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# Self-Configurable WSN using Wireless-Sensing

# 371-20-06

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# Preface

## About us

Mr. Efi Dvir and Mr. Oren Zaharia, senior students of the Communication Systems Engineering program in the Ben-Gurion Univeristy of The Negev, Israel. Intend to implement a challenging final project.

## About this report

This is our first report. Report for the final project of Communications Systems Engineering program. Throughout this document, references to our final project. Unless the context makes it clear that a reference is to an not our implementation. This report has been made using LaTeX.

## Intended audience

The report is written for the academic community that want to review and criticize our work or to be inspired or implement and learn our work. The project in a range of final projects implementations from simple ideas implementations to complex ideas implementations. The report assumed that the reader have some experience and knowledge in physics, wireless sensors networks, radio frequency, electrical wave propagation and wireless communications. The report does not assume experience of radar techniques, our tools or any concrete knowledge in our implementation.

# Table of Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

## 1.1 Background

Smart environment is a relatively new concept, emerging in the early 1990s, where urban residents are interacting on a constant basis with informative objects, devices, sensors and actuators to seamlessly better their lives. These collect information and process it in order to provide intelligent insights to the end user and assist him in his daily routine. We treat a smart environment as an intelligent agent that perceives the state of the resident and the physical surroundings using sensors and acts on the environment using controllers in such a way that the specified performance measure is optimized [CD04]. Today, the number of sensors that monitor our environment is in persistent incline. With the entry of the Internet of Things (IoT) to the common household and workplaces it is becoming more and more demanding for the user administrator to manage the rising number of sensors and actuators under his responsibility. The total installed base of IoT connected devices is projected to amount to 75.44 billion worldwide by 2025, a fivefold increase in ten years. The IoT, enabled by the already ubiquitous Internet technology, is the next major step in delivering Internet's promise of making the world a connected place [Dep16].

## 1.2 Motivation

With each new sensor added to the sensor network there is a need to configure its preferences and functions in order to comply to the network's rules and order. Whereas a new sensor placed in its place usually needs to be manually configured with the information of its location and peruse. For example, when placing a sensor in the kitchen, the sensor needs to be manually configured as the kitchen sensor in the user's system. If this sensor has several abilities, each with its own data feed to the information system, it may be bothersome and tedious to deploy many of these data gathering components of the network without some sort of automation. While exists some algorithms to organize the structure of the network's traffic flow, there is a clear lack of methods to relief the end user of the task of configuring each sensor in its network manually. With our knowledge and passion for wireless communication, the thought of trying to engage the wireless capabilities, commonly found in many sensors, in order to assist in the configuration tasks of the user came to mind. By giving the sensor the ability to recognize and analyze its surroundings, a large amount of information could be gathered, organized and used in order to help reach an assumption on what configuration profile may be best suited for a sensor. Thus, helping the user, or even relieving him entirely of the task of sensor configuration.

## 1.3 Goals

**The Primary goal** of our project is to gather new side information about the structure and composition of the device's environment using the propagation and reflection properties of wireless signals already in use in basic wireless devices. This information would be useful to assist in the classification of the room, the operations intended for the sensor and general informative data that would better with the task of configuring the device's function as part of the whole information network.

**The Secondary goal** of our project is to use the gathered information to deduct insights regarding the composition of the device's environment. By using machine learning tools and algorithms we would be able to classify the data that in turn will lead to the selection of suitable configuration profile to set to the device itself. Thus, the gathered information will be used to configure the device in the user interface.

## 1.4 Techniques

There are several techniques in our disposal to obtain our primary goal:

**Radio Frequency Imaging** Using the transmission of wireless signals via MIMO antenna array in order to compose a 2D or 3D picture of the surroundings form the reflecting signals. By applying image recognition algorithms on the generated image, we would obtain environmental data to feed to the classifier.

**Radar** A detection system that uses radio waves to determine the range, angle, or velocity of objects. The range and angle of the device in relation to discovered objects in the vicinity would generate data. Each object discovered would carry a RCS that will be used as environmental data and feed to the classifier.

**Indoor Localization** Using data from the communications protocols used by the device (RSSI for example), we would perform location triangulation survey in relation to known sources (WiFi routers for example). This location estimation would be feed to the classifier to classify in which room the device is located.

