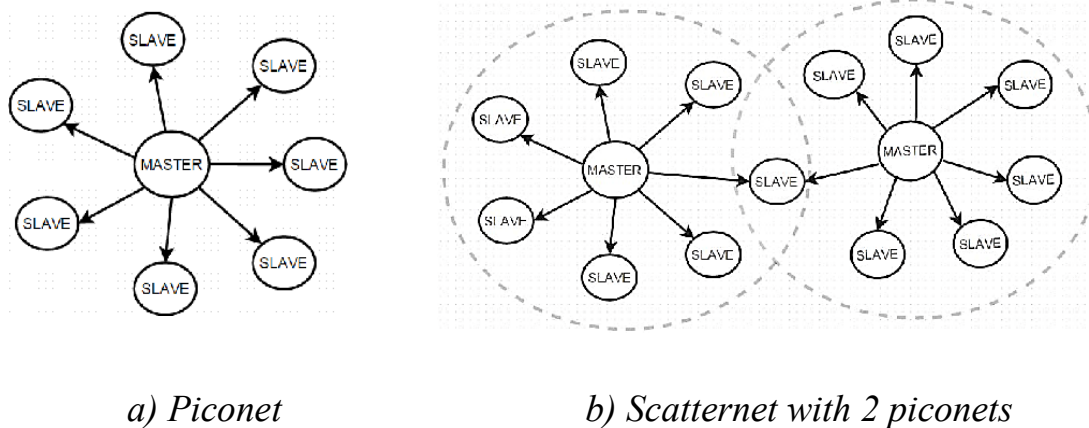

a) Piconet   b) Scatternet with 2 piconets

Figure 2.20:   Piconet and Scatternet [23]

Power consumption of BLE in different operation modes are shown in the Table 2.2, below.

Mode of operation	Power Consumption ($V_{DD} = 3V$)
Sleep mode	2.6 μW
Wake-up (RX mode)	15 mW
TX mode	15 mW

Table 2.2:   BLE power consumption [23]

2.4.2   ZigBee based wireless network

The ZigBee standard is developed by the ZigBee Alliance, and defines a set of communication protocols for low data rate, short range wireless networking. ZigBee based wireless devices work in 868 MHz, 915 MHz and 2.4 GHz frequency bands. Its maximum data rate is 250 Kb per second. ZigBee is usually targeted for battery powered applications which requires low data rate, low cost and long battery life. In the most ZigBee based applications, the total operation time in which the device is engaged in any type of activity is very limited, therefore the device remains most of the time in a power saving mode (also known as sleep mode). As a result, ZigBee based devices are capable to operate during several years before their batteries need to be replaced.

The ZigBee standard helps to decrease the cost of implementation by simplifying the communication protocols and decreasing the data rate.

In Figure 2.21 ZigBee wireless networking protocol layers are depicted. The bottom two networking layers are defined by the IEEE 802.15.4 standard. In the physical layer, radio devices working with ZigBee specifications, operates in the unlicensed ISM bands that are 2.4 GHz to 2.4835 GHz

(worldwide) divided into 16 channels, 902 MHz to 928 MHz (Americas and Australia) divided into 10 channels, 868 MHz to 868.6 MHz (Europe) divided into 1 channel. Following table shows a comparison of these bands (Table 2.3).

(MHz)	Frequency band(MHz)	Channels Number	Modulation	Bit rate (kb/s)	Symbol rate (ksymbols/s)
868	868-868.6	0	BPSK	20	20
915	902-928	1-10	BPSK	40	40
2400	2400-2483.5	11-26	O-QPSK	250	62.5

Table 2.3:   Comparison of three ISM bands

Over the air data rate is 250 kbps in 2.4 GHZ band, 40kbps in 915 MHz band and 20 kbps in 868 MHz frequency band. Outdoor line of sight communication range can reach 1500 meters. ZigBee devices employ DSSS along with BPSK or OQPSK modulation techniques [14].
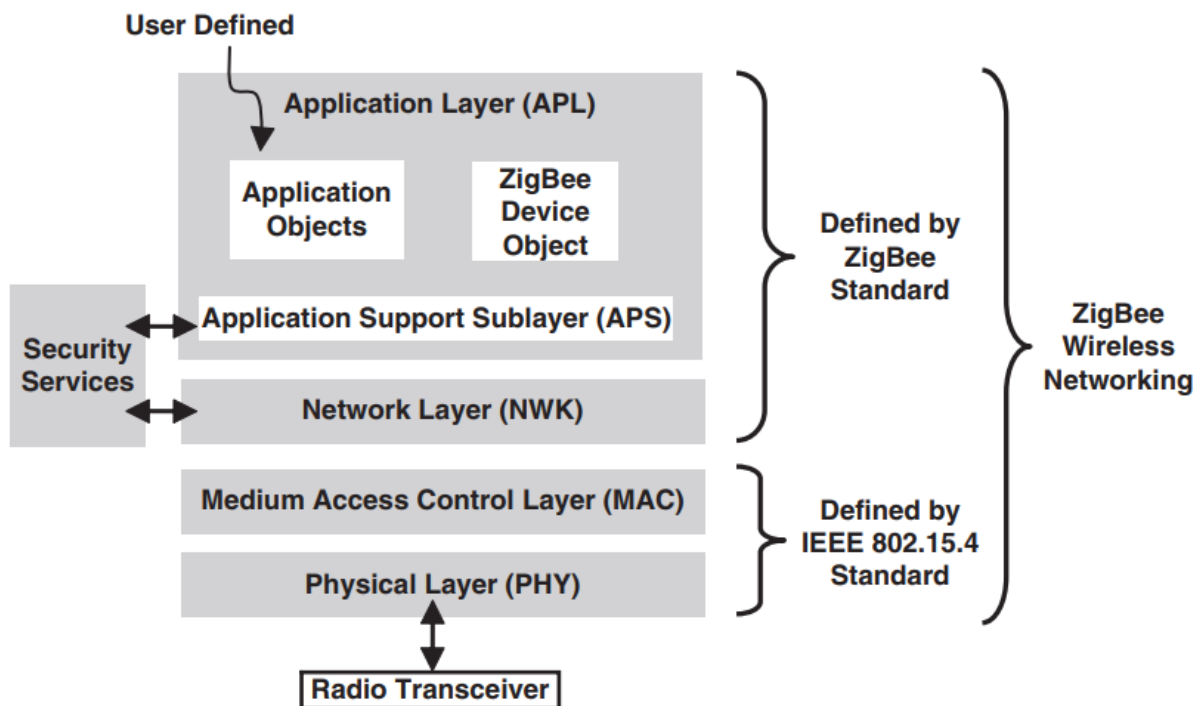

Figure 2.21:   ZigBee Wireless Networking Protocol Layers [25]

There are three types of ZigBee devices [24] :

- ZigBee Coordinator (ZC) – the most critical device, it is the root of the network. In every network, there should a coordinator, because it stores data about the network. As a coordinator, full – function device type can be utilized with the proper configuration.
- ZigBee Router (ZR) – they are employed in order to link different groups of devices together and to ensure multi – hop communication.
- ZigBee End Device (ZED) – it can include sensors, actuators and controllers that collects data. It requires minimal resources and the least amount of memory. Usually, the highest number of devices are end devices in network, therefore the cost of end devices is the least amount.

The following figure describes the ZigBee network model of mesh network topology and shows different device types by marking them according to their functionality.
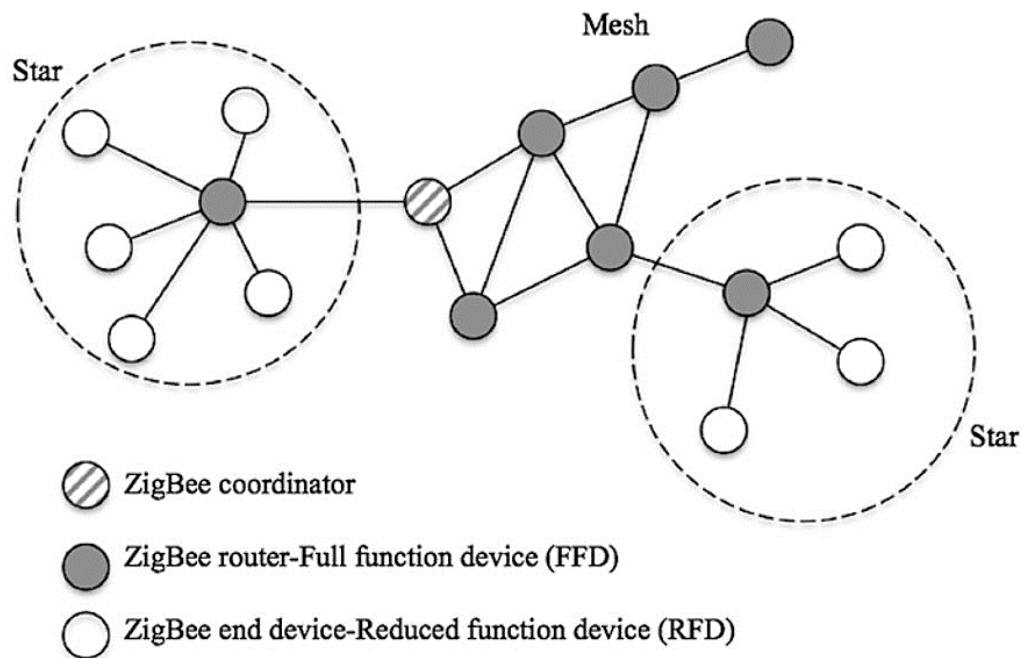

Figure 2.22:   ZigBee network model [14]

The current ZigBee protocols support beacon enabled networks and non-beacon enabled networks. In a non-beacon enabled networks, end device transmits data to coordinator when it is necessary. Than coordinator transmits

the acknowledgement back. In this type of network, coordinator should be in receiving mode continuously, thus needs more robust power supply. In beacon enabled networks, ZigBee routers should transmit periodic beacons in order to confirm their presence to other nodes. In order to extend their battery life nodes may sleep between beacons [24].

Each ZigBee node in a network has two addresses:

- 16 – bit network address assigned when it joins the network
- 64 – bit extended address that is globally unique

According to the IEEE 802.15.4 standard, receiver sensitivity is defined as the lowest received signal power with less than 1% packet of error. In ZigBee wireless networking, IEEE 802.15.4 standard requires only – 85 dBm of receiver sensitivity for transmissions in the 2.4 GHz ISM band. If 50 Ω single ended antenna is employed, the receiver sensitivity level of – 85 dBm translates to a signal with effective voltage of 12.6 uV:

$$Signal\ Power = \ -85\ dBm = \ 10^{\left(\frac{-85-30}{10}\right)} = 3.16 * 10^{-12} = 3.16\ pW$$

$$Signal\ Voltage = \ \sqrt{Signal\ Power * Antenna\ Resistance}$$

$$Signal\ Voltage = \ \sqrt{3.16 * 10^{-12} * 50} = 12.6\ uV$$

This means that receiver can detect any signal with root – mean – square (rms) voltage of at least 12.6 uV or higher and can extract data from the signal with maximum 1 % packet error rate (PER).

Besides the receiver minimum input signal level (receiver sensitivity), there is also another level to be determined is that the receiver maximum input level. A ZigBee based receiver should have a capability to receive signals with the power level of – 20 dBm or higher and maintain PER less than 1 %.

The transmitter should be capable of delivering at least – 3 dBm of output power. Reduction of output power will decrease the current consumption during transmit mode and reaches longer battery life. A transmitter should have the output power adjustment range at least 30 dB [25].

