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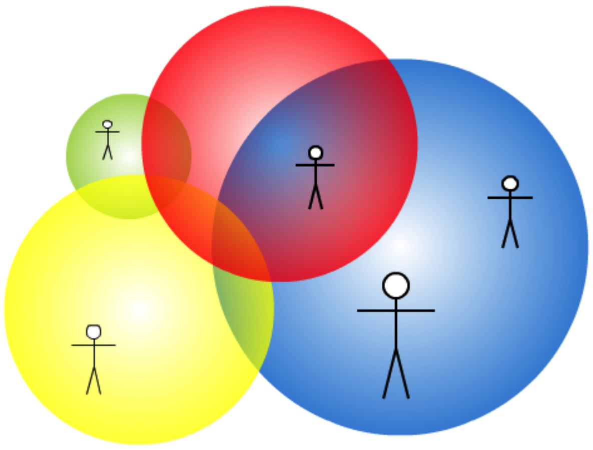

User Mobility in IEEE 802.11 Network Environments

by

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“Choose a job that you like, and you will never have to work a day in your life.”

- Confucius

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Abstract

Understanding the mobility of people within an environment without the aid of technology is almost impossible due to the fact that it is beyond our ability to remember all faces of people that appear within that environment and keeping our eyes on their movement. Even if we ask these people to report about their locations to a central coordinator every now and then, that would require the use of technology to convey these messages as well.

We develop a novel system to track the collective mobility of WiFi users within an environment and instead of a person reporting about his or her location, the WiFi gadget such as a smartphone that a person carries would inform us about his or her location and also enabling us to determine how long he or she is staying at a particular place without his or her knowledge. In this project, we would focus on collective results to understand a general mobility behaviour of people within one environment rather than focusing on an individual person. In addition, we demonstrate that our system could track the collective mobility of WiFi users by putting it to a real test, tracking the mobility behaviour of the Department Of Computing's students for 5 days.

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Abbreviations

AP	**A**ccess **P**oint
API	**A**pplication **P**rogramming **I**nterface
GPS	**G**lobal **P**ositioning **S**ystem
GUI	**G**raphic **U**ser **I**nterface
HDFS	**H**adoop **D**istributed **F**ile **S**ystem
IEEE	**I**nstitute of **E**lectrical and **E**lectronics **E**ngineers
IDL	**I**nterface **D**efinition **L**anguage
JFFS	**J**ournalling **F**lash **F**ile **S**ystem
MAC	**M**edium **A**ccess **C**ontrol
NIC	**N**etwork **I**nterface **C**ard
REST	**RE**presentational **S**tate **T**ransfer
RSSI	**R**eceived **S**ignal **S**trength **I**ndicator
SSID	**S**ervice **S**et **ID**entifier
WLAN	**W**ireless **L**ocal **A**rea **N**etwork

Chapter 1

Introduction

The internet today has evolved rapidly and it looks so different in various aspects when comparing to how it is like a decade ago. The speed of communication has significantly increased, advancing from 56 kbit/s Dial-up connection to the current high-speed broadband that can reach even more than 100 mbits/s. Another notable aspect of difference is the rapid improvement in wireless technology such as that defined by the *Institute of Electrical and Electronics Engineers (IEEE) 802.11* standard. Slowly, every single piece of device around us starts to support this standard and the name *WiFi* is given to any products that conform to the *IEEE 802.11* standards.

The initial IEEE 802.11 standard was released in 1997 and over the years, there are new protocols introduced as part of the standard. These include 802.11a, 802.11b, 802.11g, 802.11n and 802.11ac. As newer protocols are being introduced, so does the improvement in the data rate per stream that this wireless technology support. There are two main entities that are part of the IEEE 802.11 standard, namely the *client* and the *base station*. The latter can also be referred to as Access Point (AP).

Due to the higher data transfer throughput and robustness of WiFi technology, popularity of the use of WiFi has increased exponentially over the years as more and more technological gadgets are produced such as smartphones, tablets, portable gaming consoles and MP3 players.

- *"In Q2 2011, 70% of public Wi-Fi network traffic stemmed from laptops, while only 21% came from smartphones and 9% from tablets, JiWire finds. But one year changed everything. In Q2 2012, laptop traffic sunk to less than half, 48%, while smartphone traffic jumped to 35% and tablets to 17%."*
- *"Mobile devices dominated the airwaves in shopping malls and restaurants. 50% of Wi-Fi traffic in shopping malls stemmed from smartphones, 37% from laptops and 13% from tablets, JiWire finds. 72% of Wi-Fi traffic in restaurants came from smartphones, 20% from laptops and 8% from tablets, the study says."*

  The above statistics are based on 30,000 public Wi-Fi locations in North America and the findings was released by JiWire, a mobile audience media company. [28]

By infering from the facts above, we could see that the rise in the number of users utilising mobile devices to access WiFi network creates a new dimension of opportunities to exploit this trend especially when APs continue to be widely deployed to accommodate this rise in usage. The rise in the number of users carrying mobile WiFi devices around shopping malls and restaurants indicates that it would be really useful for business owners to learn about the behaviour of these users in their stores. With the large number of WiFi users, this is the right time to look for ways to harness the potential and functionalities of WiFi. Since it is also possible to identify devices that have network connectivity by finding out the globally unique network interface identifier called MAC address, this opens up a new prospect of localising WiFi-enabled devices. We could look for a mechanism to localise these users by investigating into how the whole IEEE 802.11 framework works. We could then associate the identification of such devices to the persons carrying them.

As we start to think about localisation, we may begin to relate the similarity to the functionalities of GPS, an outdoor navigation system using multiple satellites for localisation of a GPS-enabled device. Currently, outdoor localisation using GPS is quite robust. In contrast, indoor localisation is still a problem that needs to be addressed [1]. For this reason, coupled with the rise in the popularity of WiFi, it creates a huge motivation behind this project, in which we aim to understand how devices and network components under the umbrella of IEEE 802.11 standards interact and function so as to come up with a solution to detect the presence of users carrying WiFi devices. It would be more accurate to associate the presence of a user to the detection of a smaller mobile WiFi devices such as smartphones, in which users tend to carry with them everywhere, than a WiFi-enabled laptop.

Intuitively, we aim to detect the presence of users carrying WiFi terminals[2] without requiring them to perform any actions. Most of the readily available softwares that are related to sniffing network traffic usually requires that a terminal already belong to a network after authentication and association to the relevant AP in the network. What we want to have is a way to "quietly" detect the presence of a terminal, i.e., passive detection. This is because it would be extremely hard to persuade users in a public area to connect to an AP so that useful information about them could be obtained. In addition, we are interested in analysing the collective mobility behaviour of all users in

[1]It should be noted that WiFi network may also be deployed outdoor and not necessarily only indoor although they tend to be widely deployed indoor. Hence, we do not constraint the localisation of users using WiFi for indoor only.

[2]In this project, we consider 802.11 wireless network operating in the infrastructure mode, where a surface area would have at least one defined AP. WiFi terminals surrounding the AP would communicate with the AP and there is no direct terminal to terminal communications.

the environment we are monitoring rather than a specific user's behaviour. This creates a challenge to investigate into a way to achieve the aims we want above.

1.1 Objectives

In this project, we would focus on the mechanism to detect WiFi-enabled devices and use information such as Received Signal Strength Indicator(RSSI) (Section 2.1.2) to localise these devices, indirectly the users carrying them. We also aim to come up with an infrastructure design and protocols to facilitate the tracking and analysing of collective mobility of users in an environment that has WiFi APs deployed. This would allow us to yield useful statistics such as the time duration that most users spend at a particular area and the number of users staying at that area. This requires constant tracking of WiFi users within the environment, in which we have deployed the APs we have configured to carry out the job. In addition, we come up with the logic and algorithms to aggregate the data collectively, determining which AP out of all nearby APs a particular user is closer in proximity. We also aggregate the aggregated data[3] to derive other useful statistics. Lastly, we would provide an interactive web Graphic User Interface (GUI) that displays the aggregated data, showing appropriate graphs to aid the understanding of the collected data.

1.2 Contributions

Firstly, we make use of existing tools and libraries to implement a way to detect the presence of WiFi terminals from an AP. Since this requires access to the AP's Operating System (OS), it is not possible to work on the original OS shipped with the AP. In this project, we use readily available router in the market, which serves as an AP for detecting the presence of terminals. Since a router is an embedded device that usually runs on MIPS architecture, this means that we need to compile a program in a different manner using appropriate toolchain.

Secondly, we design and set up a robust infrastructure for collecting and aggregating data that scales easily even for large commercial deployment. This touches the topic of big data since there is always a continuous stream of data from all APs and overtime, the accumulated data could be very huge in size. All APs sends data about nearby WiFi terminals in a regular time interval to a central processing agent, which serves to fetch

[3]Data can be aggregated in many different ways to generate a different representation of the user behaviour in the network environment.

and interpret the data using a chosen serialisation scheme and insert it to the database for aggregation after that.

Thirdly, We devise the best possible approach to aggregate the collected information about WiFi terminals that are close to the APs that we deploy. A terminal could be detected by several APs simultaneously, hence, we need to come up with a way to work out which AP is closer to the terminal. Other statistical information could also be drawn from the information collected from all APs to derive an overall view of what is happening in the environment under monitored. In particular, we are interested in knowing the number of WiFi users[4] staying near each of the AP, the duration of time they stay and the number of users who return to a location near the AP that they have come across before.

Fourthly, we design a user-friendly GUI that could be used by business owners or administrators for displaying the aggregated results so as to make sense out of the numerical data. Histogram, piechart and a simple probability density distribution are drawn up to aid the understanding of statistical data. In order to accomplish the goal of querying data straight away in Javascript from HBase (Section 2.6.2), a database we choose for this project, we write code for a REST API wrapper and a Javascript Bytes Utility for HBase[5], which are currently not available for HBase. We release these utilities to the HBase community under Apache License Version 2.0. Majority of the Web GUI is extensively written in Javascript since this creates an "app-like" effect such that browser users do not need to refresh the page after selecting some options on the browser screen. This requires making many asynchronous calls and proper handling of the returned results.