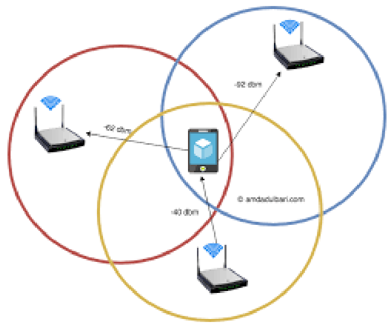

Figure 1.4.1: RSSI triangulation example

**Radiation Holography** Wireless data transmission systems such as WiFi or Bluetooth emit coherent light – electromagnetic waves with precisely known amplitude and phase. Propagating in space, this radiation forms a hologram – a two-dimensional wave-front encoding a three-dimensional view of all objects traversed by the light beam [HR17]. Holographic data would be feed to the classifier to classify what are the objects in the room along to the room structure and size.

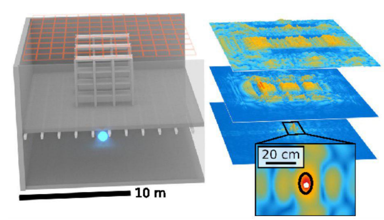


Figure 1.4.2: Holograph example

**Power Delay Profile Decomposition** The PDP gives the intensity of a signal received through a multipath channel as a function of time delay. Each PDP is unique and represents the channel time response. By decomposing individual signal paths and using statistical analysis we would be able to generate data to feed to a learning machine.

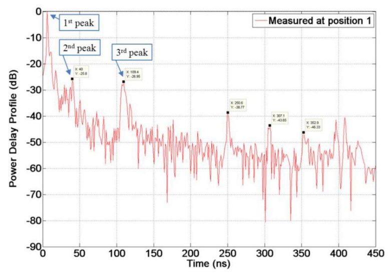


Figure 1.4.3: PDP example

There are several techniques in our disposal to obtain our secondary goal:

**Auto Encoder** an auto-encoder is a type of artificial neural network used to learn efficient data coding in an unsupervised manner [Wik19b] By inputting general sampled signal data, we would obtain an output of data coding that in turn can be inputted into a classifier.

**Machine learning** By using algorithms and statistical models that computer systems use to perform a specific task without using explicit instructions and by relying on patterns and inference instead, we would be able to infer properties that can assist in classifying the rooms and corresponding sensor configurations to suit it.

**Neural network** - artificial neural networks may be used for predictive modeling, adaptive control and applications where they can be trained via a dataset. Self-learning resulting from experience can occur within networks, which can derive conclusions from a complex and seemingly unrelated set of information [Wik19e]. By feeding the captured signals and information as a data-set to a pre-trained neural network we would derive conclusions regarding the device's environment.

# Chapter 2

# The Project

## 2.1 Theory

### 2.1.1 Concepts

In wireless radio communication, emitted signals experience a physical phenomenon known as multipath propagation. A transmitted signal reaches the receiver after traveling by two or more paths. Walls and objects can reflect and scatter arriving signals as they cause changes in angle and time along the paths of the signal.

**Mathematical Model [Wik19d]** The mathematical model of the multi-path can be presented using the method of the impulse response used for studying linear systems.

Suppose you want to transmit a signal, ideal Dirac pulse of electromagnetic power at time 0, i.e.

$$x(t) = \delta(t) \tag{2.1.1}$$

At the receiver, due to the presence of the multiple electromagnetic paths, more than one pulse will be received, and each one of them will arrive at different times. In fact, since the electromagnetic signals travel at the speed of light, and since every path has a geometrical length possibly different from that of the other ones, there are different air travelling times (consider that, in free space, the light takes $3\mu s$ to cross a $1km$ span). Thus, the received signal will be expressed by

$$y(t) = h(t) = \sum_{n-1}^{N-1} \rho_n e^{j\phi_n} \delta(t - \tau_n) \tag{2.1.2}$$

where $N$ is the number of received impulses (equivalent to the number of electromagnetic paths, and possibly very large), $\tau_n$ is the time delay of the generic $n^{th}$ impulse, and $\rho_n e^{j\phi_n}$ represent the complex amplitude (i.e., magnitude and phase) of the generic received pulse. As a consequence, $y(t)$ also represents the impulse response function $h(t)$ of the equivalent multi-path model.