In free space, signal power at a distance d from antenna is calculated as below formulation:

$$d = \frac{P_0}{d^2} \qquad (2.16)$$

where: $P_0 - signal\ power\ at\ the\ antenna$

If the distance is doubled from the antenna, the signal power will be reduced by the factor of four.

The signal power at distance d is also function of frequency. In free space, the signal power at distance d can be calculated from the path loss equation [25]:

$$P_d = P_0 - 20 * log_{10}(f) - 20 * log_{10}(d) + 27.56 \qquad (5.1)$$

where:

P_d – signal power at the distance d (dBm);

P_0 – signal power at the antenna (dBm);

f – signal frequency (MHz)

d – the distance from the antenna (meters)

When ZigBee node sending a packet, it is first generated in the application layer, than network header, MAC header and physical headers will be added. Figure 2.23 shows ZigBee frame structure and header content and footer.
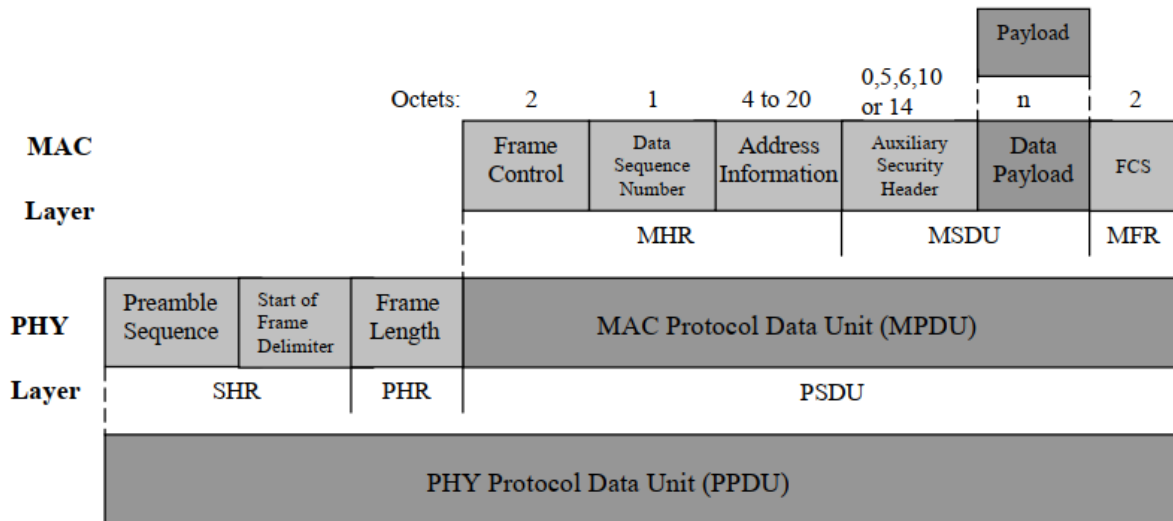
Figure 2.23:   Structure of ZigBee frame.
(See the full name of the abbreviations in the Abbreviations section above.)

The maximum physical layer packet size is 127 bytes. The actual data rate depends on the added protocol overhead. Different headers between 9 to 25 bytes can be added to payload.

Chapter 3

System design and implementation

3.1   System components

In order to accomplish the main objectives of this thesis project the system components must be carefully analyzed and selected. As we discussed the micro-irrigation types and decided to choose drip irrigation method, the designing control system will be targeted to drip irrigation of urban gardens. The control of the drip irrigation process involves remotely working actuators. That's why, wireless nodes need to have power efficient driver blocks which are capable to control the solenoid valve actuators. Figure 3.1 describes the main functional blocks of the designed wireless node.
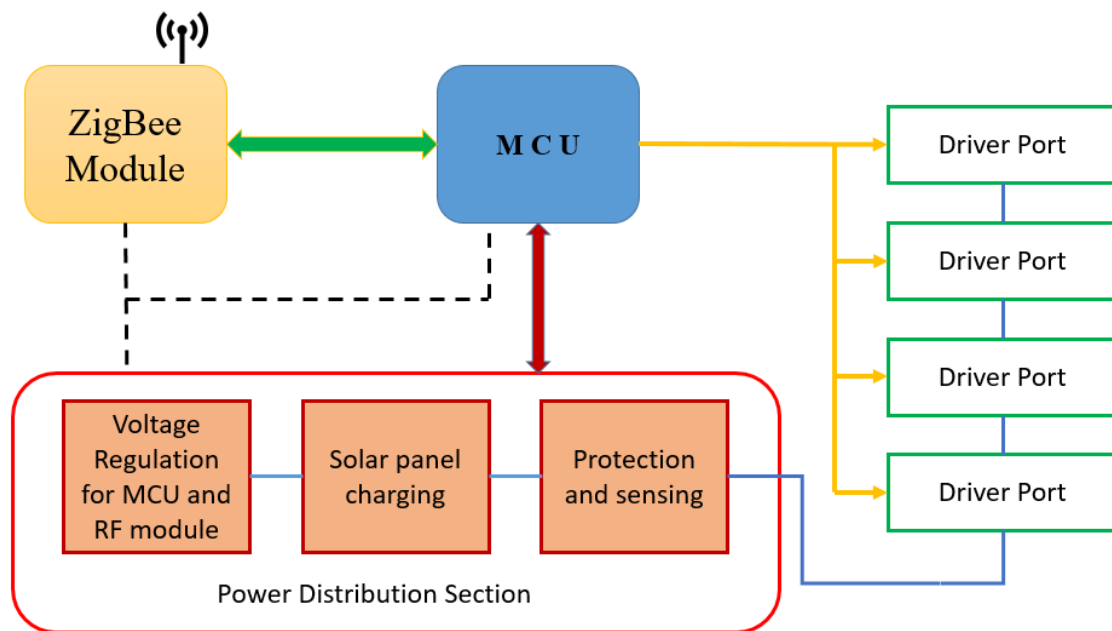

Figure 3.1: Functional blocks a wireless node

For this thesis project, ZigBee wireless technology is chosen due to its low power consumption, low cost, low complexity and sufficient

communication range for urban gardens. But, custom data transmission network architecture proposed in section 3.2 in order to design cost effective system. The components are chosen according to their operation voltage values, and the fixed 3.3 V is supplied all over the circuit of end – devices. Therefore, all the main components, such as microcontroller, radio module, sensors and actuators operate at the fixed voltage level of 3.3 V. However, in the coordinator circuit, the components do not work at the same voltage. The power distribution block provides the required supply voltages to various peripherals. The section 3.4 explains implementation details of the power distribution block. The microcontroller is responsible to control the radio module, power distribution and the actuator drivers. So, the microcontroller type and the written firmware to it are the necessary factors for the node efficiency. In section 3.8, the firmware development is discussed with some techniques to achieve long battery life.

Due to the control of water flow through low power recourses, the selection of the most suitable valve type is very crucial. Discussion of some existing valve types and chosen type for this thesis project are presented in Section 3.3.

Atmega 328P microcontroller is chosen for the project because of its power efficiency and availability. Besides that, it is decided to use XBee S2C ZigBee module from Digi, because of its suitable low – power consumption and cheap price.

3.2 Deployed network architecture for data transmission

For the control of drip irrigation system targeted to medium communication range, a simple and low cost network architecture has to be applied. Therefore, typical master – slave approach is proposed, where central

control unit is considered as master and all other end – devices are the slave nodes. Master node communicates with slave nodes only one by one. The communication is initiated by slave nodes and master node continuously listens to node signals, as it is connected to robust and unlimited power supply. Therefore, the slave nodes do not need to listen to master node signals continuously and this increases their battery life. The overview of this simple and low – cost network architecture which is based on master – slave model is presented in Figure 3.2, below.
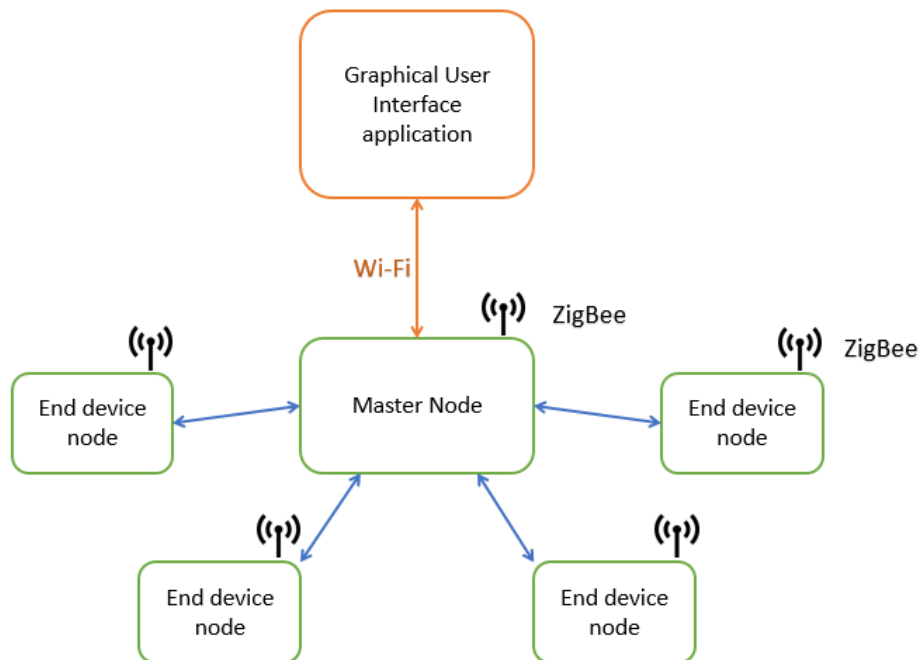

Figure 3.2: Master – slave based network architecture

End devices are the slave nodes. Its main functionality is to communicate with master node and perform required task, such as controlling actuator or monitoring sensor data.

Master node connects to the central computer through Wi-Fi. Its main function is to establish connection with end devices, gather the certain data from slave nodes and sending all the obtained information to user's central computer. The dedicated Wi-Fi connection ensures to control the implemented system with any kind of computers, such as tablets or smartphones.

Central computer unit runs the graphical user interface application in order to control the whole system. It enables user to add new end devices and control or monitor them.

3.3 Types of actuator valves in drip irrigation systems

Controlling water distribution of drip irrigation by electrical valves enables them to be automated. Solenoid valves are utilized in all cases where fluid should be controlled automatically. Generally, a solenoid valve is a combination of 2 basic functional units:

- A solenoid (electromagnet) with its core
- A valve corpus including one or multiple ports

By energizing or de-energizing the solenoid electromagnet, position of the core is changed and the flow is controlled through ports.

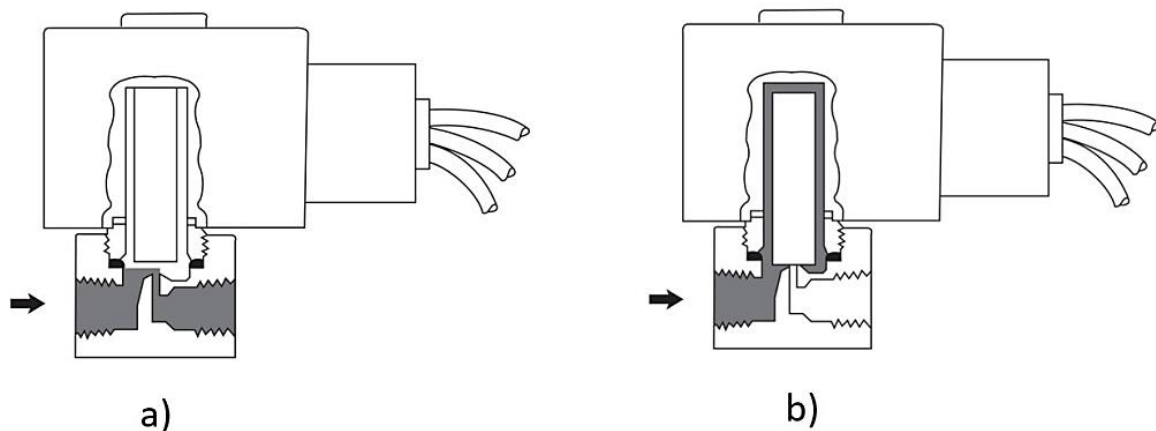a)   b)

Figure 3.3:   Normally closed direct acting two – way valve [27].
a) Energized state   b) De – energized state

Generally, solenoid of electrical valves is mounted directly on the valve body and the core is enclosed in a sealed tube in order to prevent fluid leakage.