Finally, we carry out a lab-wide experiment in the Department Of Computing Laboratory and Common room to test the effectiveness and accuracy of detecting the number of WiFi users in the vicinity and their behaviour in the tested environment.

1.3 Structure of Thesis

In this project, we propose various mechanisms to detect the presence of WiFi terminals and one of the best methods is implemented. Since there is a possibility that this project could be extended to study the mobility of users in a larger area or be used in a commercial roll-out that consists of many APs in various locations, we keep this in

[4]We may sometimes refer to WiFi users being a user who carries a WiFi terminal such as a smartphone or a tablet.

[5]The Byte Utility allows the conversion of data types from bytes array that are stored in HBase table to Integer, Long, Short and String data types directly in Javascript.

mind while designing our whole ecosystem. Other than just detecting the presence of terminals, we also define a message transfer protocols, in which data collected at each AP could be sent to a central server for processing. An appropriate database technology would be considered in conjunction with the way we need to aggregate the data collected from each AP. We choose the current most efficient way of aggregating big data, for large deployment of many APs, and also a database technology that can scale to petabytes in size.

In Chapter 2, we dive into the technical details that are relevant for understanding and implementing a working prototype for tracking user mobility. We examine and decide on an appropriate open source OS for APs that we would use in our prototype. We consider the functionalities, code libraries, stability and level of support for the OS before making our decision. We also discuss the current major chipset manufacturer for APs since we need to decide on one chipset for implementation. Different chipsets could be built based on different computer architecture, such as ARM or MIPS, hence there are different code libraries available. Thus, we can only focus on one chipset in this project. We can tap into the available open source libraries to our advantage. Furthermore, we also evaluate different database technology to select an appropriate one for our project.

We continue to discuss about related work in the field of our project in Chapter 3. A few different mechanisms are employed by different papers to track user mobility, with emphasis on different localisation techniques that aims to locate a WiFi user as accurately as possible. Although we do not focus on high accuracy of localising a user in this project, it would still be useful to understand these localisation algorithms so that we are aware of the different ways of solving the limitations that we observe in this project. Since we use only RSSI information to determine whether a WiFi terminal is closer to a particular AP or another, this leads to issue such as the "Ping Pong" effect[6], which is a phenomenon that we have observed after conducting the experiment in the laboratory.

Chapter 4 presents a simplistic view of the overall architecture of how we go about tracking WiFi terminals, managing the data and processing it, as well as storing the aggregated results for displaying on a GUI. Different server components are discussed to give an idea of how each component works together to achieve the aim of obtaining a statistical view of user mobility in general.

In Chapter 5, we explain the details behind our implementation, presenting different technical viewpoints and difficulties. We also give the rationale behind each of the

[6]"Ping Pong" effect usually happens when the received signal strength becomes unreliable at times leading to a WiFi terminal being associated with one AP at one time and to another at subsequent time although the terminal has not moved. This effect is most commonly observed when a terminal is located directly in between two APs.

decisions that we have make for selecting a suitable solution to solve each of the sub-problems, which are essential to build an overall working implementation for tracking collective mobility of users. The implementation has been designed to have the ability to scale easily and flexibly.

There are 3 main phases we need to focus on,

- Mechanism to detect the presence of terminals
- Aggregating data
- Generating graphs and displaying the results via a Web GUI

Chapter 6 details the evaluation process, in which we have conducted a variety of experiments to evaluate the performance of our system. We have also written some unit tests to verify the correctness of our algorithms. We give these details below:

1. We deployed 6 APs in the Department Of Computing (DOC) Laboratory and Common room to track the mobility behaviour of DOC students and staffs. Observations of the actual environment were make to evaluate the efficiency and accuracy of our system in tracking users in the environment where our APs were deployed.
2. We conducted a micro-benchmark experiment. This experiment involves a group of students, each carrying two WiFi terminals with them and they are supposed to stay at different intervals of distance from an AP so that we could determine how many of them we could still detect as they move together as a group away from the AP.
3. We process the raw data collected from the experiment in the laboratory and we take sample of the population of WiFi terminals to determine the frequency of probe request being sent out by the different brand of terminals. (Section 2.1.4) Examples of brand includes Samsung, Apple, LG, Research In Motion and others. It is essential to know this information to verify the accuracy of the mechanism that we have used in our implementation which we would elaborate in Chapter (5).
4. Aggregating the collected data requires understanding what the data means so as to verify that the logic in place for the aggregation is working as expected. This involves printing out the information at each step of the algorithm to check its correctness and some unit tests are written to verify that the aggregated results are the same as ground truth values. We define these ground truth values by means of using test suites that contain examples depicting different scenarios.

Finally, we conclude the thesis in Chapter 7 and discuss some of the possible future extensions for this project.

In Figure 1.1, it captures the whole idea of what we are going to do in this project.

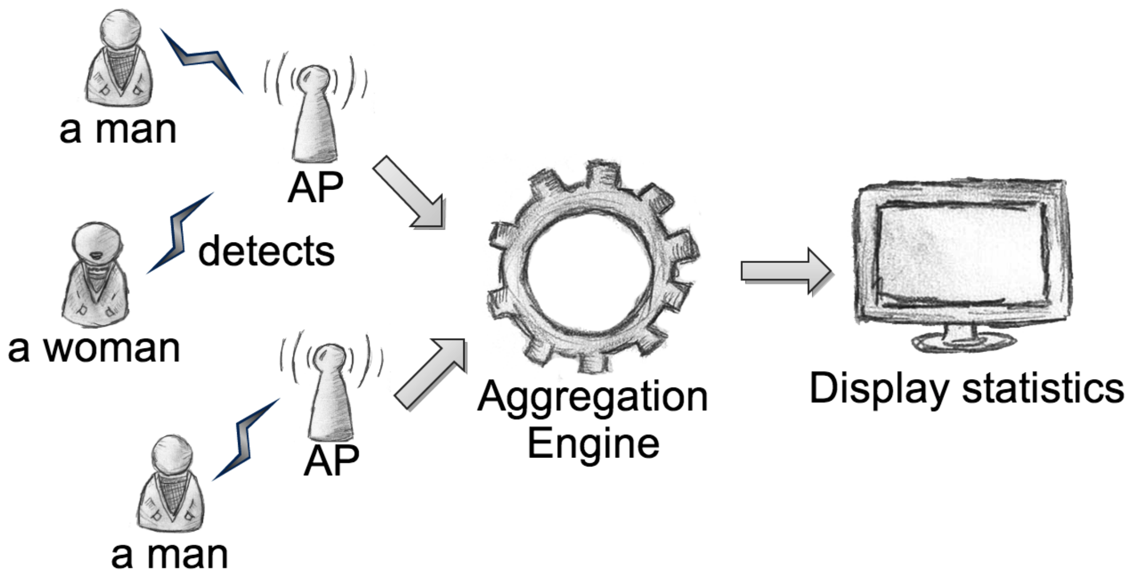


Figure 1.1: Illustrating the whole journey we are going to embark on. Images licensed under *Free for commercial use* from iconfinder.com

Chapter 2

Background

2.1 Understanding IEEE 802.11 standards

"Standards" is defined as a level of quality or attainment, or something used as a measure, norm, or model in comparative evaluations [29]. Base on this definition, we know the purpose of introducing standards is to ensure that different entities who are creating a product would adhere to the standards defined for that particular product. When it comes to products using an open technology, the products manufactured by different vendors would operate in a similar fashion and that everyone knows clearly what are the main functions and features of this type of product since it follows a standard.

Similarly, the IEEE 802.11 standards are defined so that products that are conformed to the standards are interoperable [6], even if they come from different vendors. This means that as long as a product is WiFi-certified, they would be able to operate normally in the IEEE 802.11 network environments without causing too much interference to other WiFi devices. The standards would enable each of us to have a clear understanding of how we can make use of WiFi in a new product or in the case of this project, we want to know the types of communication and interaction between an AP and a terminal. This would allow us to come up with a solution to identify terminals in a Wireless Local Area Network (WLAN)[1].

As part of the standards, there is a limit on the power output levels of radio frequency devices. Table 2.1 shows us the maximum power level allowed by the different regulatory domains. Such a limit is placed so that a wireless transmitter is not allowed to operate using a higher transmission power in order to increase the range of transmission. Since our project involves detecting the presence of WiFi terminals, too much interference in the environment would prevent us from accurately track the terminals. Hence, there is a need to consider the different types of environment the monitoring APs would be deployed. For example, the transmission range in an open space would normally be longer than that in an indoor environment, where there are many other wireless devices operating, which causes interference.

[1]From here on, we would refer the network environment that conforms to IEEE 802.11 standards, which provides network access via APs deployment in the environment, as WLAN.

Regulatory Domain	**Antenna Gain (dBi)**	**Maximum Power Level (mW)**
Americas (-A) (4 watts EIRP maximum)	2.2	100
EMEA (-E) (100 mW EIRP maximum)	2.2	50
Israel (-I) (100 mW EIRP maximum)	2.2	50
Japan (-J) (10 mW/MHz EIRP maximum)	2.2	30

Table 2.1: Maximum Power Levels Per Antenna Gain for IEEE 802.11b [7]

Another point to note is that since WiFi devices operate within the electromagnetic spectrum, there is bound to be contention for resources within the channel in which the devices operate (Section 2.1.1). The more the number of WiFi devices operating on a particular channel, the lower the data transmission throughput each device experiences. We will elaborate more on the topic of WiFi channels in the following section.

2.1.1 WiFi Channels

In this project, we would focus on the 14 channels that are operating within the 2.4 GHz Industrial, Scientific and Medical (ISM) band. We would not cover the WiFi channels operating within the 5 GHz ISM band. Channels falling within the 5 GHz ISM band are used by 802.11a and n.

WiFi channels are used for transmission of data and not all the 14 channels are being used. Their usage depends on a country by country basis. Table 2.2 shows us the different channels that are allowed in some countries. The crosses in the table means that the channels are allowed to be used in the corresponding country. It is very important to understand the regulation behind the usage of channels in our project. This is because if our project is supposed to be based in North America, we know that the WiFi terminals that are operating over there would use only channels between 1 and 11, hence we do not need to worry about detecting WiFi terminals in the other channels.