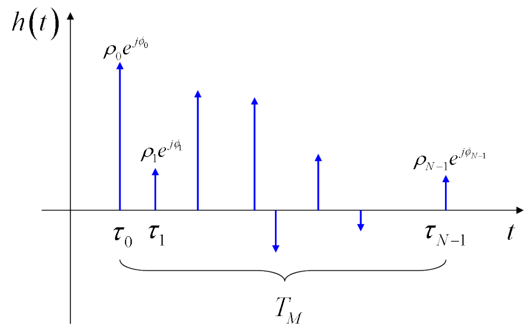


Figure 2.1.1: Multipath impulse response

The multi-path phenomena is always present in wireless communication, especially in indoor environments. It has been a long time that we consider multi-paths as interferences, noise, or simply nuisance. Profiles of multi-paths changes from location to location, thus, multi-path channel profile works as a unique and location-specific signature. Thus, instead of being considered as a nuisance, one can design various types of analytics based on the uniqueness of the multi-path channel state information. By fully exploiting the rich multi-path information, technology can decipher the propagation environment, revealing information that is usually disregarded. Such technology approach can enable many cutting-edge IoT applications.

The multi-path phenomena can be further exploited by using multiple-input and multiple-output (MIMO) in the transmitting as well as in the receiving device.

In MIMO systems, a transmitter sends multiple streams by multiple transmit antennas. The transmit streams go through a matrix channel which consists of all $N_r$ paths between the $N_t$ transmit antennas at the transmitter and $N_r$ receive antennas at the receiver. Then, the receiver gets the received signal vectors by the multiple receive antennas and decodes the received signal vectors into the original information. A narrow-band flat fading MIMO system is modelled as

$$y = Hx + n \tag{2.1.3}$$

where $y$ and $x$ are the receive and transmit vectors, respectively, and $H$ and $n$ are the channel matrix and the noise vector, respectively.[Wik19a]

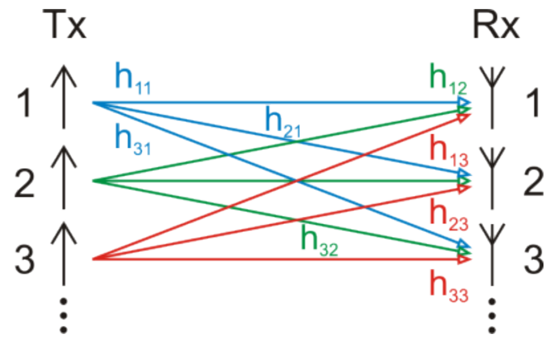


Figure 2.1.2: MIMO channel model

Each transmitting antenna is received differently in each receiving antenna, thus, multiplying the amount of captured multi-path impulse responses. This expansion can further achieve unique spatial properties such as depth direction and other 3D information.

### 2.1.2 Techniques Survey

**Radio Frequency Imaging** is not a new technology, yet it has has seen little commercial success due to the cost and power consumption of the large number of antennas and radio transceivers required to build such a system. Huang, Nandakumar and Gollakota [HNG14] describe the feasibility and limits of WiFi imaging by leveraging multi-path propagation. Their work introduce design and implementation which was able to identify objects inside a room (like a couch). Scott's thesis [Sco17] introduces 3D microwave imaging for indoor environments which involves the use of antenna arrays, operating at microwave and millimeter-wave frequencies, for capturing images of real-world objects. His work focuses on using planar antenna arrays, operating between 17 and 26 GHz, to capture three-dimensional images of people and other objects inside a room. Scott suggests 3D microwave imaging algorithms for both dense and sparse antenna arrays as well as other algorithms such as colocated range migration algorithm RMA and a MIMO range migration algorithm which assist in the the evaluation of the 3D space. Scott also suggests a design of antennas for microwave imaging and uses the Vivaldi tapered slot antenna in his implementations.

We intend to apply variations on Scott's work in order to comply with our hardware limitation and aspiration to use only popular protocols such as 2.4GHz WiFi which is much lower and narrower than Scott's implementation. Yet, we need to obtain lower resolution than Scott in order to apply room analysis processing on the data acquired. By trying to combine Huang, Nandakumar and Gollakota's work with Scott's we would be able to achieve the collection of the information that we strive to obtain in order to be able to apply the inference of the surrounding environment.