According to the mode of actuation, the valves make a distinction between direct – acting valves and internally piloted valves. Besides, the number of ports differs according the requirements of application. Furthermore, according to the de – energized position, valves are categorized as normally open and normally closed valves.

If *direct acting solenoid valve* is energized, the core closes the port of a normally open valve or opens the port of a normally closed valve. When the solenoid of two – way valve is de – energized, the spring returns back the valve to its original position. Two – way valves can be considered as shut – off valves, because of having one inlet port and one outlet port. The normally – closed direct acting two – way valve is depicted in Figure 3.3, with energized and de – energized states.
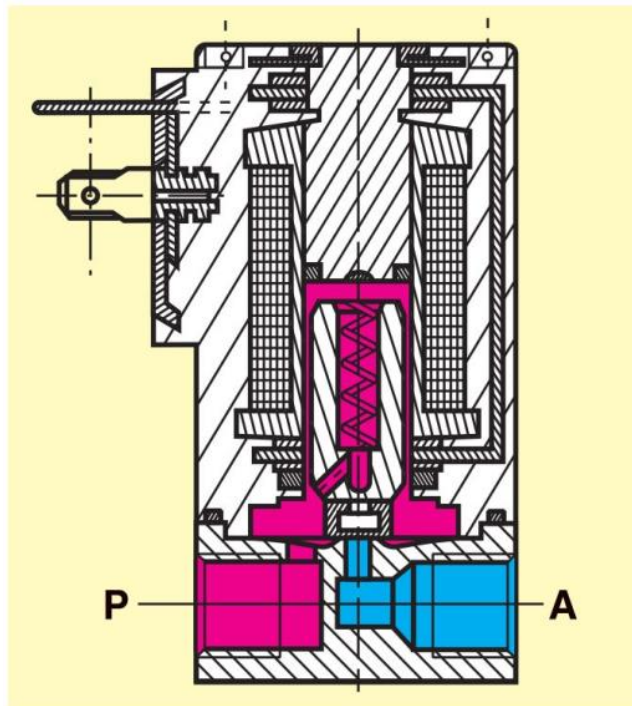

Figure 3.4: Cross section drawing of two way, normally closed direct acting solenoid valve [26]

The direct acting valve can work at its rated maximum pressure. The required force to open the valve is proportional to the port size and fluid

pressure. The electromagnetic force need to be greater than the combined spring force. In order to open big orifices, the solenoids need to be very large and energy intensive. That's why, generally, pilot operated constructions are used for obtaining demanded force with small size solenoids. Figure 3.4 exhibits cross section drawing of typical normally closed, two way direct acting solenoid valve.

3.3.1   Internally piloted solenoid valves

In direct – acting valves, static pressure forces increase with increasing port diameter. It means that the electromagnetic force becomes correspondingly larger in order to overcome the pressure. Therefore, internally piloted solenoid valves are employed to switch higher pressures with larger port sizes. In this case, the main operation – opening and closing the valve is performed by differential fluid pressure.

Generally, de – energizing the solenoid makes the pilot orifice to be closed and fluid pressure builds up on both sides of the diaphragm through a bleed orifice. Due to the larger effective area on the top of diaphragm, a shut – off force is created.

Energizing the solenoid causes the pilot orifice to be opened and the pressure on the upper side of diaphragm is decreased by the outlet side of the valve. The higher effective net pressure from below lifts the diaphragm and consequently, opens the valve.

Naturally, internally piloted valves demand a minimum pressure differential to provide suitable opening and closing. However, some internally piloted valves work even at zero pressure difference. Following figures illustrate cross section drawing of internally piloted solenoid valve and its energized and de – energized states.
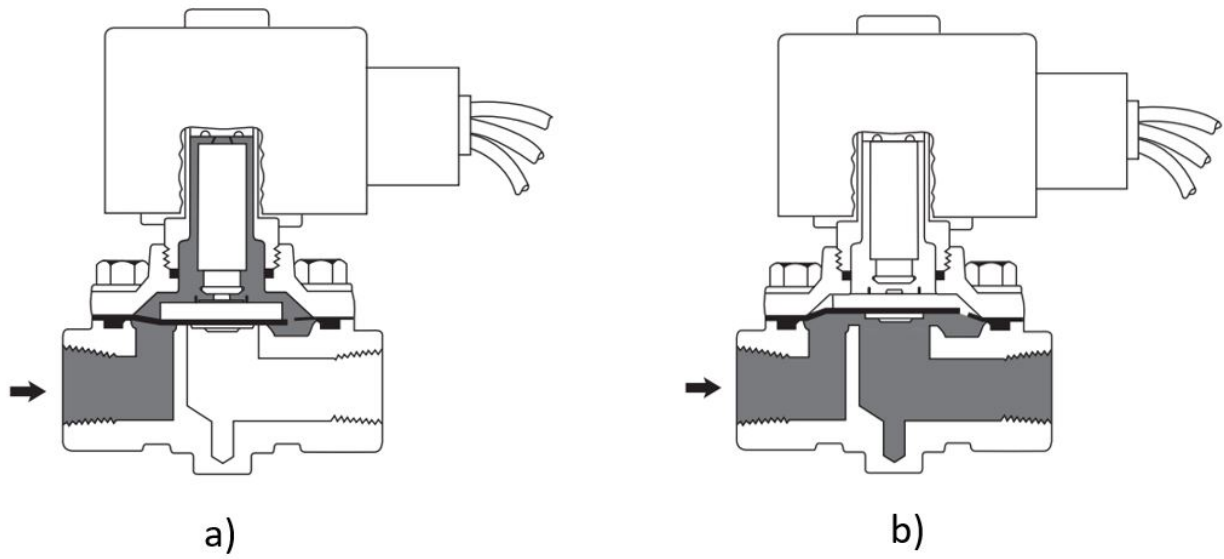
Figure 3.5: Normally closed, internally piloted solenoid valve [27]
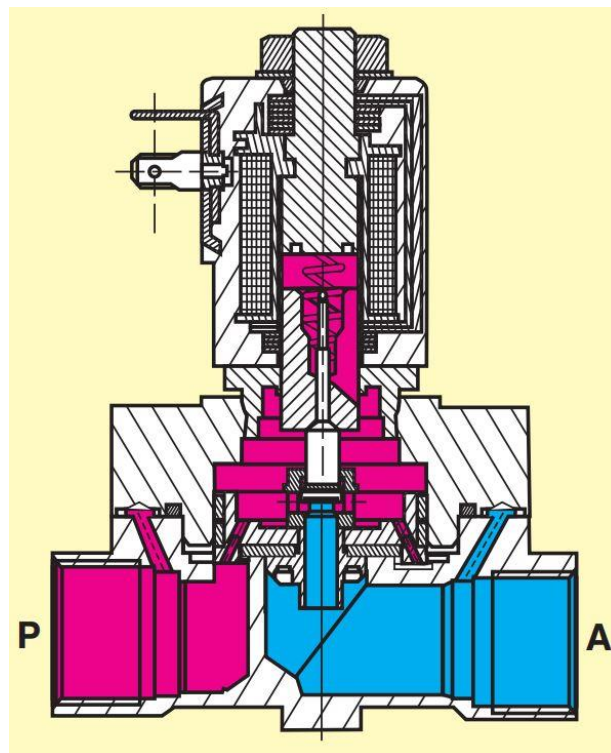a) de – energized   b) energized

Figure 3.6: Cross section view of internally piloted solenoid valve [26]

3.3.2 Latching solenoid valve

The use of pilot operated valves can help to reduce energy consumption for controlling the flow. But, a normal solenoid should be energized continuously, in order to keep the valve in open position – pushing the core against the spring. Even though, the power consumption to keep small solenoid valve active is not very huge compared to general direct acting solenoid valves, perceptible amount of energy is consumed if the solenoid valve operates frequently and keeps open position during a longer time of period. On the contrary, the valve operation is extensive and plants should be irrigated frequently in drip irrigation systems. Consequently, this type of solenoids cannot be employed in low power and battery operated irrigation control systems.

Another solenoid actuator type, which does not demand constant application of power supply in open and closed states, is called *Latching solenoid*. Latching solenoid contains a permanent magnet in order to keep the armature position once it has been varied (Figure 3.7). Therefore, this valve does not require power to maintain the state. Latching solenoids are sometimes called as *bistable solenoids*, due to having two stable positions. The position can be latched through very short electrical pulse applying to the coil. In order to move (reverse) the position back, the same kind of short electrical pulse with opposite sign should be applied to the coil. Figure 3.8 compares normal solenoid and latching solenoid from the energy consumption point of view.
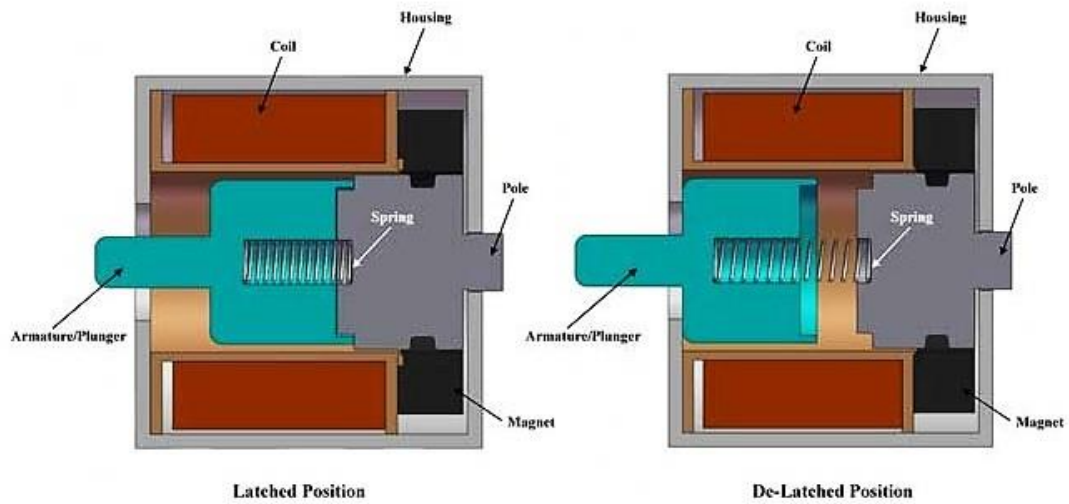
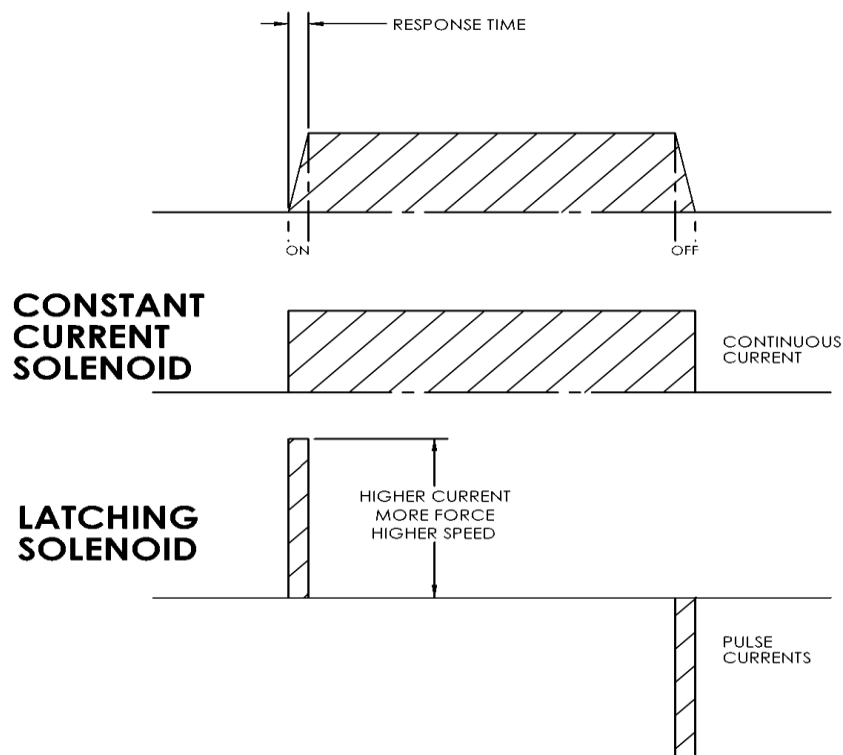Figure 3.7: Main components of typical latching solenoid valve [28]