The way WiFi channels are spread out in the 2.4 GHz ISM band is that there are overlapping of channels [16]. Figure 2.1 shows Channel 1 with centre frequency of 2.412 GHz and continue all the way to Channel 14 with centre frequency of 2.484 GHz. Each channel occupies 22 MHz of the ISM band and each of the first 13 channels are spaced at 5 MHz apart. Channel 14 is only permitted in Japan. By looking at the figure, we can see that Channel 1, 6 and 11 (bolded semi-circle line) are non-overlapping. This

Channel	**Center Frequency** (GHz)	**North America**	**Europe**	**Spain**	**France**	**Japan**
1	2.412	X	X			X
2	2.417	X	X			X
3	2.422	X	X			X
4	2.427	X	X			X
5	2.432	X	X			X
6	2.437	X	X			X
7	2.442	X	X			X
8	2.447	X	X			X
9	2.452	X	X			X
10	2.457	X	X	X	X	X
11	2.462	X	X	X	X	X
12	2.467		X		X	X
13	2.472		X		X	X
14	2.484					X

TABLE 2.2: IEEE 802.11 Channels [6]

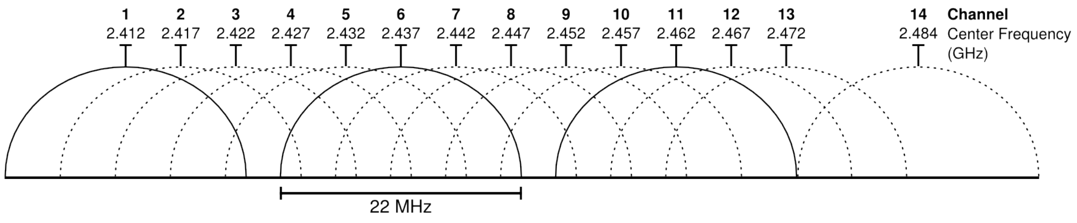


FIGURE 2.1: Representation of WiFi channels overlapping [16]

means that if there are 3 adjacent WLANs and each of them operate in only one of the channels and no two WLANs operate in the same channel, interference between the WLANs would be significantly reduced.

Useful Consideration Points for Our Project

After understanding the concept of channels overlapping, we could apply this to the way we are going to detect WiFi terminals. In order to save scanning through all 13 channels, following Europe regulations, we should only scan through Channel 1, 3, 6, 8 and 11. By referring to Figure 2.1 again, we would notice that these channels provide a continuous overlapping of all 13 channels. Hence, it means that we are most likely able to detect different WiFi terminals operating in any of these 13 channels.

2.1.2 RSSI & SNR

IEEE 802.11 standards defines RSSI as an arbitrary measurement of received signal strength [6]. The way this measurement is implemented varies from vendor to vendor.

This is because the standard does not make RSSI a compulsory element of it but leave it as optional. This means that the rating that RSSI takes varies depending on which AP vendor we are referring to. However, the vendor would have to provide the rating to the device's driver. The range that RSSI takes for Cisco devices, an AP manufacturer, is between 0 and -120 [23]. The more negative the RSSI value is, the weaker is the signal. The RSSI we are discussing here is measured in dBm.

SNR stands for *signal-to-noise ratio.* As you can probably understand simply from this phrase, SNR gives the relative difference between the power level of the radio frequency and the noise floor. *Noise* is the result of any devices or natural causes that produce energy in the electromagnetic spectrum. 802.11 networks can cause interference to each other, which is known as co-channel and adjacent channel interference [8]. However, networks that follows the IEEE 802.11 standards would generally work together harmoniously such as the sharing of the channel capacity if the networks are on the same channel. The major cause of interference appears to be devices that operate using the unlicensed band that does not belongs to 802.11 such as microwave oven and Bluetooth devices.

SNR is an important parameter that we need to consider in WLAN. For example, if the received signal strength is x in a low noise environment, x would decrease in an environment with high noise, due to the interference affecting the transmitted signal. If the noise level is close to the RSSI, this means that the signal would be corrupted.

Useful Consideration Points for Our Project
SNR is useful especially when we need to use RSSI to assist in localising a WiFi terminal. An RSSI with a low value does not always mean that a terminal is far away from an AP. We could make use of both RSSI and SNR to come up with a technique to localise a device as accurately as possible.

2.1.3 Management Frames

There are 3 types of frames that is defined in IEEE 802.11, namely management frame, control frame and data frame. In this project, we are more interested in the management frames, which would shed some light on the possible ways we could detect the presence of WiFi terminals. Management frames are used for the purpose of establishing a connection between an AP and a terminal. A terminal in a WLAN, with multiple APs deployed, may move around and as a result, the terminal may need to switch association from one AP to the next using management frames. In addition, the usage pattern and the type of Operating System(OS) of a terminal would also trigger some of these management frames to be sent either occasionally or regularly. For instance, a smartphone may be in *sleep mode* initially. When it wakes up, it would send out a probe request frame to determine whether there are any APs nearby with sufficient signal quality for it to associate. On the other hand, the OS of the smartphone may choose to send out probe request frame every now and then to determine whether there are any APs nearby that would provide better signal quality. *Probe request and response* would be covered further in Section 2.1.4.

Apart from probe request frame, there is also the beacon frame, which is being broadcasted by each of the APs in WLAN in a regular time interval. A beacon frame [17] consists of frame header like any other frames, which includes the source and destination MAC addresses. It also contain information such as *beacon interval* and *Service Set Identifier (SSID)*, which is the name of the WLAN. The SSID is important for a terminal to know which network it is trying to establish a connection with. A beacon frame allows a terminal to be aware of the APs nearby so that it could choose whether to associate to it. The terminal is able to work out which AP has a better signal quality by determining the RSSI of the beacon packet. Table 2.3 shows some of the management frames that are crucial in our project. Some of these frames would be further elaborated in the following sections 2.1.4 and 2.1.5.

Frame Subtype	**Subtype Field Value**
Association request	0000
Association response	0001
Reassociation request	0010
Reassociation response	0011
Disassociation	1010
Probe request	0100
Probe response	0101
Beacon	1000
Authentication	1011
Deauthentication	1100

Table 2.3: Type of Management Frames [6]

2.1.4 Active versus Passive Scanning

In *active scanning*, a WiFi terminal could choose to send out two types of probe request frames by choosing whether to specify a SSID in the frame or leave the SSID field as null. If the SSID field is specified, the APs that belong to a WLAN being configured with that SSID will need to respond to the request by replying back with a probe response frame. The response frame has a frame header which contains the AP's MAC address, in which the terminals would be able to establish a connection if it chooses to. If the SSID field of a probe request frame is left as null, any APs in the surrounding that is configured to respond to such frame would reply with a probe response. However, for security reasons, it is possible that APs would not respond to such frame.

In *passive scanning*, the terminal would listen for any beacon frames that are being broadcasted by nearby APs. The terminal might receive multiple beacon frames from different APs. In this case, the terminal would make use of RSSI to determine which AP it should associate to.

Useful Consideration Points for Our Project
As we might notice, since terminals are sending out probe request frames every now and then, it is highly that we could make use of these probe request frames to detect terminals. Furthermore, a probe request frame also contains the source MAC address in the frame header, which means that we can identify a terminal easily since MAC address is globally unique.

2.1.5 Joining and Leaving a WLAN

The Join Process [9] involves 3 stages before a terminal could start sending data over WLAN. The first stage involves discovering an AP to begin establishing a connection.

The second stage requires the authentication of the terminal . There are two types of authentication methods, namely *open authentication* and *shared key authentication*. Open authentication does not involve any true authentication at all and the AP would just reply to any authentication frames it receives. Shared key authentication, as the name implies, makes use of a common key for the authentication process. The *wired equivalent privacy* (WEP) key is used for authentication but is currently the most insecure way. However, in order to meet the IEEE 802.11 standards, WEP is still being implemented by AP vendors. Other more secure authentication methods are available such as EAP and WPA.

The third stage involves the association process before data transmission through the network can take place. The main part of this process involves the terminal sending an association request frame to the AP, in which the AP would reply back with an association response frame if everything goes well.

There are also other processes such as reassociation, deassociation and deauthentication. Reassociation happens when a terminal moves beyond the range of an AP to another AP that is still within the WLAN. Reassociation is similar to association but the APs within the WLAN would transfer the information of the terminal between each other. On the other hand, dissociation and deauthentication happens when a terminal is disconnecting from a WLAN. A dissociation frame and deauthentication frame are sent to the AP the terminal is previously connected to.

Useful Consideration Points for Our Project
The process of association and dissociation could form a good mechanism for detecting the presence of a terminal within a specified WLAN. This is because the association of a terminal to an AP is a good indication of the relative location of the terminal to the AP. Using this association information with RSSI, we would be able to localise a terminal easily. The dissociation process would mark the end of a terminal's existent near an AP. Furthermore, with the reassociation process, we could easily track the movement of WiFi users from one AP to the next. However, there are a few shortfalls in this mechanism. For instance, a terminal may not attempt to reassociate to a closer AP after moving away from the previous AP it associated to due to the way its association algorithm is implemented. This is further discussed in Section 3.2. We will also be evaluating the different mechanisms that can be used in detecting the presence of WiFi terminals in Chapter 4 on Design.

2.2 Wireless Chipset and Network Interface Card (NIC)

This section will discuss some of the major wireless chipset manufacturer for both APs and other WiFi devices. In particular, we would focus on the chipset for APs since we are going to implement a solution using off-the-shelf WiFi APs. We would like to discuss about the chipset manufacturers so that we could decide on one that is widely adopted by most of the AP manufacturers[2].