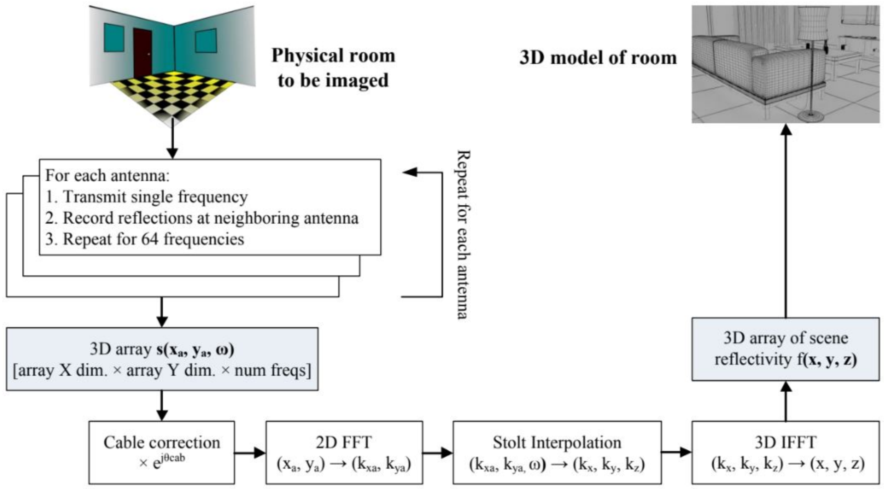


Figure 2.1.3: Block diagram for the colocated RMA

**Indoor Localization** is a network of devices used to locate people or objects where GPS and other satellite technologies lack precision or fail entirely.Sen, Radunovic, Choudhury and Minka [Sen+12] explore the viability of precise indoor localization using physical layer information in WiFi systems.The algorithm they suggest demonstrate localization accuracies in the granularity of 1m x 1m boxes, called spots. They show through experiments that PHY layer channel information from existing WiFi deployments can be an indicator of location. By synthesising phase and time Lags and modeling the channel response they are able to apply clustering and classification algorithms which results in spot localization.

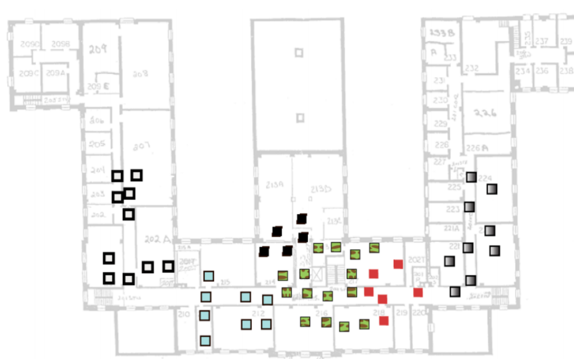

Figure 2.1.4: Engineering building floor plan. Different sets of spots shown in different colors

Huang, Zheng, Xiao and Peng [Hua+15] suggest localization based on the RSSI ranging Scope. In a RSSI based ranging algorithm, a node applies RSSI measurements to estimate its distances from the beacons, by using a known signal propagation model. Such location information is only relative to the location of all connected APs in range. Thus, for exact localization there is a need to know where the APs are located. By combining RSSI localization and the PHY localization with other data obtained from other techniques we would be able to better analyze and infer information about the device's environment.

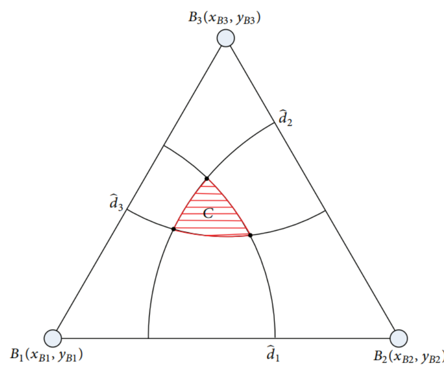


Figure 2.1.5: Region division based on the RSSI value

**Holography** is the science and practice of making holograms. Typically, a hologram is a photographic recording of a light field, rather than an image formed by a device without lens. [Wik19c]. In its pure form, holography requires the use of laser light for illuminating the subject and for viewing the finished hologram. Yet, Holl and Reinhard [HR16] demonstrate a scheme to record a hologram in a phase-coherent fashion and recover three-dimensional views of objects and emitters and feeding the resulting data into digital reconstruction algorithms.