Figure 3.8: Comparison of latching solenoid with constant current
solenoid [28]

In this thesis project, the wireless nodes are designed to control only latching solenoid valves. Due to the main objective of the project is low power

consumption, low cost and the compactness of the wireless nodes, it is decided to choose the latching solenoid valve with the following parameters:

Nominal voltage of the pulse (V)	Pulse duration – T_{pulse} (ms)	Coil resistance – R_{coil} (Ω)
3.3 V	30	9

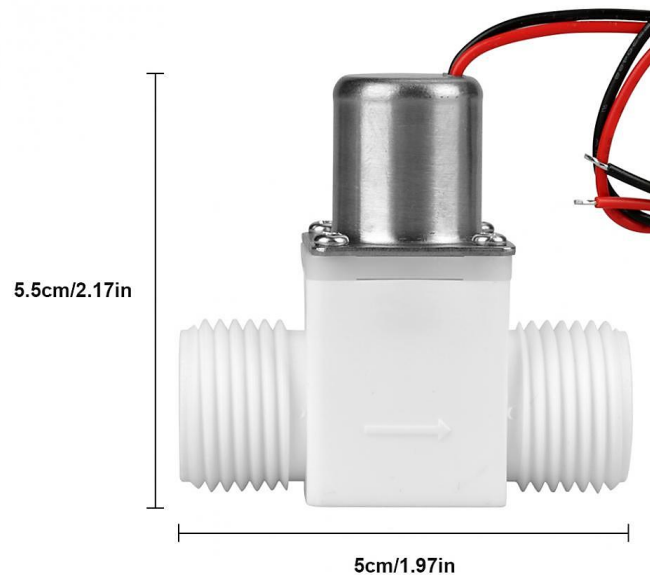Table 3.1: Electrical characteristics of the deployed latching solenoid valve

Figure 3.9: Dimensions of the employed latching solenoid valve

3.4   Power section design

The different electronic components need different value of operating voltages. Therefore, it is required to design robust power section for the nodes to provide each component with suitable power supply. Besides that, it is very

necessary to keep the thesis objectives which are the low cost and the low – power consumption goals.

3.4.1   Master node power section

The power supply of master node gives the whole circuit 12V. Supply voltage for the chosen XBee module and Wi-FI module should not exceed 3.3V. However, there are some components that operate at 5V, such as water pump, water tank level sensor and microcontroller (Figure 3.10).
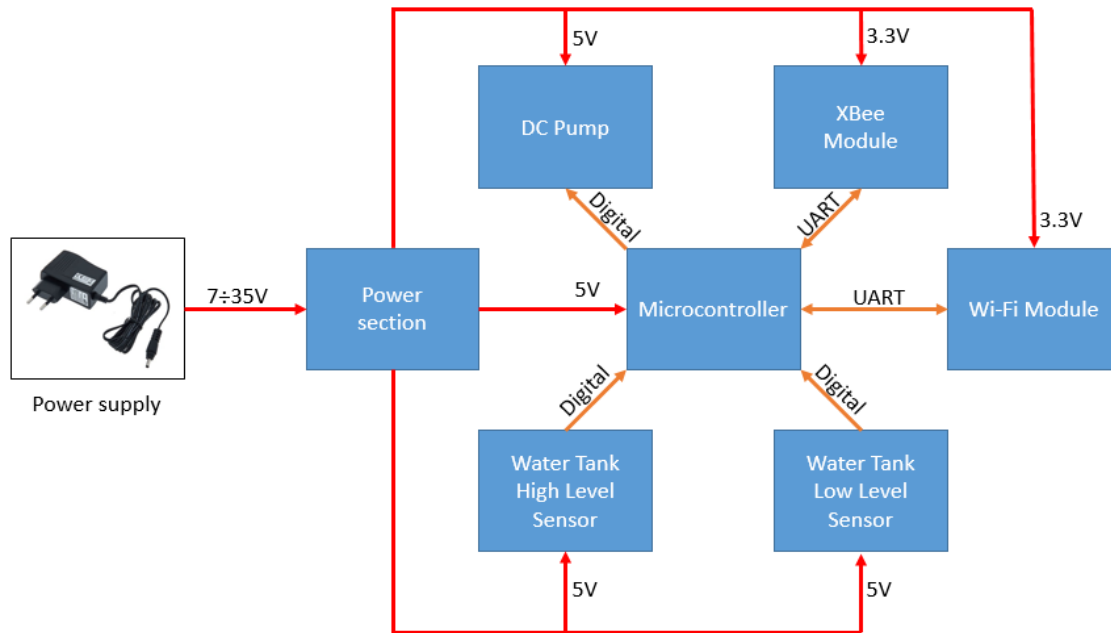

Figure 3.10:   Master node block diagram

In order to adapt the input 12V power supply for each components, it is decided to employ voltage regulators. In order to minimize the cost, all the components are categorized into two groups:

- Components operating at 5V: Microcontroller, DC water pump and water level sensors

- Components operating at 3.3V: XBee module and Wi-Fi module

We need to insert two voltage regulators, one should output 5V to supply 5V operating components and another should output 3.3V to supply 3.3V operating components.

Taking into account the availability and price, L7805CV is chosen for the first voltage regulator. Its $7 \div 35V$ input range enables to change the power supply voltage of master node widely. Due to the robust power supply connection with master node, 5.2 mA quiescent current is acceptable [30]. Besides that, maximum output current of 1A is sufficient to provide all the components of master node. This regulator supplies not only 5V operating components. But also 3.3V operating components, too. We need to put another voltage regulator with 3.3V output between L7805CV and XBee, Wi-Fi modules.

The second voltage regulator should have lower quiescent current and higher output current. The minimum limit of output current is

$$I_{min} = I_{XBee} + I_{Wi-Fi} = 33mA + 215mA = 248mA$$

However, the Wi-Fi module and XBee module do not work at the same time. Therefore, the minimum output current limit can be 215mA. For this regulator, low quiescent current voltage regulator MCP1700-3302E/TO is selected. Its current output can reach up to 250mA at 3.3V. Furthermore, it has only 1.6 μA quiescent current [29]. In order to ensure voltage stability, 1μF ceramic capacitor is sufficient to connect on input and output pins. This IC is powered by L7805CV regulator and supplies XBee and Wi-Fi modules.

3.4.2 End device power section

Designing the power section of the end device is a bit different compared to master node. In order to minimize the number of voltage level conversions from one level to another, it is decided to choose all the components that operate at the same voltage. Taking into account the low power requirement of the project, the 3.3V of voltage level is accepted, thus all the components operate at 3.3V (Figure 3.11). The input power supply of the end-device is only single rechargeable battery with 3.7 Volts. Therefore, low dropout voltage regulator MCP1700-3302E/TO is used for supplying all the system components, owing to its 3.3V output voltage that enough to supply with current all the sensors, microcontroller and XBee module. Low quiescent current (1.6 μA) and high output current (250 mA) ensures the wireless node to be characterized as low power.
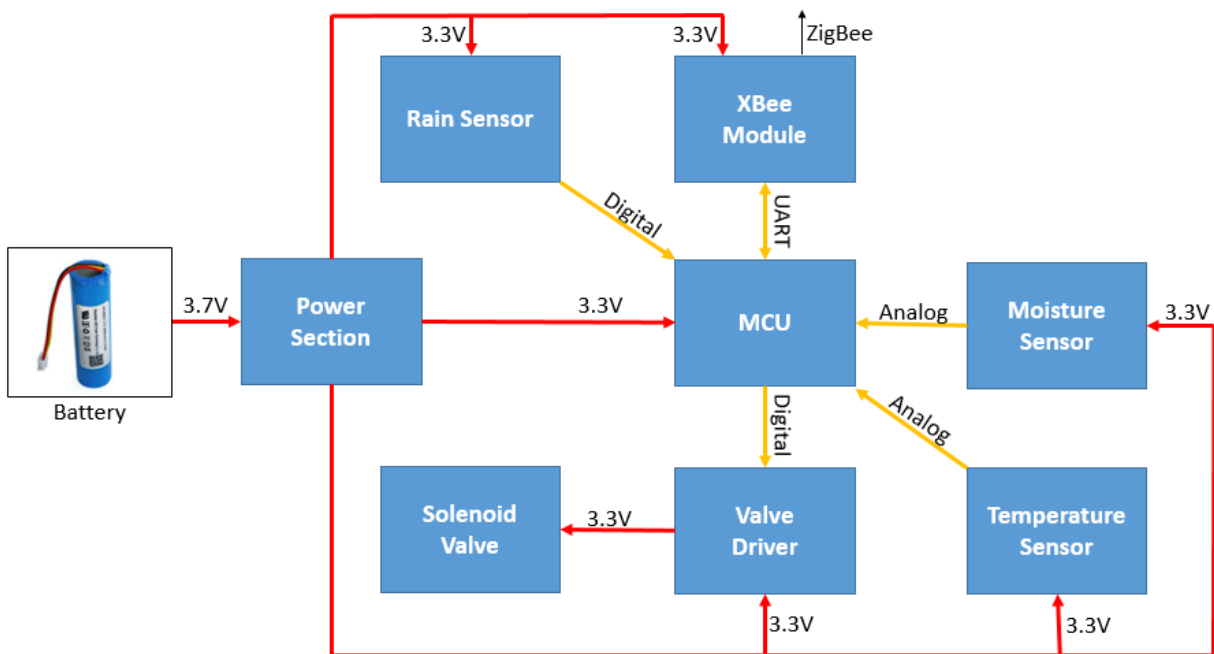
Figure 3.11:   End – device block diagram