2.2.1 Types of Chipsets

There are a few top semiconductor vendors that manufacture chipsets for APs. Although there are many brands such as *Cisco LinkSys*, *TP-Link*, *NETGEAR* and *D-Link*, which manufacture APs, the chipsets that these AP manufacturers use could come from a few major semiconductor vendors. We have listed these vendors below:

- **Broadcom** - Based in USA and manufacture most of the 802.11 chipsets for a variety of AP manufacturers. Most of Broadcom chipsets are used in *Cisco LinkSys*, *Buffalo* and *Belkin* APs. Broadcom has a huge success with the high sale of APs from Cisco LinkSys. It has a good device driver which is available for use.

[2]Note that chipset manufacturers are not the same as AP manufacturers. For example, Cisco LinkSys uses both Broadcom and Atheros in different models of its APs.

The *broadcom-wl* driver allows us to perform many operations that are offered by the chipset. [4]

- **Qualcomm Atheros** - Also based in USA and its chipsets are used mainly by *TP-Link* and *D-Link*. Atheros has two main drivers which allows us to invoke some operations on the chipset. They are *ath5k* and *ath9k*. [27]
- **Ralink** - Bought over by a Taiwanese company MediaTek and famous for manufacturing WLAN chipsets. Its chipsets are used only in some model of *D-Link* and *TRENDNet*.

A typical AP that we have used in this project has a specification as listed in Table 2.4. As we can see from the table, there are really a limited amount of space that we can use for executing our code on the AP for this project. Although we do have other newer models of APs that has slightly higher specification, we want to aim to keep our program as small as possible, making use of the limited CPU performance, RAM and flash storage space.

Feature	**Information**
CPU	125MHz
Architecture	MIPS32$^{\text{TM}}$
RAM	16MB
Flash storage	4MB
WLAN NIC	Broadcom BCM4306
WLAN standard	b/g

TABLE 2.4: Specification of an AP

2.2.2 List of Broadcom Chipset Commands

Command	**Description**
wl -i eth1 status	Gives information about the network interface specified, *eth1*. This includes MAC address associated with this network interface
wl radio	Get status of radio
wl radio on	Turn on radio
wl ap 0	Set AP in client mode
wl ap 1	Set AP in Access Point mode
wl assoclist	Retrieve MAC addresses of associated devices
wl rssi ⟨ MAC addr ⟩	Get RSSI for the terminal with the specified MAC address
wl channel n	Set the channel to n

TABLE 2.5: List of Broadcom chipset Commands [10]

The Broadcom device driver provides functions that we can call from within the custom OS. Some of these functions are essential for instructing the chipset to carry out certain operations we require in order to detect the presence of terminals. Some of these commands are illustrated in Table 2.5.

2.2.3 NIC modes

For a particular model of NIC, there are a few possible modes of operation. They are *AP Infrastructure, Client, Repeater, Ad-hoc* or *monitor mode*. When we place the AP's NIC into monitor mode, the NIC would pass all packets it receives to the OS without any filtering [24]. This means that we can pick up management frame such as probe request frame, which we have mentioned earlier in Section 2.1.4 (Active versus Passive Scanning) that we can use probe request frames as a mechanism to detect the presence of terminals near an AP.

2.3 Custom OS for AP

In this section, we evaluate some of the open source OSs that allow us to make customisation and install it to an AP. Custom OS is required because the originally shipped OS from AP manufacturer usually do not provide *SSH or telnet* access to the AP's OS. Even if we can have access to the OS, it is extremely hard to write a program to be executed on the AP shipped with the manufacturer's OS. We will look at two different freely available OSs that we could use to replace the originally shipped OS below.

2.3.1 DD-WRT

DD-WRT is an open source Linux-based OS for wireless router and embedded systems [3]. This OS is very powerful and stable which was released back in 2005 and is still in continuous development by the author and other open source developers. DD-WRT has a few major releases which saw its code base being changed completely. The latest version of the OS makes use of *Open-WRT[14]* kernels which in turn builds on top of the original Linksys WRT54G V1 router OS which was released as open source software under *GNU General Public License*. This means that the OS is very stable since it has a solid foundation. This OS supports *Broadcom*, *Qualcomm Atheros* and *Ralink* chipset. These chipsets are mainly based on *MIPS architecture*.

The main language that is supported natively on DD-WRT OS is C programming language. C is a powerful language and the OS also supports dynamic memory allocation feature of C. This is very useful because it allows developers to write memory efficient code, i.e., allocate memory only when required. Although the chipset may only have one processor, the OS supports concurrent execution of programs by interleaving the execution of the processes. There is also feature such as forking, which creates a new child process that is a duplicate of the original calling process. The main challenge to writing a program to execute on DD-WRT OS remains to be the cross compiling stage. Cross compiling involves using a toolchain on a *build machine* to compile an executable binary program to be run on a different platform, which is different from the platform of the build machine.

There are two types of storage space that can be used within the AP. One is the *Random-access memory (RAM)* which operates just like the normal RAM on common computers. Another is called the *Flash memory* which allows the storage of files permanently even when the AP is turned off. There is also Non-volatile random-access memory (NVRAM) available which provides a good place to store configuration settings or any other information for a program and this information can be accessed easily by calling a command available in C. The information that has been saved on NVRAM will stay on even after the AP is switched off and back on again.

Within the OS, there are two different types of file system. One is non-writable and the other is re-writable. *Journalling Flash File System (JFFS/JFFS2)* is a re-writable area on an AP's OS. This filesystem is very useful for developers because it enables them to use C Input/Output (IO) library like the following example:

fopen - Open an existing file or create a new one

fread - Read the content of the opened file into a buffer

fwrite - Write content from a buffer to a file

Not only the main IO operations can be carried out using the functions above, there are many other useful things that can be accomplished on DD-WRT OS, thus enabling us to develop a powerful program to be run on the AP.

2.3.2 OpenWrt

OpenWrt is another linux distribution for embedded devices. It supports *Broadcom*, *Qualcomm Atheros*, *Ralink* and *Intel* chipset. OpenWrt provides a framework for developers to build applications around it [14]. OpenWrt is licensed as a free and open source software under *GNU GPL* and is actively driven by the community.

OpenWrt provides a very easy tool to install new features to the AP by using a package management tool. This tool makes installation of new program on the AP a breeze just like how one would do on *Ubuntu Linux Operating System*, i.e., using *apt-get install PROGRAM-NAME.*

Since the later version of DD-WRT builds on top of OpenWrt, most of the functionality that OpenWrt has also appears on DD-WRT OS. However, DD-WRT has a broader functionalities which OpenWrt seems to be lacking in some areas. Other than that, OpenWrt supports program written in C and it also supports concurrent execution of processes.

2.4 Related Wireless LAN Software tools

In this section, we would look into some of the available software tools and libraries that are related to the capturing of data, management and control frames. Some of these tools require a particular model of NIC in order to work. Later on, we would summarise and evaluate which tools might be useful for us to explore and use if appropriate.

2.4.1 Kismet

Kismet is a free wireless network sniffer and detector program [34], which detects wireless network even those that do not broadcast their SSIDs. It can determine the range of IP addresses of a wireless network. Another good thing about Kismet is that it could pick up 802.11 management frames for a wireless network. Kismet is mainly used for locating APs within a WLAN, troubleshoot a WLAN and as a site survey tool for learning about the received signal strength at different spots within a WLAN. This allows network administrators to decide how to deploy APs within a defined area.

Apart from using it as a site survey tool, it could also be used to pick up probe request frames which are sent out by WiFi terminals. Kismet *sniff* network packets passively. It places the NIC into *monitor mode* so that it could pick up any management frames that are broadcasted by either terminals or other APs. Kismet runs on Linux OS but requires that the computer it runs on has a compatible NIC.

2.4.2 NetStumbler

NetStumbler is free but not available as open source. It is a tool for detecting and finding APs around an area. It works slightly different from Kismet because it tries to find APs actively by broadcasting a probe request frame with the SSID field filled with the name “ANY” [35]. This creates a problem when the APs are configured not to broadcast their SSID, hence they would not respond to a probe request frame with SSID as “ANY”. For this reason, Kismet could detect more APs than NetStumbler.

2.4.3 Wireshark

Wireshark is a network packet analyser [38], which provides a very detailed GUI for interpreting and analysing of network packets. The network packets could come from any network interfaces of the computer which runs Wireshark. These includes both LAN and WLAN. It also supports placing a NIC into *monitor mode*, which then allows the capturing of management frames. Wireshark uses *pcap*, a software library for capturing network packets.

Wireshark seems to be more suitable for network administrator to analyse network traffic or find out problems that occur within the network. It provides a very nice GUI with advanced sorting and filtering of each record representing a network packet.

2.4.4 Wiviz

Wiviz is a wireless network visualisation tool [32], which works pretty much like Kismet. However, Wiviz is an old tool that has not been updated since 2005 and is no longer working on many of the newer models of APs. Wiviz is able to place NIC into monitor mode just like Kismet, in order to pick up probe request frames that are being broadcasted by nearby terminals.

2.4.5 Tcpdump and libpcap

Tcpdump, as its name implies, is a powerful command-line tool for capturing and dumping of network packets on a Linux machine. On the other hand, *libpcap* is a C/C++ library for capturing network packets, which works by accessing the low-level packet capture utility of the OS [22]. The library provides a high level interface for accessing the packets that comes in through the NIC. There are many functions available via this library which makes it one of the most powerful packet capture library ever. Even Wireshark and Kismet also makes use of this library. When NIC is placed into monitor mode, NIC would supply all the frames it receives, which also include the header frame that contains MAC address information. `pcap_can_set_rfmon()` could be used to check whether a NIC can be placed into monitor mode. If NIC cannot be placed into monitor mode, the libpcap would only be able to capture normal network traffic but not management frames such as probe request and beacon frames.

2.4.6 Summary

We could see that there are a variety of tools out there that are mostly open source and relates to packet capturing. However, since these tools involve code base that spans more than hundreds of source files, some tools would not be that easy to fork and modified it to work according to the objectives that we have for this project. There is a need to consider the feasibility of understanding and getting a piece of tool or library to work. This usually only happens after we experiment with trying the tools. In Chapter 5 (Implementation), we would discuss about the experimentations that we have with some of these tools, in which we have to try them on different models and brands of APs. It would be slightly easier if we choose to implement our project using a PC or a laptop, since we can see from above that most softwares are compiled to work on either Linux or Windows OS of a computer.