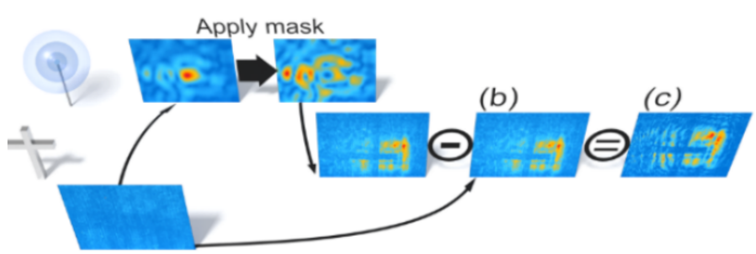


Figure 2.1.6: Reconstruction of objects using holography

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**Wireless Sensing** Embedded in wireless signals is information on an indoor environment which is captured during radio propagation, motivating the development of emerging wireless sensing technologies. Intelligent systems have become popular recently, in that with the help of learning they are capable of comprehending an object or even the world in the way humans do. For example, researchers have spent decades on computer vision or machine vision systems that achieve a high-level understanding over digital images and videos that is comparable or even better than the human visual system. Can WiFi perceive an indoor environment? According to Liu and Wang[LW19] the answer is yes. Applying statistical analysis on a data-set of captured signals is used for centimeter-accuracy indoor positioning and tracking, biometrics and vital signs estimation, motion and speed detection and more. We intend to apply similar methods on data-set of captured signals in order to create a sense of the device's environment. Many methods exist to apply indoor furniture and room recognition, Varvadoukas, Giannakidou, Gomez and Mavridis [Var+12] use internet-derived models and object context to achieve this. While there are plenty other methods to map and reconstruct the environment like 3D point clouds [SKR11] or set of 2D slices or just range measurements, they all relay on a data set the we would obtain from the wireless sensor.

## 2.2 Block Diagram

The following block diagram describes the inner goings of a sensor device in the stages taken to infer its surrounding environment using wireless-sensing.