Due to higher current consumption rate of solenoid valve compared to other electronic components, it is decided to employ separate voltage regulator for it. AP7366-33W5-7 fast transient low dropout linear regulator is used for this purpose. Its output voltage is fixed 3.3V and output current can reach up to 600mA which is sufficient for the solenoid valve's current consumption (367mA). The only issue with this choice is that its higher quiescent current of 60 μA, that means it consumes 60 μA from the battery all the time. This issue can be solved very perfectly by putting the voltage regulator into sleep mode by microcontroller when the solenoid valve is not operating. In sleep mode, the quiescent current of the regulator is only 0.05 μA. When the solenoid need to operate, the MCU wakes up the voltage regulator by sending active high signal to its EN port and the solenoid is ready to be controlled.

a)   b)
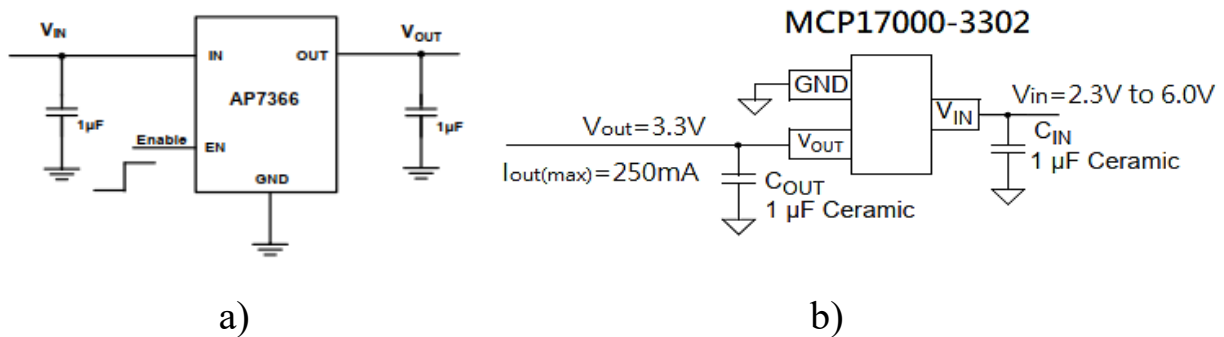
Figure 3.12:   Typical application circuits:
a) AP7366-33W5-7 [31]   b) MCP1700-3302 voltage regulator IC

3.5   Valve driver design

In order to operate the latching solenoid valve, the sign of control signal has to be reversible that means H – bridge should be utilized as a valve driver. In this project, each wireless node (end – device) should have the capability to control one solenoid actuator. Therefore, valve driver circuits are designed inside the end – device boards.

An H-bridge driver must be able to operate by the 3.3V logic signals and capable of providing at least $I_{solenoid} = 367mA$ current. TC78H651FNG is bridge driver integrated circuit (IC) from Toshiba, which fully satisfies those requirements. It can operate with 3.3V and can drive an actuator with 3.3V and up to 1.5A of a current [33]. Besides that, the TC78H651FNG integrates two H-bridge circuits (two channels). If the wireless node need to control multiple solenoids, this IC can control up to four solenoid valves ($\frac{I_{driver}}{I_{solenoid}} = \frac{1.5A}{367mA} \approx$ 4.1) by two channels simultaneously. The most advantage of this IC is its 0 μA current consumption in standby mode. Because, all circuits in the IC configure with complementary metal oxide semiconductor (CMOS) elements that greatly reduce the standby current [32]. Due to being thin shrink small outline package (TSSOP) with the dimensions of 5mm X 4.4mm, it contributes the end device's size to be compact.

The opening and closing of the solenoid valve can be performed according to the input and output function shown in the Table 3.2.

First channel control inputs		Second channel control inputs		First channel outputs		Second channel outputs		Mode
IN1	IN2	IN3	IN4	OUT1	OUT2	OUT3	OUT4	
H	L	-	-	H	L	-	-	First channel opening
L	H	-	-	L	H	-	-	First channel closing
-	-	H	L	-	-	H	L	Second channel opening
-	-	L	H	-	-	L	H	Second channel closing

Table 3.2:   Input/Output functions of TC78H651FNG IC

As we are controlling one solenoid actuator by an end device, we need only one channel of the driver IC. Thus, opening of the solenoid is performed by sending logic high signal to IN1 pin, and closing is done by logic high signal to IN2 pin. The minimum boundary of logic high signal is 2.0 V.

In order to prevent circuit components from back EMF (electro motive force), a protection circuit with four diodes is built, as well. Figure 3.13 illustrates the designed driver circuit to control the solenoid valve.
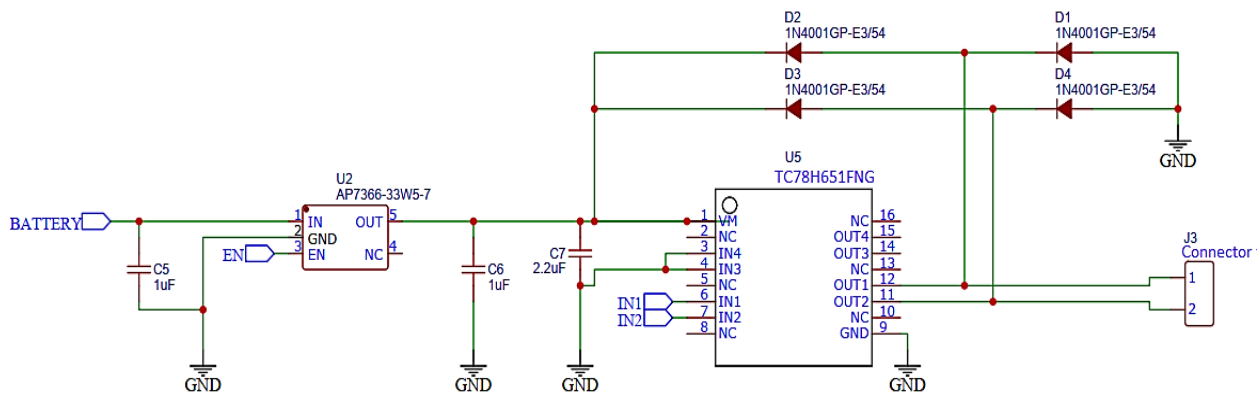
Figure 3.13:   Designed driver for solenoid actuator

3.6   Battery charging section design

The designing WSAN system is required to operate for several years, it is decided to employ solar panel for charging the battery. Therefore, the end device needs to include charging section and it should have following characteristics:

- Battery protection from over charging
- Reverse discharge protection
- Controllability by microcontroller
- Faster charge current regulation
- Compact dimension

The charge management controller MCP73831 (Figure 3.14) from Microchip for single-cell Lithium – Ion and Lithium – Polymer batteries meets the above mentioned requirements perfectly. This IC is highly advanced linear charge management controller to use in space limited and cost – sensitive applications.
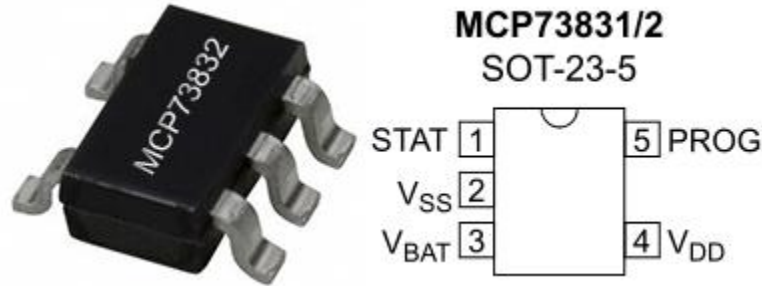

Figure 3.14:   MCP73831 IC view and pinout

This IC has the fast charge constant – current mode and during this mode the programmed charge current is supplied to the battery. The charge current value is established using a single external resistor from PROG pin to V_{SS} pin. In this project, this controller is programmed to charge at 100 mA constant current at 4.2 V. The microcontroller reads the charge status from the STAT pin of MCP73831 and switches of when the battery is fully charged by connecting the PROG pin of IC to GND.

The charge status output pin (STAT) of the MCP73831 has three different states: High (H), Low (L) and High Impedance (High Z) as shown in the Table 3.3, below. The microcontroller reads those values and make a decision to terminate or initiate the charging process at any time by sending signal to PROG pin of MCP73831 through a transistor as illustrated in Figure 3.15, below.

The program resistor and the charge current are calculated using the Equation 3.1 [37].

$$I_{reg} = \frac{1000V}{R_{prog}} \qquad (3.1)$$

In this equation, R_{prog} is in kΩ and I_{reg} is in mA. In order to charge with $I_{reg} = 100mA$ current $R_{prog} = 10$ kΩ resistor is connected to the PROG pin.

Charge Cycle State	STAT1	
	MCP73831	MCP73832
Shutdown	High Z	High Z
No Battery Present	High Z	High Z
Preconditioning	L	L
Constant-Current Fast Charge	L	L
Constant Voltage	L	L
Charge Complete – Standby	H	High Z

Table 3.3: State of the status output during charging cycle [37]

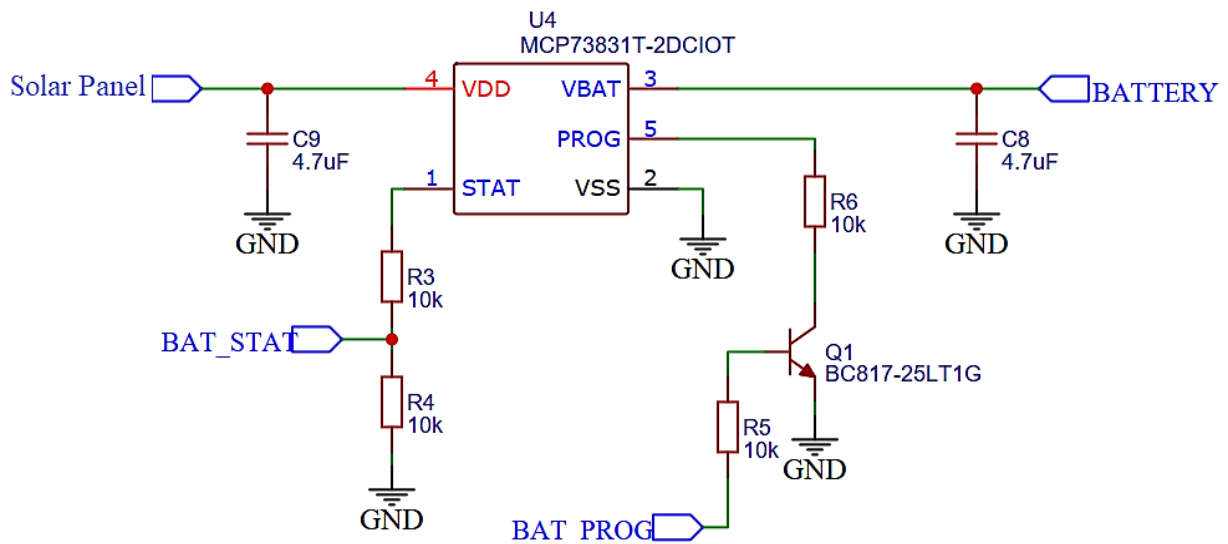Furthermore, MCP73831 provides the input overvoltage protection and reverse discharge protection.

Figure 3.15: Designed battery charging section of the end device

3.7   XBee module

XBee S2C ZigBee Standard module (from Digi) that has been chosen for this project is based on the EM357 system on chip (SoC) radio ICs made by Silicon Labs, utilizing 32-bit ARM Cortex M3 processor and works at unlicensed 2.4 GHz frequency band. The EM357 enables for robust co – existence with other communication standards in the 2.4 GHz spectrum, such as IEEE 802.11-2007 and Bluetooth, due to the integrated receive channel filtering. Furthermore, in built regulator, voltage controlled oscillators (VCO), loop filter and power amplifier keeps the number of external components low. An optional high performance radio mode referred as boost mode is software selectable in order to boost the dynamic range [36].