2.5 Data Transmission

Since this project involves deploying APs in multiple locations so that they could detect the presence of WiFi terminals, we need a way to transmit all the collected data from each AP to a central server for processing. Since our project involves creating a program to run on an AP, which is an embedded device running on a different computer architecture with limited computing resources, we need a good serialisation method and a data transmission library that has little memory footprint and utilises low flash storage space.

2.5.1 Serialisation of Data

Before client and server could exchange messages using TCP or UDP, the data has to be *serialised* into a stream of bytes so that they could be stored or sent later [25]. After transmitting the messages over to the other party, these messages have to be *deserialised* into appropriate data structures that is understandable. Over the years, there have been many methods for serialising data and a few prove to be the most adopted either for their convenient uses, example *JSON*, or for their great efficiency in terms of storage and parsing speed, example *Protocol Buffers*. Below gives detail about some of the possible serialisation methods that we could use in this project.

1. **Tab-delimited:** If the structure of the data that we are going to transmit is not that complex, it is possible to simply use *tab-delimited* technique, which stores values in rows and columns and for each row, the values are separated by a *tab*

space. Each row is considered a string and there is a *newline* character at the end of the string to mark the end of the row. This format is simple but since it is too simple, it is not good enough to represent complex data structures. It is also not efficient for reading and writing data, which mostly involve carrying out string operations such as concatenation and splitting.

2. **JSON:** It is a lightweight data exchange format that makes use of key-value pairs extensively. JSON is supported by many programming languages, which provide native serialising and deserialising of the data stored in JSON format. It is a human-readable form that is easy to understand by simply looking at the data stored in this format alone. This is also partly the reason why most web applications tend to use JSON for client-server data exchange. Most of the big web applications such as Flickr, Tumblr, Instagram and Facebook provides a REST API that returns data in JSON format.

3. **Protocol Buffers (PBs):** It is a method of encoding structured data in an efficient, yet extensible format [5]. PBs are developed by Google and are used extensively in Google for almost all its applications. The way PBs work is by defining an Interface Definition Language (IDL) file stored in *.proto* format, which serves to describe the structure of the data that is being stored. PBs are designed to be fast, efficient and simple. The data that is serialised using PBs is much smaller than XML[3]. Google reports that PBs are 3 to 10 times smaller than XML and the time to parse data in PBs is 20 to 100 times faster than that for XML. Storage space and parsing time are two crucial elements that we want to consider when deciding which serialisation format to use for serialising data on each AP so that it could be sent to a central server.

4. **Nanopb:** It works the same as PBs but Nanopb is a C-based implementation of PBs with small code base [26]. It is built with the constraints of embedded devices in mind with low memory and small flash storage space. In particular, Nanopb targets 32-bit microcontroller. Nanopb encodes and decodes data in almost the same way as PBs, using a slightly similar *proto* IDL file as its template for encoding and decoding data. It is possible to encode data using Nanopb on embedded device and decode the data on another machine using Google BPs with slight changes to the *proto* file.

2.5.2 File Transfer Library for Embedded Devices

cURL stands for Client for URLs. It is a project started in 1997, which develops the *libcurl* library, a client-side URL transfer library [11]. It supports many application

[3]XML is a format for data serialisation. It is too verbose and takes up a lot of space.

protocols such as *FTP, FTPS, HTTP, HTTPS, IMAP, IMAPS, POP3, RTMP, RTSP, SCP, SFTP, SMTP, TELNET* and *TFTP*. Furthermore, it supports important HTTP methods such as the *GET, POST* and *PUT*. This makes it a very powerful client-side library and also an ideal library for data transmission over the internet using HTTP or HTTPS protocols. Another good thing about *libcurl* is that most of the file transfer errors or exceptions are properly managed and handled in a graceful way.

2.6 Storing and Aggregating Big Data

As we need to store the collected data from each AP for later processing and querying from a GUI for displaying the statistical view of the aggregated data, we need to select a suitable database that fits our use case, i.e., ever growing amount of data collected. We also need to understand the available data analytic methods that would allow us to aggregate our data efficiently.

2.6.1 Relational SQL versus NoSQL database

10 years ago, the terms *Big data* and *NoSQL* are probably not as often heard as today. These words are appearing everywhere on the internet because of the exponential growth in the amount of data that is being generated within the last few years alone. More and more data is accumulated due to more user interactions on the web, example via Twitter or Facebook, increasing amount of server logs, generation of more scientific data such as gene sequencing and analysis, as well as more Wireless Sensor Networks (WSNs) being deployed. This means that there is a need for a new way to handle this data, which leads to the adoption of the widely used *Hadoop Distributed File System*, which is a distributed file system modelled after the Google File System and has the capability to scale across thousands of machines.

NoSQL is based on the idea that it can scale massively, provide very fast write operations, quick key-value pair lookups and has very flexible data types and schema. Most of the NoSQL implementations do not require the developer to specify the types of the data to be stored in advance and this is one of the beautiful characteristics of NoSQL. In addition, it does not provide any ACID-compliance transaction feature, which helps to boost its read and write performance tremendously. Since tracking user mobility involves collecting data from each AP, which could increase to hundreds of them in commercial roll-out, a NoSQL database is an ideal choice. Furthermore, since we are not dealing with data that involves transaction such as bank account details, we do not need the strict consistency of relational SQL.

Relational SQL has a strict schema that we need to follow. The data types for each attributes have to be defined in advance when creating the table. It provides feature such as *join* operation and transactions, which observe the *ACID* properties[4]. Furthermore, it provides easy-to-use SQL query language, which allows developers to query data from the database simply by writing a SQL statement. MySQL is a relational database management system (RDBMS), which is free and open sourced. MySQL is powerful up to a certain point when the amount of data becomes too much for it to handle. In order to scale its capacity up, it would involve the deployment of a master node, which handle write operations, and slave nodes that take care of read operations. Data from master node will be replicated to the slave nodes.

2.6.2 NoSQL Databases

In this section, we would discuss in further detail the different types of NoSQL solutions available so that we can make a more informed choice of choosing one, which is the most suitable for the nature of our project and not just for our initial prototype. It should be noted that the explanation of how HBase works below would aid in the understanding of Chapter 5 (Implementation), in which we use HBase for our data storage.

	packet_details			
	ap_mac	terminal_mac	rssi	timestamp
row_key1	01:02:03:04:05:06	22:22:22:AS:BB:CC	-65	1369908231
row_key2	...	...	...	...
row_key3	...	...	...	...

Table 2.6: HBase Table Structure

1. **HBase:** Hbase literally means *The Hadoop Database*. This is because it is part of the Hadoop ecosystem and is built on top of the famous Hadoop Distributed File System (HDFS). It is available under the Apache Software License, version 2.0. HBase is actually an open source implementation of Google's Bigtable [18]. A prototype was created back in 2007, a year after Google published its paper on Bigtable. HBase is highly scalable and is designed for terabytes to petabytes of data [13]. HBase depends on the data redundancy and batch processing of some of the key components of the Hadoop ecosystem.

   In Table 2.6, we have attempted to draw up a simple structure of a way we can store the data that we have collected from each AP. HBase stores data as key-value pairs. It stores a value in a cell, which can be located by (rowKey, columnFamily,

[4]ACID stands for Atomicity, Consistency, Isolation and Durability.

columnQualifier) coordinates of the table. This is analogous to a 3-dimensional array. These 3 terms are crucial terms that we would used extensively in Chapter 5 (Implementation) to explain how we retrieve values from the table for aggregation. In Table 2.6, *row_key1* is a row key, *packet_details* is a column family and *ap_mac, terminal_mac, rssi* and *timestamp* are column qualifiers. Under a column family, we could have as many column qualifiers as possible and when we mention *many*, it refers to millions of them. As for the number of rows, we can have billions of them in a table. This is why we have said earlier that HBase is highly scalable. We could define as many column family as we need but this parameter should be kept to a minimum. As an example, we can have another column family such as *extra_information*, which would hold column qualifiers such as *ap_GPS_coordinates* and *ap_nearest building*.

HBase is very flexible on the data types and schema of the table. Each cell of the table could be data in any formats since HBase store them as bytes. This means that we can store the content in a cell as *Integer* and later replace the data type of the cell to *String* without any problems. HBase does not require the developer to specify the column qualifier in advance, which is in contrast to relational database that requires the specification of table attributes during table creation. However, HBase does require the developer to specify the column family in advance for a few reasons. One of them is that the content of a whole row might not be stored on a single server. Each of the column families of a row would be stored on a different *RegionServer*[5].

Finally, since HBase uses HDFS as a filesystem for storing its data, it inherits some of the features that are available in the Hadoop *ecosystem*. One of this is the Hadoop MapReduce. HBase allows us to use the data stored in it as input to the Map function and the output of the Reduce function could be inserted back directly into HBase. We will elaborate more on MapReduce in the next section.

2. **CouchDB:** CouchDB is a new type of database management system that stores data as "documents", in which we can call this as "self contained" data [1]. CouchDB is very relaxed on the schema of the data model. Let's us use the example of receipts to explain the concept behind CouchDB. Let say we have 5 receipts from different shops and they are all of different formats, i.e., some may contain the fax number of the shop, some may not and some may contain other details. All these receipts would be analogous to the documents in CouchDB. Each document may contain different informations and does not have to follow the same structure. We can have a fax number field in one document and not having it in another. We can add more data to a document at a later time or remove some

[5]RegionServers are just servers that host small chunks of the HBase tables for the purpose of high availability and scalability.

data without affecting other documents since the structure of each document can be different. This is one of the beautiful elements of CouchDB, which makes it a very flexible data storage system.

If we use the example in Table 2.6, each row would be stored as a separate *document*. We may add extra details such as GPS coordinates of an AP to a document and not have this detail at all in another.