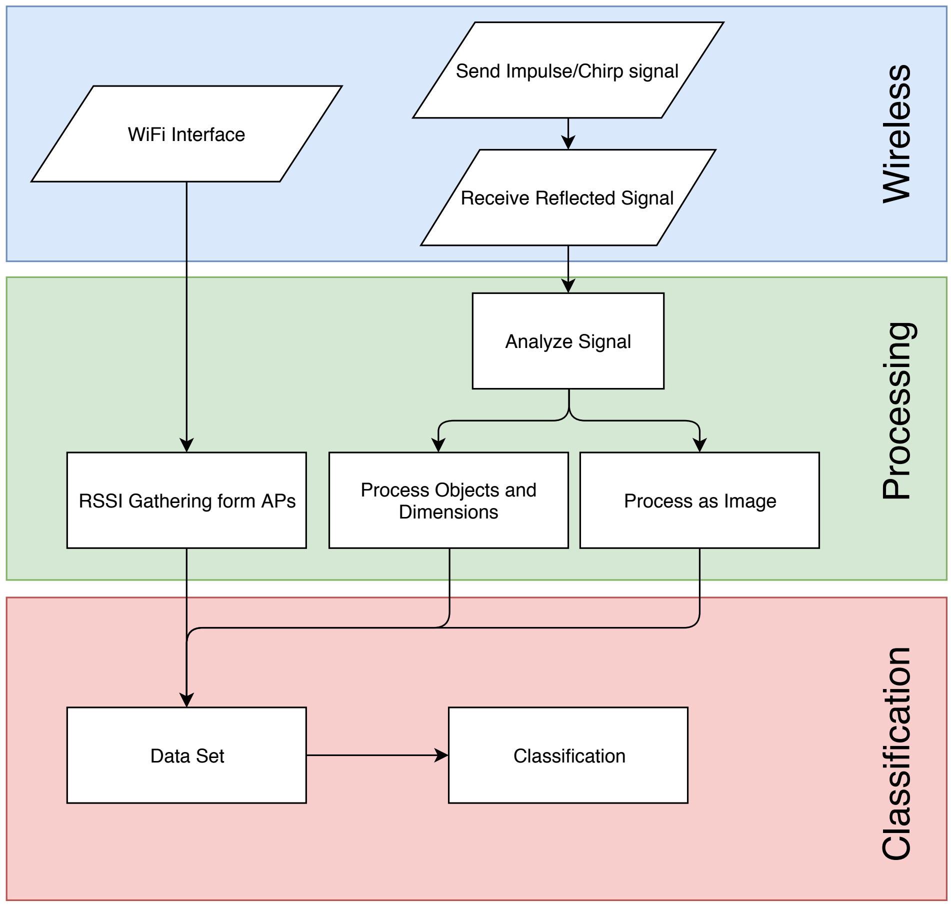



Figure 2.2.1: Block Diagram

The Block Diagram is divided in to three sections:

- **Wireless Section** - The transmission and and reception of Ad-Hoc and standardized WiFi protocol signals.
- **Processing Section** - analyzing the received signals and processing them to an image or objects and dimensions. Creating data set from WiFi interface.
- **Classification** - Classifying space according to the combined created data sets.

## 2.3 Practice

### 2.3.1 Hardware

**Software-Defined-Radio** In our project we are using SDR as our main hardware. Software-defined radio (SDR) is a radio communication system where components that have been traditionally implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer or embedded system [Wik19f][Mar03, p. xxxiii]. While the concept of SDR is not new, the rapidly evolving capabilities of digital electronics render practical many processes which were once only theoretically possible.

**LimeSDR** is a low cost, open source, apps-enabled (more on that later) software defined radio (SDR) platform that can be used to support just about any type of wireless communication standard.[Lim19]

**Ettus USRP B210** provides a fully integrated, single-board, Universal Software Radio Peripheral (USRP$^{TM}$) platform with continuous frequency coverage from 70 MHz – 6 GHz. Designed for low-cost experimentation, it combines the AD9361 RFIC direct-conversion transceiver providing up to 56MHz of real-time bandwidth, an open and reprogrammable Spartan6 FPGA, and fast SuperSpeed USB 3.0 connectivity with convenient bus-power. Full support for the USRP Hardware Driver$^{TM}$ (UHD) software allows you to immediately begin developing with GNU Radio, prototype your own GSM base station with OpenBTS, and seamless transition code from the USRP B210 to higher performance, industry-ready USRP platforms. An enclosure accessory kit is available to users of green PCB devices (revision 6 or later) to assemble a protective steel case.[The19]

**Raspberry Pi** a series of small single-board computers. The last release of Raspberry Pi was in June 2019 with a 1.5GHz 64-bit quad core ARM Cortex-A72 processor. The board includes two USB 3.0 ports and support 802.11ac WiFi.

### 2.3.2 Programs

**GNU Radio** GNU Radio is a free & open-source software development toolkit that provides signal processing blocks to implement software radios. It can be used with readily-available low-cost external RF hardware to create software-defined radios, or without hardware in a simulation-like environment. It is widely used in research, industry, academia, government, and hobbyist environments to support both wireless communications research and real-world radio systems [GNU19]. The toolkit that is provided under GNU Radio is written with C/C++ and Python. The libraries that are being used with are Boost for C++ and NumPy that used Boost and compiled under C/C++ to be used with Python.

**CST Studio** a high-performance 3D EM analysis software package for designing, analyzing and optimizing EM components and systems.

### 2.3.3 Work-space

**Overleaf** is an online LaTeX editor that allows real-time collaboration and online compiling of projects to PDF format. Overleaf is a freely-hosted and allows:

- Track changes
- 2 collaborators per project
- Spell check

**Github** is a free cloud-based version software development version control using Git.

**Slack** is a cloud-based that provides instant messaging platform. Slack offers features that goods for incollaboration projects.