XBee S2C uses ZigBee protocol and DSSS modulation method. It operates on a fixed channel of 16 channels (channels 11 to 26) in the 2.4 GHz frequency band. The line-of-sight communication range is up to 1200 meters with 250 kbps data rate.

The transmit current is 33 mA (45 mA in boost mode) at 3.3 V and the maximum transmission output power the module provide is +8 dBm. The receive current is 28 mA (31 mA in boost mode). The receive current is 28 mA (31 mA in boost mode) at 3.3 V and the receive sensitivity is -100 dBm (-102 dBm in boost mode). The typical current consumption in sleep mode is less than 1 μA [35].
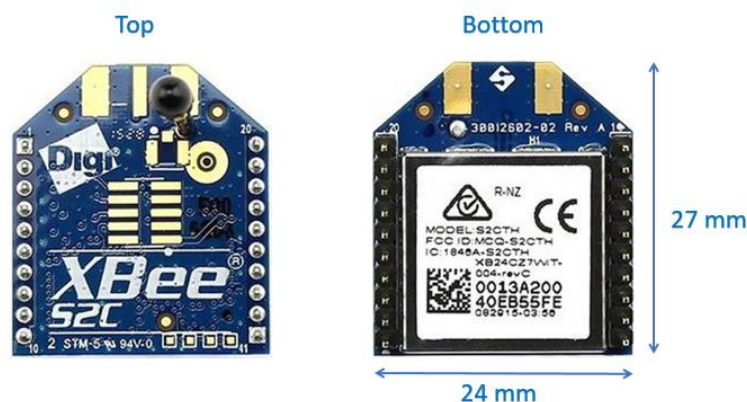

Figure 3.16:   XBee S2C ZigBee standard module (through-hole form)

There are two forms of this module, through hole and surface mount forms. In order to be easy for replacements and reconfiguring the module, it preferred to use through-hole form for this project (Figure 3.16).

3.7.1   Parameter selection

The parameters of XBee modules are configured by XCTU application through UART or SPI serial data interface. The serial interface speed is up to 1 Mbps. The parameters, such as transmission power level, power mode and function set and other settings can be configured using XCTU application.

Thus, settings have been configured as:

- Function set: ZigBee TH Reg
- Power Mode: 0 (Boost mode disabled)
- TX power level: 4 (+5 dBm)
- API enable: 0 (Transparent mode)
- Sleep Mode: 1 (Pin sleep enabled)
- D8:   1 (Sleep request)
- D9:   1 (Awake/Asleep indicator)
- P3:   1 (DOUT)
- P4:   1 (DIN)

Besides that, the link budget is 110 dB in this RF module and the above parameters set receiver sensitivity as -100 dBm.

In order to achieve a long battery life, the XBee module and microcontroller have to be put into sleep mode periodically. Since the companion microcontroller is Atmega 328P, the optimal technique to wake-up from the deep sleep mode is employing built-in watchdog timer. However, the maximum predefined value of Atmega 328P watchdog timer is 8 seconds, as shown in Table 3.4. So, the sleep duration can be a multiplication of 8 seconds. For example, $450 * 8\ seconds = 3600\ seconds\ (1\ hour)$. In another

words, microcontroller wakes up at every seconds and counts one more, and sleeps back immediately. After 450 times of sleeping periods, it starts to operate in wake-up mode.

The average current draw of the microcontroller decreases down from 5 mA to $10\mu A$ if it is putted into sleep mode.

Watchdog timer values
16 ms
32 ms
64 ms
125 ms
250 ms
500 ms
1.0 s
2.0 s
4.0 s
8.0 s

Table 3.4: Predefined values of watchdog timer in Atmega 328P microcontroller [34]

3.8 Board design and Firmware development

The designing wireless sensor and activator network consists of two different node types: Master node (Coordinator) and Slave node (End-device). The following sections present the corresponding design and implementation of their printed circuit board (PCB) and firmware. The schematics and electronic prints of PCBs for master and slave nodes are designed in the EasyEDA online PCB Layout Software.

3.8.1   Master node

Master node integrates the Wi-Fi module in addition to XBee. As a Wi-Fi module, ESP-01 has been chosen because of its low-cost, ease of use and small size. ESP-01 has an UART (universal – asynchronous receiver – transmitter) serial interface and AP configurations commands can be sent or the data can be received through UART. ESP-01 may be configured to work in Access Point mode in order to enable external devices to connect to the wifi access point created by the module. Following is the example of AP command for creating an Access point:

_____

AT+CWMODE=2

AT+CWSAP="wifi ssid","password",1,3

_____

The main functions of the master node are the followings:

- Receiving data from slave nodes through XBee modules
- Transmitting the gathered data to user application through Wi-Fi module
- Automatically controlling the water pump

The general flow of the master node operations is described in Figure 3.17, below.

The main components of master node are microcontroller, Wi-Fi module, XBee module and water pump. Microcontroller and water pump operate at 5 V and there is one voltage regulator – L7805 IC dedicated for both components. Because, the sum of current consumptions of microcontroller and water pump is less than the output current rate of L7805. In order to power supply the components work at 3.3 V, the MCP1700-3302 low dropout voltage regulators are employed. Although the Wi-Fi module and XBee module work

at the same voltage (3.3 V), they cannot be supplied from one voltage regulator. Because the ESP-01 Wi-Fi module consumes up to 215 mA at 3.3 V and the XBee module may consume up to 33 mA at 3.3 V. In case they operate simultaneously, the total current consumption (248 mA) is almost equal to output current (250 mA) of the MCP1700-3302 voltage regulator. Therefore, for each of both components separate voltage regulators are used. It does not make problem, due to the reasons of very low cost of MCP1700-3302 IC (few cents) and very low quiescent current (1.6 μA). Figure 3.18 and Figure 3.19 illustrate the board layout of PCB and the picture of the implemented PCB for the master node, respectively.
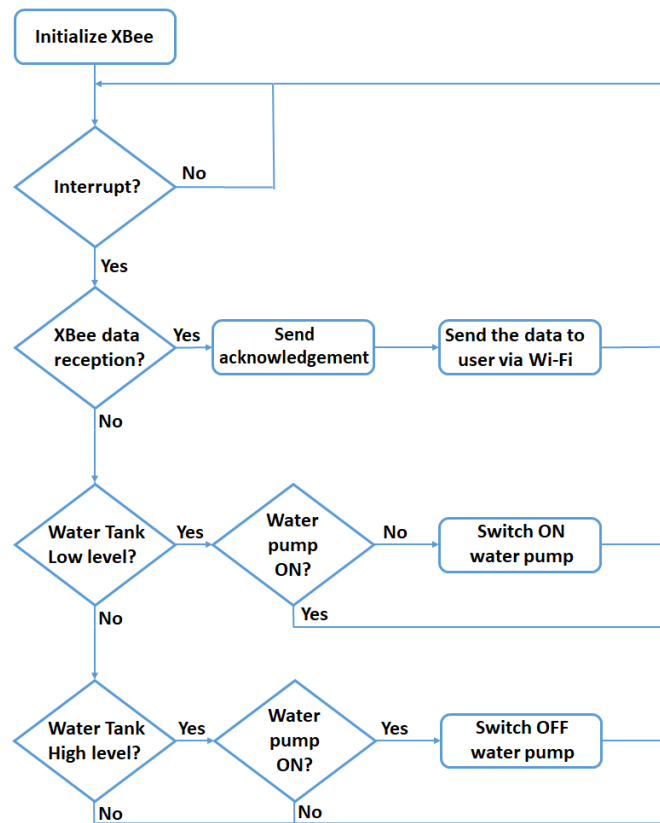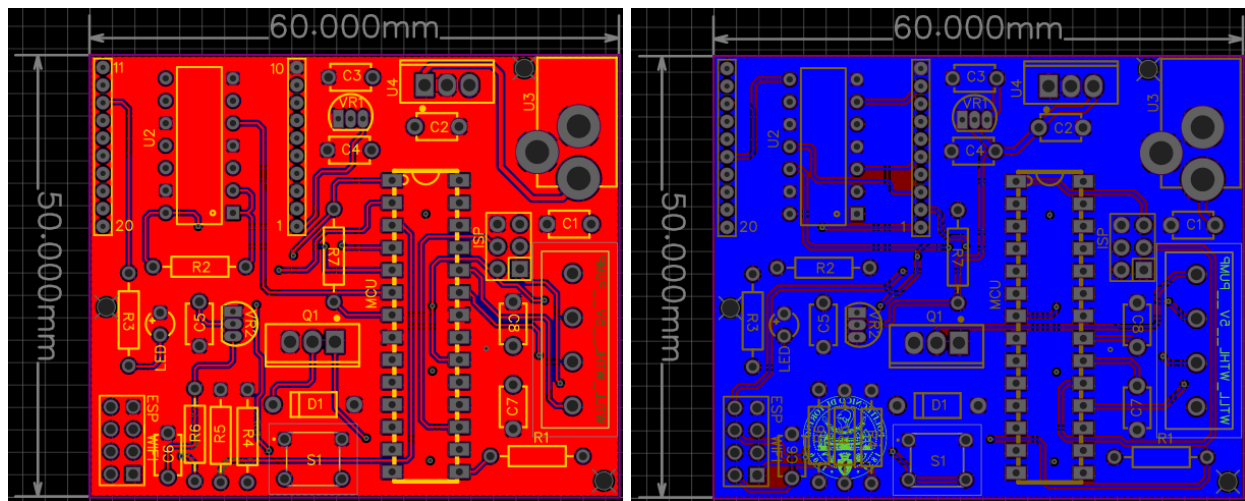

Figure 3.17:   General flow operations of master node

TOP   **BOTTOM**

Figure 3.18:   Board layout of master node PCB
(made in EasyEDA online PCB Layout Software)
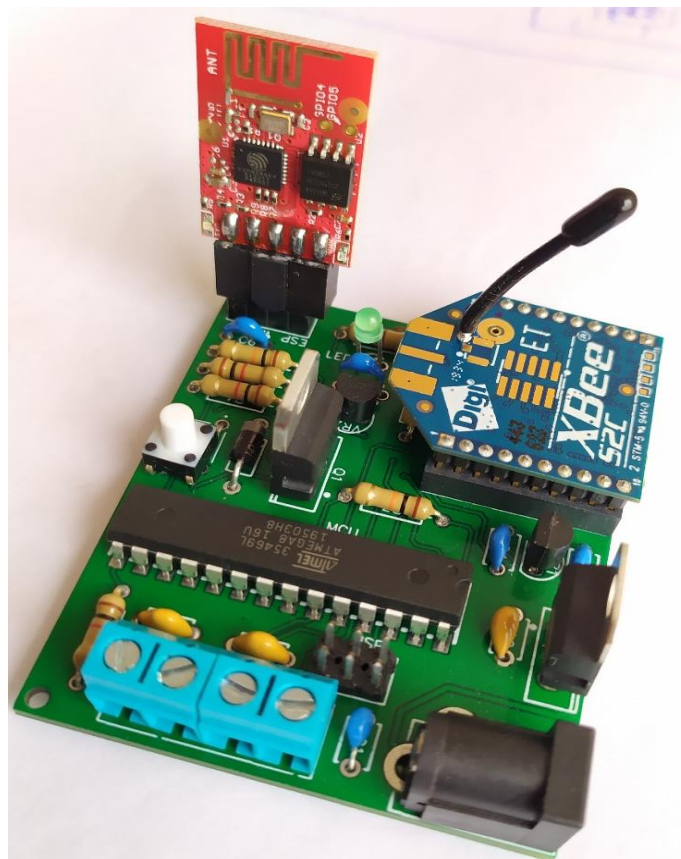