However, the downside of CouchDB is that it uses too much space to store each document. In Chapter 5 (Implementation), we have attempted to experiment with the use of CouchDB and HBase and we compare the size of disk space used for storing the data we collected from APs for each type of database. Apart from using a lot of space, the only way we can communicate with CouchDB is by making HTTP/HTTPS request via its extensive REST API. Adding, retrieving and deleting data on CouchDB has to be done by this way, which is also its shortfall since HTTP/HTTPS protocol is not a quick way for transmitting data across the internet.

Lastly, CouchDB has a built-in MapReduce feature, in which the *Map* and *Reduce* functions could be written in Javascript. CouchDB would apply the Map function to each documents and the outputs from the Map function is passed on to the Reduce function. We will discuss more about how MapReduce works in the following section.

2.6.3 MapReduce Framework

MapReduce is a framework that uses functional programming concepts to process large datasets in a parallel and distributed manner [36]. MapReduce was designed with the aim of processing massive amount of data in a scalable manner. This means that as long as we can afford to add more machines to process the data, its performance should increase linearly [18]. MapReduce uses the *divide and conquer* approach to process smaller chunks of data in parallel and at the end, these chunks would be aggregated to produce a consolidated results.

Processing data using MapReduce involves two phases: the *map* phase and the *reduce* phase. The input and output of both phases take the form of a key-value pair. For MapReduce to work, we need to specify both the map function and the reduce function.

- **Map phase:** The map function is executed once for each input key-value pair. Within the map function, we could do some computation on the key-value pair and at the end, we need to choose a new key to emit out. After the map function is executed, MapReduce would sorts the output of the map function and group together key-value pairs that have the same key and pass these to the reduce phase.

- **Reduce phase:** The reduce function is run once for each group of key-value pairs that share the same key. This means that we have a bunch of data that share certain similarities since we choose to emit them with the same key from the map function. Hence, we could do some aggregation on the group of key-value pairs such as adding up all the values together to find out the total sum. We can then output the result with another key that we choose or we may also choose to output the key that is passed into the reduce function.

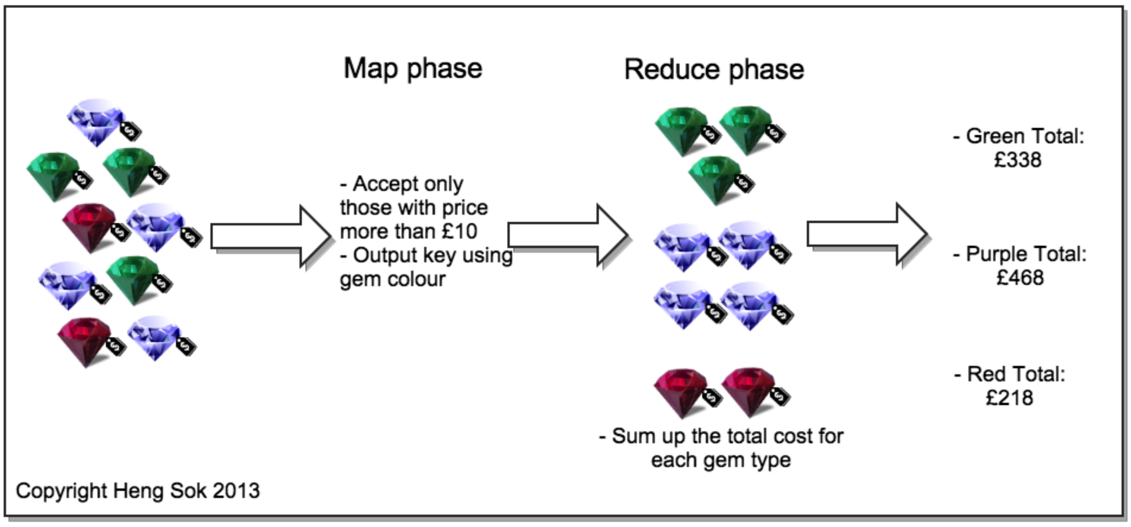

Map phase
Reduce phase
- Accept only those with price more than £10
- Output key using gem colour
- Green Total: £338
- Purple Total: £468
- Red Total: £218
- Sum up the total cost for each gem type
Copyright Heng Sok 2013

Figure 2.2: Illustration of how MapReduce works
Images licensed under Creative Commons and GPL from iconfinder.com

In order to illustrate how MapReduce works, we have come up with an original unique example to explain the concept as illustrated in Figure 2.2. Imagine that we have a whole bag of gem stones, which could be hundreds of them, that are mixed together. Each gem stone has a price tag attached to it. In this case, we consider the colour of gem stone as the key and the price tag as the value.

Each of the gem stone is passed into the map function one by one, which could happens in parallel. In the map function, the input key is gem stone colour and the input value is the price. Within this function, we have a logic to accept only gem stone that is worth more than £10. For gem stone worth more than £10, we will emit out an output key which is the gem stone colour and an output value which remains to be the price. For those worth lower, we will not emit out a key-value pair, i.e., we would not pass the gem stone to the next phase and just throw it away. Note that we could choose any parameter to emit out as key. If we have other information that is available to the map function such as the continent the gem stone is found, we can even emit this as output key.

Sorting will takes place after the map phase and all gem stone that has the same colour will be grouped together since they share the same key.

In the reduce phase, each group of gem stones is passed into the reduce function. The input key is the gem stone colour and input value is a bag of all gem stones of the same colour with their price tags. Within this function, we have a logic to sum up the total cost of all gem stones of the same colour. After finishing our aggregation, we will output the key as gem stone colour and output value as the total cost that we have calculated.

2.7 Summary

In this section, we begin by looking into what IEEE 802.11 standards are and we go through the key components of the standards, which allow us to understand how we can benefit from the standards. For instance, we could make use of the probe request frames that are sent out by WiFi terminals to detect the presence of the terminals. Since this frame also consists of MAC address of the terminals and it is possible for AP to determine the received signal strength, using this mechanism to detect terminals is a feasible approach. The association, reassociation and dissociation process could also be an alternative way for us to detect the terminals although it has its shortfalls. We will look into these shortfalls in Section 3.2 under Related Work, which we get to learn from what other researchers have achieved via this mechanism and also its advantages and disadvantages.

We also discuss some of the OSs available for embedded devices such as APs and attempt to explain some of the functions provided by the chipset manufacturers via their device drivers. After that, we looked at the different serialisation methods and the types of databases system available as well as a framework for aggregating large datasets.

MapReduce is a good framework, which abstracts the complicated underlying scheduling and parallelising of MapReduce tasks from the developers, allowing developers to focus just on writing the logic for the map and reduce functions. Since HBase is built on top of HDFS, there are many benefits that it gets apart from the scalability and availability of the filesystem. This includes using HBase table as both source and sink of a MapReduce job, i.e., the input can come from the table and the output gets written to the table directly. Finally, since HBase is used by big web companies such as

Facebook for its messaging and StumbleUpon for its realtime analytics, it has an active development environment, in which it will become very popular in the future.

Chapter 3

Related Work

Over the years, there have been numerous papers published about localisation using various mechanisms. Attempts have also been make to track the movement of users carrying WiFi terminals within a pre-defined compound under the area of experimentation. In this chapter, we explore the various mechanisms that other researchers have come up with in order to track WiFi users movement. It would be helpful to go through and evaluate others' work in this field so that we could understand the terminologies, constraints and limitations of various mechanisms. Hence, from there, we could decide on a better mechanism that is envisioned to address some of the constraints and limitations.

3.1 Mechanisms for Tracking WiFi Terminals

Real traces of users' location can be used to derive a mobility model that would be useful for researchers working on applications, systems or devices in which the movement of users is significant to their work, especially for location-aware applications and network optimisation. This provides the motivation for some researchers to look into tapping the potential of using WiFi to track user mobility and from this data, they could generate a user mobility model, which would be available to other researchers interested in the data model.

Amongst the papers we have reviewed, we notice that there two main different mechanisms that are being used to track terminals' location and network activity, in which network packets are being monitored. We explain the two main ideas below.

1. One is the use of *syslog* at APs to record information regarding association and dissociation of WiFi devices. *syslog* traces do not provide information regarding the signal strength between client and AP. In order to obtain extra information regarding the network activity that a user engaged in, *SNMP* and *tcpdump* are being employed to get the MAC address of devices and other information by capturing the header of network packets [21]. This allows analysis of which application layer protocols are being used by the users such as *Hypertext Transfer Protocol (HTTP), File Transfer Protocol (FTP) and Gnutella (Peer-to-peer).*

How it works:
The APs are configured to send *Syslog* message whenever a user authenticate, associate, dissociate and deauthenticate. User Datagram Protocol (UDP) is chosen as the transport layer protocol. This means that error checking and correction would not be carried out at the transport layer, thus, lowering the overhead. Apart from *syslog*, Simple Network Management Protocol (SNMP) is used to poll the APs every 5 minutes. MAC addresses, together with inbound and outbound traffic of the recently associated clients would be returned in each poll. In addition, *tcpdump*, is also used to *sniff* the wireless network traffic of the users. This tool captures the packet headers, enabling more in-depth analysis of the network traffic to be carried out. A sniffer server is placed in each major location for this *sniffing* purpose.

2. Another approach is a client-side implementation in which most of the logic is being put on the user's device. For instance, a smartphone would detect user's motion using accelerometer, environment light using device's camera and sound using microphone. The phone also collects information such as the presence of APs nearby as *fingerprint* and all the information can be sent from the user's device across to a server for processing [2].

   Fingerprinting works when the smartphone scans the surrounding for WiFi APs. A fingerprint is formed from the list of MAC addresses that is being captured by the phone in a short period of time. Based on a formula, this test fingerprint will be compared with the one stored in the database as candidate fingerprint.

   With the extra information provided by the smartphone, the *logical location* of a phone user can be determined very accurately as opposed to just relying on GSM or WiFi for localisation. This is because different environment looks differently with a variety of different decorations and lightings. For instance, a pub can be distinguished easily from a book store from the difference in light ambience. If only GSM or WiFi is used to determine the user's location, it could lead to ambiguity. For example, if there are two shops, A and B, next to each other, a user entering Shop A may mistakenly be interpreted as entering Shop B and vice versa. This ambiguity cannot be ignored if the shop owner wants to use the localisation data to send the user coupons or there is a need to aggregate the number of users visiting each shops.