**TeamGantt** is a cloud-based gantt chart software can help plan your projects.

**JetBrains** CLion and PyCharm that are and IDEs for C/C++ and Python respectively.

# Chapter 3

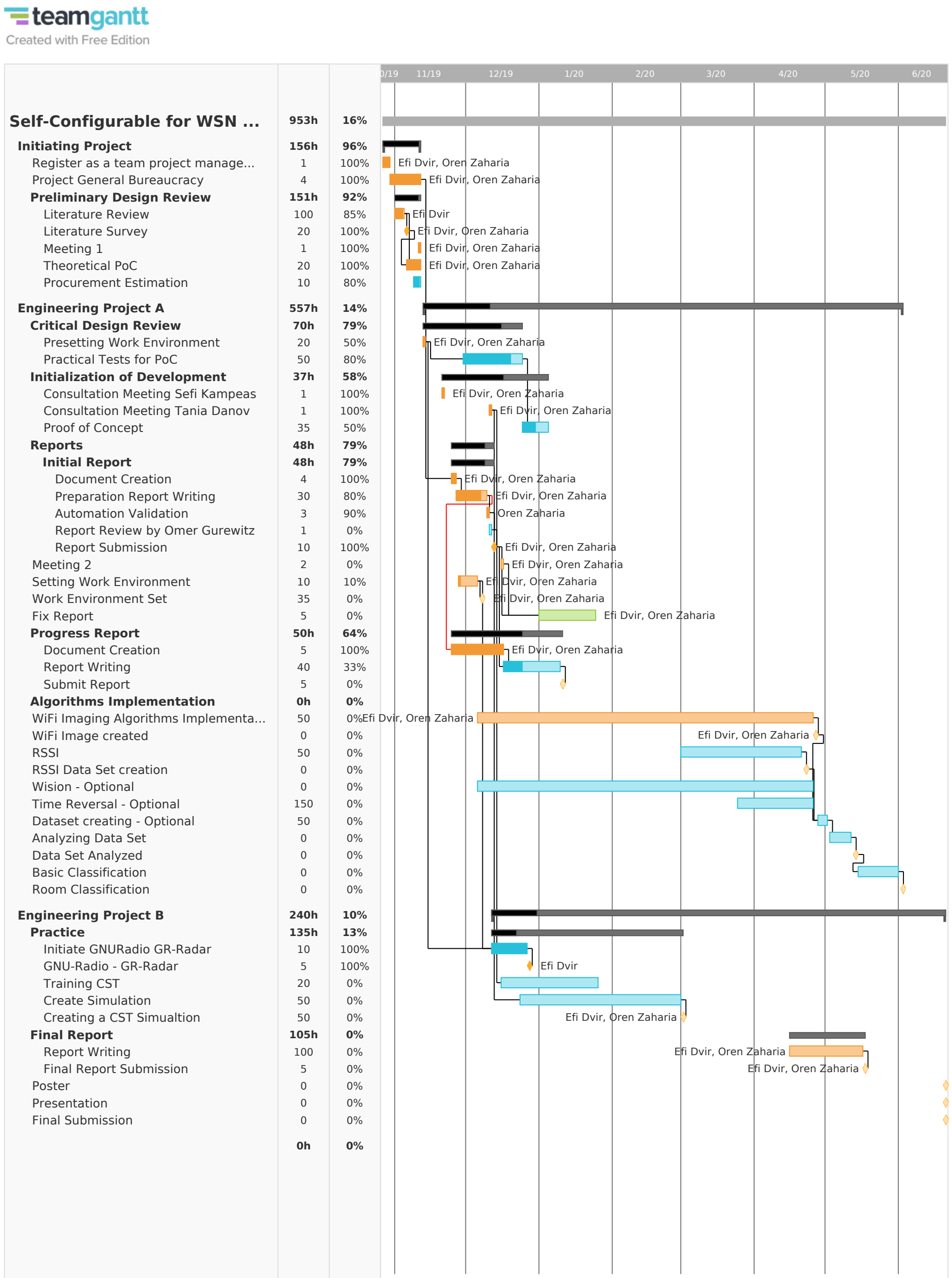
# Timeline & Progress

## 3.1 Milestones

| # | Name | Deadline | Hours | Measurable Outcome |
|---|---|---|---|---|
| 1 | Literature Survey | 05/11/2019 | 100 | Knowledge |
| 2 | Prepartion Report | 12/12/2019 | 48 | The Report itself |
| 3 | Toolkit Testing and Software Training | 12/12/2019 | 100 | Ability to Work |
| 4 | GNU-Radio Gr-Radar | 27/12/2019 | 15 | PoC |
| 5 | Progress Report | 24/01/2019 | 50 | The Report itself |
| 6 | Simulation Creation | 01/03/2019 | 100 | Simulation |
| 7 | RSSI Data Set Creation | 04/2020 | 100 | Raw Data Set |
| 8 | WiFi Image Creation | 04/2020 | 100 | Images |
| 9 | Optional Basic Classification | 05/2020 | 50+ | Inferences of Basic Environment |
| 10 | Optional Analysis of Data Sets | 05/2020 | 75+ | Inferences of Environment |
| 11 | Create Hardware Setup for Presentation | 05/2020 | 175+ | Hardware Setup |
| 12 | Poster | 06/2020 | 25 | A commercial poster |
| 13 | Presentation | 06/2020 | 80-100 | PPT and Videos |
| 14 | Final Submission | 08/2020 | 80-100 | Outstanding Project |