Figure 3.19:   Master node: printed circuit board and mounted
components

3.8.2 End - device (Slave node)

The main functions of end – device are follows:

- Performing the specific measurements (Temperature, soil moisture, rain presence and battery status) by sensors
- Transmitting the collected data to coordinator
- If the coordinator does not send acknowledgement back to the end – device, retransmitting the data again
- Automatically controlling the solenoid actuator according the soil moisture level
- Automatically controlling the battery charging through solar panel

The necessary parameters that need to be controlled frequently are battery charging status and soil moisture level. Because, if the battery is left at charging state during longer time, the overcharging damages it. Besides that, if soil moisture is left at lower level during a longer time of period, the drought damages the irrigating plant. Therefore, those two parameters should be frequently measured and control actions must be performed. In this project, the battery charge status and soil moisture levels are measured in every 8 minutes. During this 8 minutes, the microcontroller puts itself in sleep mode (power down) with switched off most of the its internal peripherals except the watchdog timer and consumes average $10\mu A$ current.   If the battery state is full the microcontroller terminates charging process, if not full, microcontroller starts (at the beginning) or continues the charging operation.
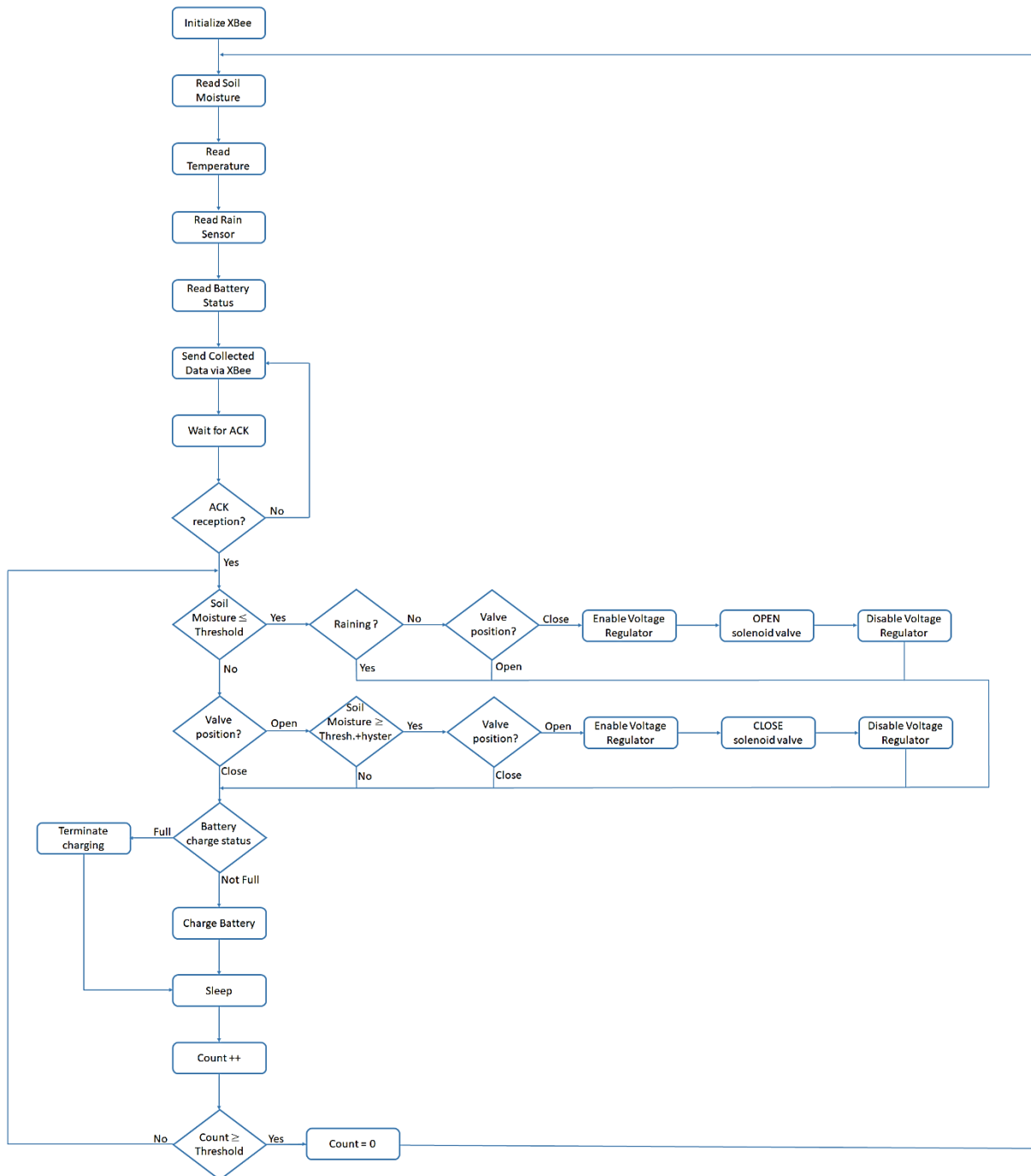
Figure 3.20:   The program flow of the slave node

The soil moisture level is also measured as frequent as the battery status. The solenoid actuator is opened when the moisture level decreases from the threshold level and is closed when the moisture increases up to the threshold plus some hysteresis. The actual values for threshold and hysteresis can be set

according to the sort of the irrigating plant, soil composition and the distance between plant root and water dripping point. Furthermore, the microcontroller does not open the solenoid valve during rainy weather. Figure 3.20 illustrates the operation flow of the slave node.

The end – device measures and sends temperature, soil moisture level, rain presence and battery status parameters to coordinator in every one hour.

The following figures show the end – device board layout of PCB, designed in EasyEDA online PCB Layout Software and the picture of the implemented PCB, respectively.
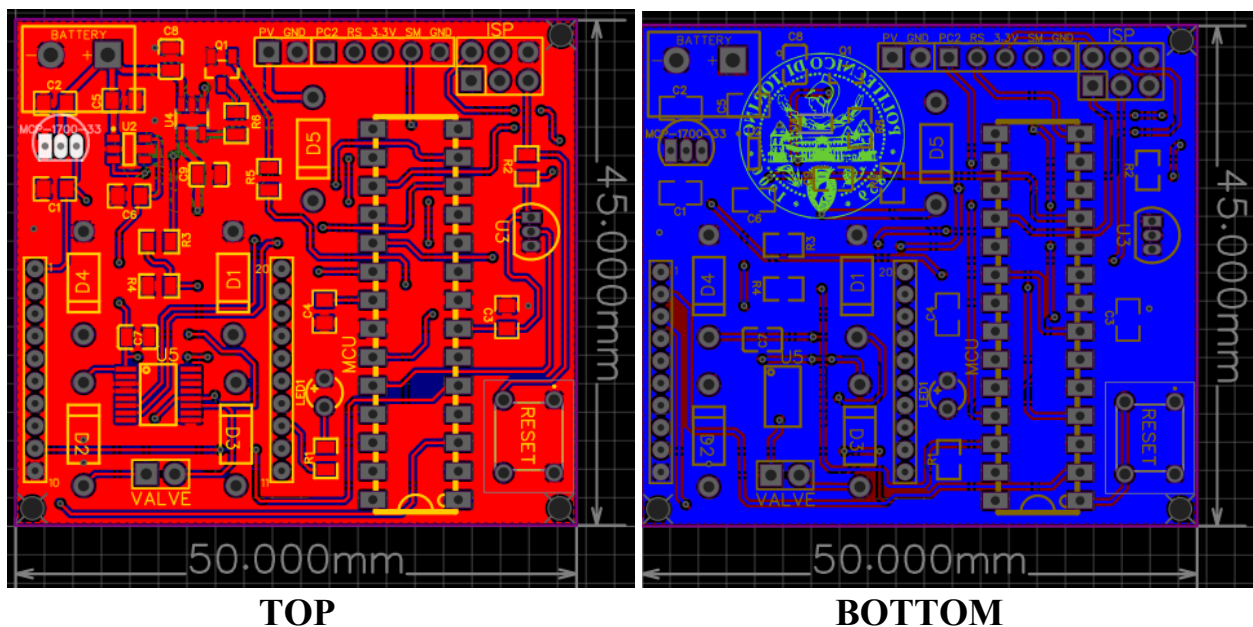

TOP   **BOTTOM**

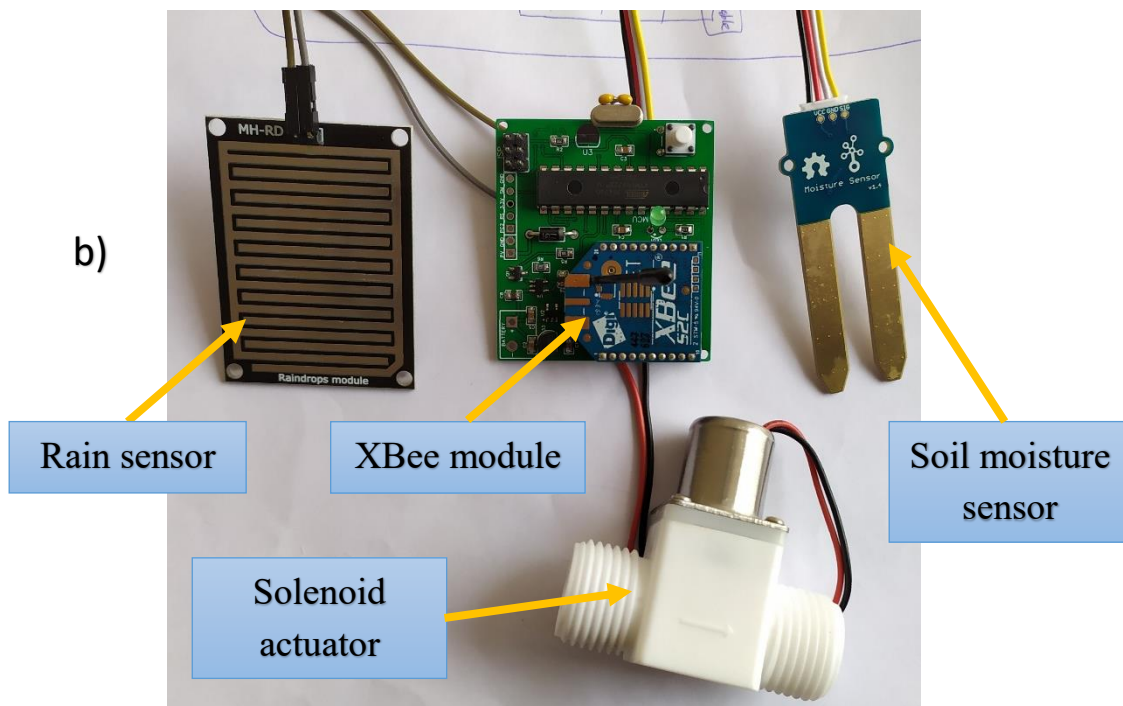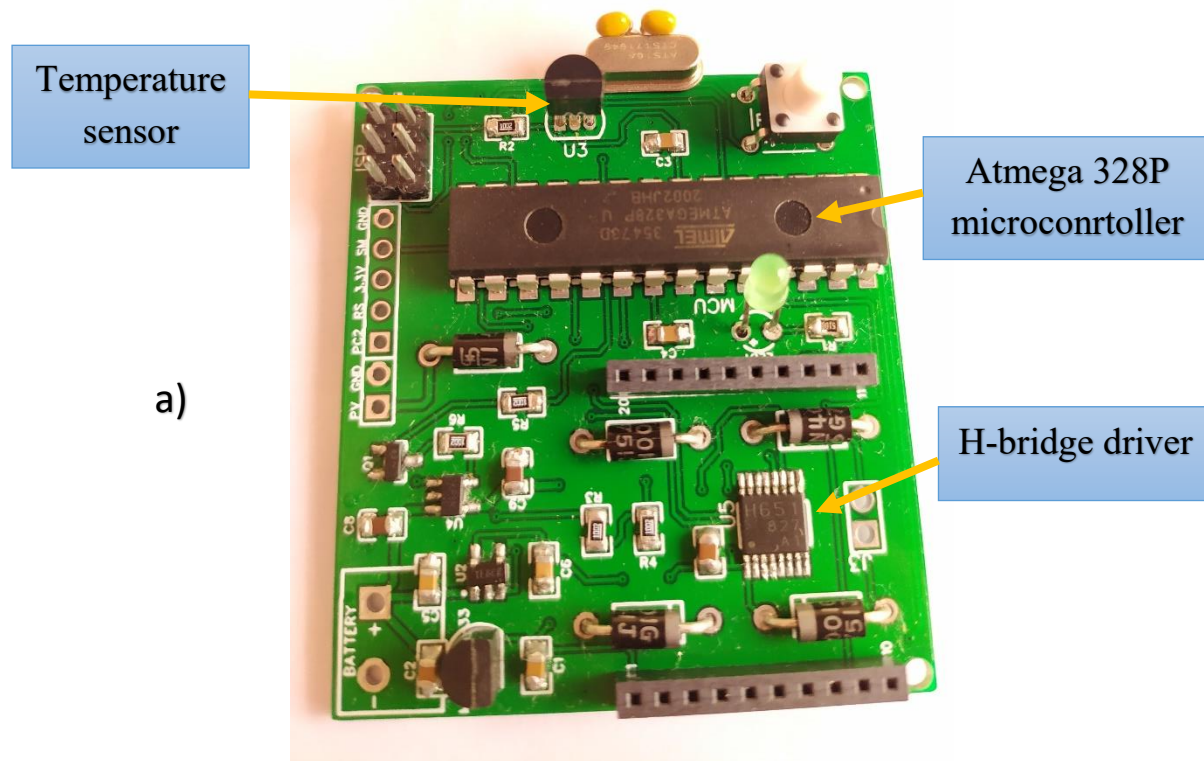Figure 3.21:   Board layout of end – device PCB