   A user may also move differently in different types of shops. For example, a person visiting the supermarket may move up and down the rows frequently while a person visiting a restaurant may move only for a short distance before sitting down. The accelerometer helps to detect the user's movement.

3.2 Factors Affecting Accuracy of Detecting WiFi Terminals

Since we need to estimate the location of a user, we may also need to consider some of the factors that would affect the accuracy of our estimation. The first two factors discussed below is more relevant for using association and dissociation of a terminal from an AP as a detection mechanism. The last three are general phenomenons that would not be easy to solve.

1. A user's terminal may be associated to an AP but it may not be close to the AP. Furthermore, the terminal might not associate to an AP that is closest to it in terms of real distances [19]. This is due to the fact that different terminals have different algorithm regarding AP association, i.e., it might not choose to associate with the closest AP.
2. Different terminals may have different level of reluctance to change association. For example, Cisco VoIP phone tends to stay connected with an AP for a longer time than other mobile devices. This highlights a factor which could potentially affects the accuracy of tracking users since different users uses different models of mobile devices.
3. The AP may be blocked by an object, thus the received signal strength by AP from a terminal may be lower than it should be. This means that using just RSSI in estimating a terminal's location would not be accurate anymore.
4. Different environments have different levels of interference. The noise in one environment may be higher than in another due to the existent of many wireless devices transmitting electromagnetic waves.
5. There could be refraction, reflection, diffraction, absorption and scattering of radio signal, which causes the signal strength to be weaken [6].

Thus, all these factors may affect the location of a terminal being estimated, giving us a false sense of the terminal's location. For some of the problems above, they could be resolved by using a different terminal detection mechanism such as the detection of terminals by capturing the probe request frames that are being broadcasted rather than using a terminal's association and dissociation information.

3.3 Localisation Techniques

After reviewing some of the related work, a common concern that has been brought up is the accuracy of determining a user's position using 802.11 radio signal. Thus, a number of different mechanisms and algorithms have been devised to estimate the position of the user. Some of the methods and algorithms are summarised briefly below.

- Triangle Centroid - Using three APs as points of reference to determine a user's position. This involves using 3 points of association with APs to accurately determine the user's position.
- Ambience Fingerprinting - Making use of different sensors available on smartphones to provide additional information necessary to determine a user's position accurately. This works because different environments look and feel differently. This includes the sound and behaviour of the user in the environment.
- Signal strength - Using signal strength value between a WiFi terminal and an AP could allow us to estimate a user's position to a limited extent. This assumes that no obstructions occur between them.

3.4 Summary

The use of authentication, association, dissociation and deauthentication information as a mechanism for detecting WiFi terminals is a good method but it lacks robustness. This is because only those users who are able to authenticate and associate with the APs could be tracked. If a user choose not to associate or unable to associate with one of the AP, inaccuracies would be introduced in the tracking results because the results does not reflect the real environment. This could be a problem for this project because we aim to collect information about WiFi users in an 802.11 network environment without requiring users to do anything on their devices. Furthermore, we want to track as many users as possible within this environment so that we can derive useful statistics about the users.

For client-side implementation, the approach is not scalable. This is because it is very hard to persuade or even reach out to users to install an application. However, it is useful to learn how a client-based solution could be developed in contrast to relying on data collected from APs. For our project, a client-side solution may not be that useful since our objective is to track users anonymously without asking them to do anything, which would be ideal and is the solution we are looking for.

Chapter 4

Design

In this chapter, we will give an overview of the design and architecture of our system. We will explain the functionalities of each components and provide justifications for having them. After that, we will go through all available options of WiFi terminal detection mechanism and carry out an evaluation to decide which mechanism we would use for implementation in our project. Last but not least, we will look at what kind of analytical results we would like to aggregate out of the raw data that we have collected from all APs.

4.1 Overview of Design Architecture

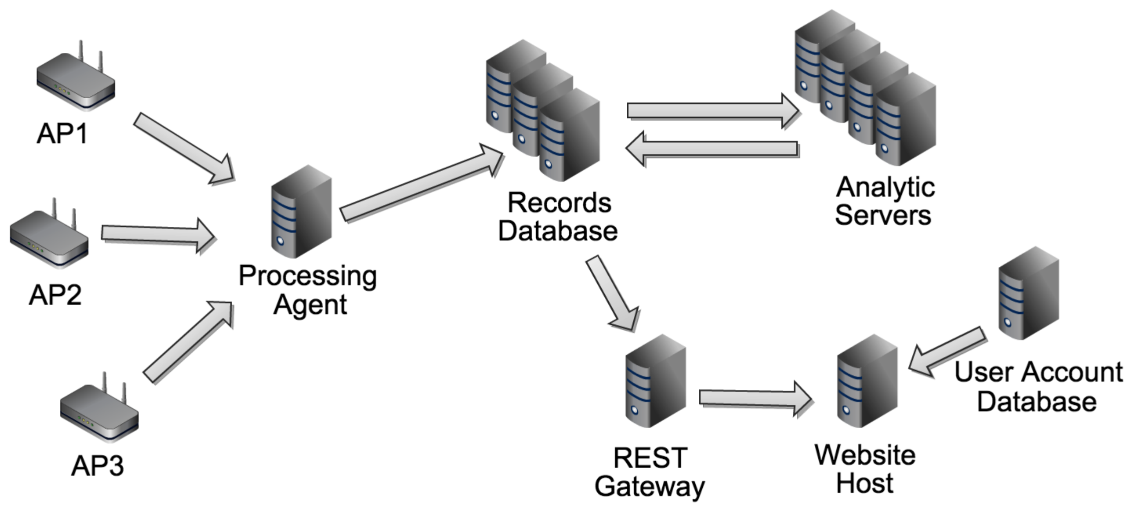


FIGURE 4.1: Overview of our deployment strategy

As we can see from Figure 4.1, we aim to come up with a deployment strategy that has characteristics such as scalability, loose-coupling, composability and interoperability. We aim to have an architecture, which permits us to change the implementation of each component, if require in the future, without affecting the operation of the whole system. We will attempt to explain each components in the order of data flowing in the system as illustrated in Figure 4.1.

1. **AP:** We will write a program to detect WiFi terminals that are close to each AP that we have deployed. The job of the AP is to simply *scan* through each WiFi channel, listen for incoming probe request frames that are being broadcasted by terminals and send this information to the Processing Agent. The whole duration of scanning and listening will take 30 seconds and all the information collected is sent together once every 30 seconds. We will explain why we choose detecting probe request frames as our detection mechanism later in Section 4.2.

   We choose to send all the records[1] together every 30 seconds to save the overhead of establishing too many connections to the Processing Agent. We choose to scan for 30 seconds to allow sufficient time for iterating through each WiFi channels. This is because after some experimentations, any duration lower than 30 seconds would cause the AP to miss detecting some terminals.

   A custom OS would be installed on each AP to run our program. This is because the originally shipped OS with the AP does not allow us to run our program on the AP. Finally, a file transmission library would be used to transmit all the records to the Processing Agent. Such a library is needed because we want to have the transmission error handling and exceptions of the library.

2. **Processing Agent:** At the Processing Agent, we have a REST API, which can be invoked from each AP to upload the data collected. After we have received the data from an AP, we will check the *secret key* that we have packed together with the records. The purpose of using a secret key is to prevent a *rogue* AP that does not belong to our system from uploading data to our Processing Agent, which could results in a disastrous effect on our aggregated statistics. We will explain how we implement the secret key more in detail in Section 5.2.3.

   We decide to insert the timestamp for the records at the Processing Agent before we push them to the database. This is because synchronisation of time on the AP is currently not that reliable using a custom OS. If the clock time on the AP is wrong, we will end up aggregating incorrect data, leading to false analysis of the behaviour of users that we are tracking Hence, we decide to follow a more reliable approach of inserting the timestamp at the Processing Agent. We understand that there are disadvantages of this solution. Firstly, the granularity of detecting each terminal would be about 30 seconds since the data collected by the AP is sent to the Processing Agent every 30s and timestamp will only be inserted at that time. Secondly, there is a possibility of some transmission delay, which would add to the final timestamp for each record.

[1]From here on, when we mention records, we mean the unique WiFi terminal MAC address and its associated RSSI. Within the 30 seconds window, the AP may pick up multiple probe request frames from the terminal but we only consider the first one that we have captured. The terminal's MAC address and RSSI forms a record.

Finally, we will push all these data to the database using the default protocol for connecting to the database that we choose. Our choice of database would be justified in the next chapter on Implementation. Note the arrow in Figure 4.1, which shows that data only flow in one direction from the Processing Agent to the database.

3. **Records Database:** This is the database that we will hold all the raw records that we have collected from each AP and also the aggregated data that we are going to generate by employing an analytic framework. The Records Database should have the ability to scale easily because of the continuous stream of data from all APs if we deploy them 24 hours a day and 365 days a year.

4. **Analytic Servers:** The Analytic Servers only has one main job to do, i.e., to aggregate the raw records that we have collected by fetching them from the database and put the aggregated results back into the database. This explains the two-ways arrows in Figure 4.1, which shows that data flows in both way. It should be noted that we may also aggregate the data once, put them back into the database and aggregate on the aggregated data again to derive a different analytical model of the data. This is done this way because data from the first aggregation may be used several times for generating different statistics.

5. **REST Gateway:** This component is subjective to the type of Records Database and the front-end GUI that we are using. For our implementation in this project, we require a REST[2] Gateway. The database that we choose provides a client library for retrieving data from code written in Java but not from any other languages. Although it also provides basic REST API for retrieving data via HTTP, the REST API only allow simple querying of data and does not allow us to specify the criteria such as what range of data we want to retrieve. Hence, we decide to implement our own REST Gateway, which is written in Java so that we can use the database Java client library to provide additional ways of querying data from a GUI written in Javascript and HTML. For example, we allow the Web GUI to specify the range of records, from which date to which date, that it wants to retrieve. We aim to keep this description at minimal here in Design and will attempt to explain them in detail later on in Section 5.6.1 under the Implementation chapter.