Table 3.1: Milestones and Products

## 3.2 Gantt


teamgantt
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0/19 11/19 12/19 1/20 2/20 3/20 4/20 5/20 6/20
Self-Configurable for WSN ... 953h 16%
Initiating Project 156h 96%
Register as a team project manage... 1 100%
Project General Bureaucracy 4 100%
Preliminary Design Review 151h 92%
Literature Review 100 85%
Literature Survey 20 100%
Meeting 1 1 100%
Theoretical PoC 20 100%
Procurement Estimation 10 80%
Engineering Project A 557h 14%
Critical Design Review 70h 79%
Presetting Work Environment 20 50%
Practical Tests for PoC 50 80%
Initialization of Development 37h 58%
Consultation Meeting Sefi Kampeas 1 100%
Consultation Meeting Tania Danov 1 100%
Proof of Concept 35 50%
Reports 48h 79%
Initial Report 48h 79%
Document Creation 4 100%
Preparation Report Writing 30 80%
Automation Validation 3 90%
Report Review by Omer Gurewitz 1 0%
Report Submission 10 100%
Meeting 2 2 0%
Setting Work Environment 10 10%
Work Environment Set 35 0%
Fix Report 5 0%
Progress Report 50h 64%
Document Creation 5 100%
Report Writing 40 33%
Submit Report 5 0%
Algorithms Implementation 0h 0%
WiFi Imaging Algorithms Implementa... 50 0%
WiFi Image created 0 0%
RSSI 50 0%
RSSI Data Set creation 0 0%
Wision - Optional 0 0%
Time Reversal - Optional 150 0%
Dataset creating - Optional 50 0%
Analyzing Data Set 0 0%
Data Set Analyzed 0 0%
Basic Classification 0 0%
Room Classification 0 0%
Engineering Project B 240h 10%
Practice 135h 13%
Initiate GNURadio GR-Radar 10 100%
GNU-Radio - GR-Radar 5 100%
Training CST 20 0%
Create Simulation 50 0%
Creating a CST Simualtion 50 0%
Final Report 105h 0%
Report Writing 100 0%
Final Report Submission 5 0%
Poster 0 0%
Presentation 0 0%
Final Submission 0 0%
0h 0%
Efi Dvir, Oren Zaharia
Efi Dvir
Oren Zaharia

# Chapter 4

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# Glossary

**802.11ac** IEEE 802.11ac is a wireless networking standard in the 802.11 set of protocols. 17

**AP** Access Point . 14

**BTS** Base transceiver station. 25

**EM** Electromagnetic. 18

**FPGA** Field-programmable gate array. 17

**Git** Distributed version control. 18

**GNU** An extensive collection of free computer software licensed with GPL. 17, 25

**GPL** The GNU General Public License. 25

**GPS** Global Positioning System. 13

**GSM** Global System for Mobile Communications known as 2nd generation of the cellular. 17, 25

**IoT** Internet of Things. 6, 11

**MIMO** Multiple Input Multiple Output. 4, 7, 11, 12

**OpenBTS** Open BTS is a software-based GSM. 17

**PCB** Printed circuit board. 17

**PDP** Power Delay Profile. 4, 8, 9

**PHY** Physical Layer. 13, 14

**RCS** Radar Cross Section. 7

**RFIC** Radio-frequency integrated circuit. 17

**RMA** Range Migration Algorithm. 4, 12, 13

**RSSI** Received Signal Strength Indication. 4, 8, 14

**SDR** Software Defined Radio. 17

**USB** Universal Serial Bus. 17

**USRP** Universal Software Radio Peripheral. 17

**WiFi** Wirless Fidelity is a family of wireless networking technologies. 8, 12, 13, 15–17