Figure 3.22:   Slave node: printed circuit board (a) and
                 mounted components (b)

3.9   Battery characteristics

The end device of designing WSAN employs one Lithium – ion rechargeable battery. In order to estimate the total energy capacity, typical AA – size Li-ion battery model LIR14500 is taken as a case study. One this kind of Li-ion battery has a nominal voltage of 3.7V and nominal capacity of 800 mAh. The voltage regulator outputs a fixed value of 3.3V and its minimum input value is 2.3V. However, end of discharge voltage of the battery is 2.8V (Figure 3.23).
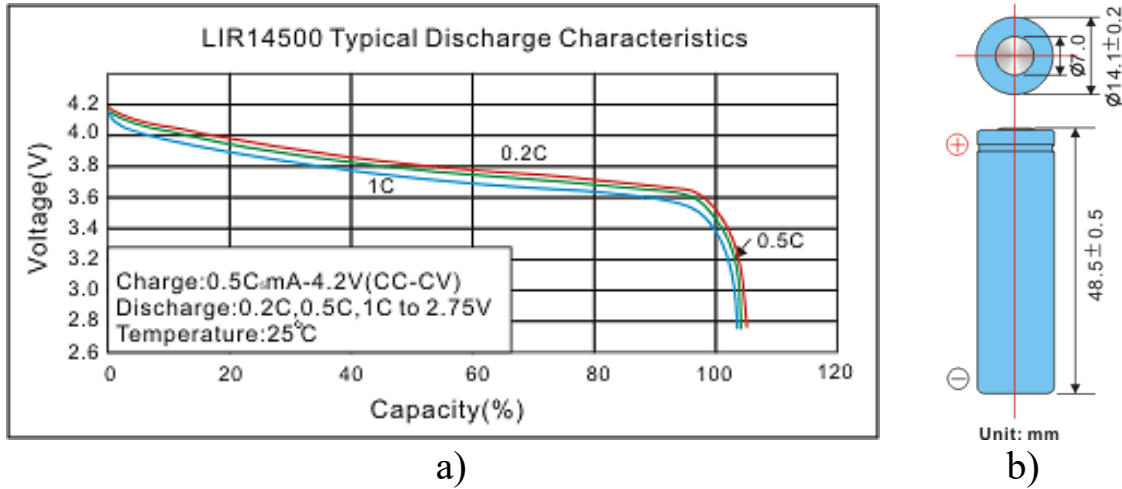
Figure 3.23:   a) discharge rate characteristics of a Li-ion battery
b) battery dimensions [38]

As shown from the figure, lower the current consumption causes higher the usage of battery capacity. In order to calculate the initial stored energy, the following rough calculation can be performed:

$$E_{init} = V * I * t = 3.7V * 800mA * 3600sec$$

$$E_{init} = 10656\, Joules$$

As the current consumption rate of end – device is less than 0.2C, referring to the Figure 3.23 we can assume that the end – device can consume 100% of the total stored energy in the battery.

3.10 Estimated energy consumption and battery life

Taking into account all the design considerations, the life-time of a battery can be estimated and checked whether the requirement is satisfied or not.

A single state change of the latching solenoid valve consumes the energy that is calculated as

$$E_{state\_change} = \frac{V^2}{R_{coil}} * T_{pulse} = \frac{(3.3V)^2}{9\Omega} * 30ms = 36.3 \text{ mJ}$$

As it is assumed that the solenoid valve activates 4 times per day, and the 60% of efficiency in power conversion, the total energy consumption for controlling the solenoid valve is

$$E_{daily}^{solenoid\_actuator} = 10 * E_{state_{change}} * \frac{100}{60} = 0.605 \text{ Joules}$$

In order to calculate the total energy consumption for all processing and radio operations of one end-device, each type of operation and its current consumption should be considered.

Following table shows the maximum energy consumption of XBee module during one cycle of data transmission from end-device to coordinator. This one cycle occurs in every hour and consumes $18.31 * 10^{-3}$ Joules from battery. Considering this cycle happens 24 times in a day, the total energy consumption of XBee module's active communication is:

$$E_{daily}^{XBee} = 24 * 18.31 * 10^{-3} \approx 0.44 \text{ Joules}$$

Action	Duration (max)	Average current	Energy (Joules)
Device is in sleep	≈1 hour	$1 \mu A$	$11.88 * 10^{-3}$
Transition to active mode	10 ms	$50 \mu A$	$1.7 * 10^{-6}$
Data transmission and re-transmissions	50 ms (max)	33 mA	$5.5 * 10^{-3}$
Waiting and receiving acknowledgement	10 ms (max)	28 mA	$0.93 * 10^{-3}$
Device goes back to sleep			
Total energy for one hour activities:			$18.31 * 10^{-3}$

Table 3.5: XBee energy consumption of single cycle active communication

In one hour, MCU operation time is maximum $T^{MCU}_{hourly\_operation} \approx 78.5$ ms (1 ms for reading sensors, 70 ms for XBee active communication time, 1ms for 8-minute cyclic checking of soil moisture level and battery charge status) and almost $T^{MCU}_{hourly\_sleep} \approx 3600$ sec sleeping time. Furthermore, as required in the thesis objectives section above, in one day maximum 10 times actuation of solenoid valve takes $T^{solenoid}_{daily} = 10*30\text{ms} = 300$ ms. Thus, daily operation time of MCU is

$$T^{MCU}_{daily\_operation} = 24 * T^{MCU}_{hourly\_operation} + T^{solenoid}_{daily}$$

$$T^{MCU}_{daily\_operation} = 24 * 78.5ms + 300ms = 2.184 \; sec$$

The daily maximum energy consumption of microcontroller in active mode is

$$E^{MCU}_{daily\_active} = 3.3V * 10mA * 2.184s \approx 72.1 * 10^{-3} Joules$$

The daily maximum energy consumption of microcontroller in sleep mode is

$$E_{daily\_sleep}^{MCU} = 3.3V * 44\mu A * 24 * 3600sec = 12.55\ Joules$$

The total daily energy consumption of MCU is

$$E_{daily}^{MCU} \approx 12.62\ Joules$$

Another energy consumption calculation is for voltage regulators. The voltage regulator MCP1700 has quiescent current 1.6 μA and operates 24 hours per day. Another voltage regulator AP7366 has quiescent current 60 μA and operates only when the solenoid actuates (max 4 times in a day) for 30ms.

The total daily energy consumption of voltage regulators is

$$E_{daily}^{VR} = 3.7V * 1.6\ \mu A * 24\ hours + 3.3V * 60\ \mu A * 4 * 30ms$$

$$E_{daily}^{VR} \approx 512.5 * 10^{-3} Joules$$

All the sensors and H-bridge driver ICs consume less than 1 Joule of energy per day. Because, they are powered up when MCU should measure the parameters.

Finally, the total daily energy consumption of end-device is calculated as

$$E_{daily\_total} = E_{daily}^{solenoid\_actuator} + E_{daily}^{XBee} + E_{daily}^{MCU} + E_{daily}^{VR} + 1$$

$$E_{daily\_total} = 14.5\ Joules$$

As a result, the 10656 Joules initial available energy in the battery should last for 734 days, which means more than 2 years. However, there are some factors, for example temperature and self-discharging, which effect the overall battery life – time. The colder temperature causes the energy loss of battery. Therefore, there is a battery charging section on the end-device PCB, and the charging can at least compensate the discharging caused by temperature fluctuations and self-discharging phenomenon or increase the battery lifetime. So, the requirement is satisfied.

Chapter 4

Conclusion

The establishment of cost effective wireless sensor and actuator network for application requiring minimum 100 – meter – range communication has been studied in this thesis. Specifically, implementation of the wireless control drip irrigation systems for the urban gardens has been the main objective of the project. In the first chapter, numerous studies related to the use of network technologies in the field of gardening and agriculture have been reviewed. In the following chapter, as the project requires to design and implement wireless sensor and actuator network (WSAN), the most widespread existing WSAN technologies have been thoroughly studied and compared. The key concepts of wireless communication, such as modulation methods or link budget analysis have been reviewed in order to clarify the advantages and drawbacks of a particular WSAN standard. Besides that, long range and short range wireless network technologies have been analyzed. Despite the LoRa and BLE being low cost and widely used technologies, higher power consumption of LoRa and shorter communication range of BLE are the main reasons to be unsuitable for the designing project. Consequently, ZigBee wireless network standard has been chosen for this thesis project, taking its availability, flexibility and other characteristics into account.

Hardware boards integrated the XBee ZigBee standard modules. As the actuator of designing WSAN, latching solenoid valves have been chosen due to its very suitable characteristics for drip irrigation method of micro-irrigation.

In future work, a graphical user interface (GUI) in different forms, such as Android application or web-page form can be developed in order to display the data collected inside the coordinator though the Wi-Fi module integrated the hardware of coordinator.

Another future work can be designing compact enclosures/boxes with good vision in order to house the implemented hardwares. Designing suitable enclosure effects the

In general, this thesis work has demonstrated the feasibility of implementing low-power, cost effective and compact size WSAN which may have great impact for the automation of urban garden irrigation systems.

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