6. **Website Host:** This will provide the hosting for our Web GUI, which has a back-end written in PHP and front-end in Javascript and HTML. We need the back-end to be in PHP because we want to provide *login functionality* for administrators and business owners to login and check out the different statistics and graphs that

[2]REST is a software architecture that involves client-server, in which the server provides a standardised application programming interface for accessing and modifying data.

we have for them. Javascript is used in the front-end for querying data directly from the database as we have mentioned earlier. Some element of HTML5 is also used in this project. Javascript enables a website to look and operate just like an *app* on the phone without having to refresh page often for selecting certain options on the page. That is what we aim to achieve in our Web GUI.

7. **User Account Database:** This is implemented using a relational database for account keeping purposes. We store the accounts for administrators and business owners in this database as well as the APs that each account is allowed to view the statistics associated with them.

4.2 Detection Mechanisms

In this section, we will outline the different mechanisms for detecting the presence of WiFi terminals using what we have learnt from background and related work. We will evaluate each mechanisms, highlighting any advantages or disadvantages, and justify our choice of the mechanism we use for our implementation.

- **Mechanism 1**

  Based on the association and dissociation records of a user's WiFi terminal, the MAC address of the terminal, and the time the terminal is detected can be determined. If the AP does not use an open system authentication, the terminal would have to authenticate itself first before association with the AP can take place.

  By using this mechanism, everything can be done entirely without the user's knowledge and that also means that this approach is practical. However, the downside is that, only users who can associate with the AP will be tracked by this mechanism. In addition, a terminal could still be associated to an AP even after it has moved quite far away and not reassociate to a closer AP. This could be due to its AP reassociation algorithm. This means that the data collected for deriving the collective mobility of users will not reflects the actual environment.

- **Mechanism 2**

  A terminal may send out *probe request frames* to search for nearby APs to associate. The frame includes the MAC address of the terminal involved and we can determine the received signal strength of the probe request frame on the AP. With this information, we can localise a terminal to a certain extent of accuracy.

  To explain *Mechanism 2* visually and in an interesting way, we have come up with an analogy for this mechanism, which we have chosen for our implementation.

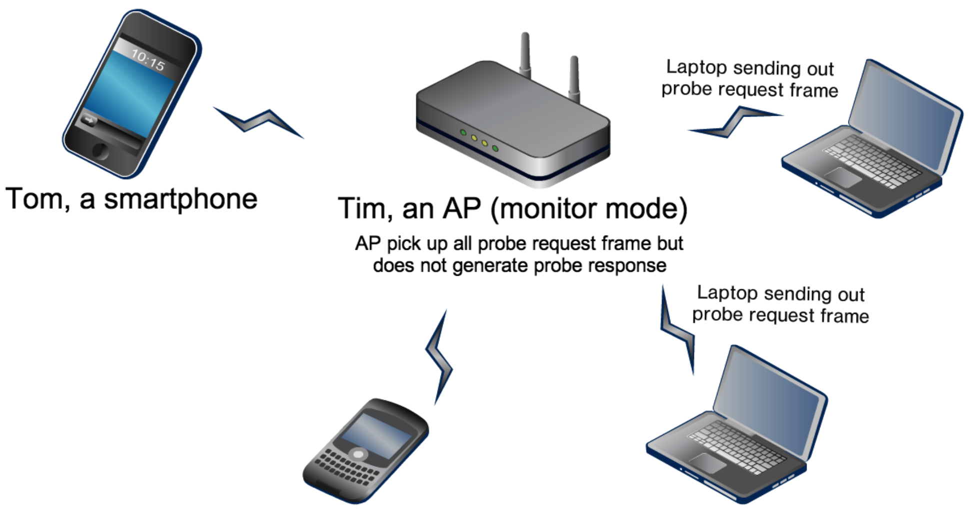

Tom, a smartphone
Tim, an AP (monitor mode)
AP pick up all probe request frame but does not generate probe response
Laptop sending out probe request frame
Laptop sending out probe request frame

Figure 4.2: Detecting presence of terminals using probe request

From Figure 4.2, Tom, a smartphone, may choose to ask two types of questions in a wireless network environment as illustrated in the conversation box.

Tom, Jerry and Tim's story

Q1 Tom: *My name is Tom, I am looking for any available APs nearby that I might know for connection.*

Q2 Tom: *My name is Tom, I am looking for an AP by the name Jerry for connection. Please respond if you are Jerry.*

Tim thought: *I am not Jerry but now I know you are Tom.*

From the conversation above, it illustrates that a terminal may choose to send probe request destined for any APs nearby or only for a particular AP it wants to associate by specifying the SSID. As an AP nearby to the terminal, the AP would be able to pick up this frame without the knowledge of the terminal since it is the terminal's choice to broadcast this frame.

This mechanism has a huge advantage over *Mechanism 1* explained earlier. However, the downside of it is that, we could not control how often the terminal would send out a probe request frame, thus the presence of a terminal might not be detected if the terminal does not send out probe request frames during the period it is in the environment we are monitoring. This is because the frequency of probe request frames being sent out varies according to the different implementations of the OS of each WiFi device.

- **Mechanism 3**

  The last mechanism that we can employ is based on client-side implementation. This would involve the development of a mobile application that we can recommend users to install. The application will download a list of MAC addresses of APs that belong to us and if the mobile phone finds any one of these MAC addresses[3], it will send this information to our server. Hence, we are able to deduce the location of the phone simply by associating its location to the the location of the AP or APs.

This solution is the easiest to implement. However, it has many downsides. Firstly, we would have to develop a range of applications for different mobile platforms such as iOS, Android, Windows Phone and BlackBerry 10 in order to track the users of these devices. Furthermore, there are many versions of computer platforms to account for as well. Secondly, it would be extremely hard to persuade a user to install the application so that we can track their whereabouts. They would be highly unwilling to commit that, thus, this last solution is not very practical.

This project aims to employ the best mechanisms to track collective mobility of users in IEEE 802.11 environments, hence, *Mechanism 2* explained above is being investigated and implemented. This is because that mechanism does not require user interaction in order for tracking to work. Furthermore, since most WiFi terminals would send out probe request frames as part of their procedure to find nearby APs for association, we would make use of this frame information to our advantage. This means that we would be able to detect more terminals, which would give us a better representation of the number of WiFi users in the environment under monitored.

The only downside to this mechanism is that since some terminals do not send out probe request frames that often, it would be hard to accurately determine whether a user is still staying at a place due to the fact that his WiFi terminal might not send out probe request frames during that time period. In Chapter 6, after we have conducted our experiment in the Department of Computing laboratory, we would observe another phenomenon, in which the number of terminals detected are higher than the surrounding area under monitored due to two reasons. Firstly, a user may have more than one WiFi terminals since they are university students, who might possess a laptop, tablet and a smartphone. Secondly, unless we use a good filtering technique, we may detect terminals that are located outside the area under monitored if these terminals are transmitting packets at a stronger signal strength.

[3]It is not hard to obtain the MAC addresses of APs in the surrounding by conducting an active scan and using the mobile phone provided library to obtain the APs' MAC addresses.

4.3 Types of Aggregation

After we have collected the raw data about terminals' presence, indirectly the users' presence, we need a way to aggregate the data in order to derive useful meaning out of it, or else, the raw data would be like a *rough diamond*, which does not have much of a value and attraction. Analysing data is a difficult process, which is just like what the big companies are doing right now to analyse Big data. We aim to use an analytic framework that is easier to understand and easier to manage the logic of data aggregation. However, for this, we will leave it to the next Implementation chapter. Below, we will list out an overview of the types of aggregated results that we want to obtain out of the raw data we have collected.

1. As the presence of a terminal could be detected by several APs in the same environment, we need to put in place a logic to determine which AP the terminal is closest to.
2. We want to obtain a *near real-time* aggregation of the number of counts of WiFi terminals near each AP in the environment we are monitoring. A delay of 1-2 minutes would be accepted. This information would then be displayed on the Web GUI for us to see a *near real-time* overview of the number of terminals we are detecting near each AP.
3. As part of our aim to understand the collective mobility of users, we want to know how long a collective of users stay near an AP, indirectly a particular place in our monitored environment. We would call this the *residence time* of users staying at a place.
4. We want to know the number of New versus Returning users to a particular place. In particular, we want to answer the following question. "Do users usually return back to the place they used to visit?"

4.4 Web GUI

Again, even after we have the aggregated results, if there is no GUI to display the results, it is hard to visualise what those data means. The GUI's job is to take the aggregated data and plot pretty graphs and charts so that we, as human, can understand and use the statistics to make useful judgement and decisions. The GUI is designed to have good navigability, intuitiveness and modern style.

Chapter 5

Implementation

In this chapter, we will look into how we manage to implement and cross compile a program to run on an embedded device such as an AP. The cross compiling process is probably the most challenging part because the AP OS that we use, DD-WRT, does not provide any documentations on cross compiling a program to run on it. Since an embedded device has limited flash storage space and RAM, it is impossible to compile program on the AP itself, which would be easier if this is permitted. After that, we look into how we find a way to transfer the data out of the AP to a server for processing. We also explain the aggregation logic that we have written in our code to turn the raw data into useful statistics. Finally, we will discuss about how we manage to implement an app-like website for displaying the aggregated results, drawing beautiful graphs and charts that are simple to comprehend.

5.1 Chipset and Custom AP Firmware

Before we start this section, we would like to explain the difference between OS and firmware. The terms *OS* and *firmware* refer to the same thing, when we are talking about an embedded device such as the AP. However, it should be noted that a firmware could be unique for each brand and each model of AP. Furthermore, a firmware may have many different versions that are built at different point in time. Certain versions of a firmware may cause certain functionalities of the AP to be unusable. When we use the term *OS* in subsequent paragraphs, we use it to refer to the internal running of a system on the AP, which has process scheduling, memory allocation and system call management. When we use the term *firmware*, we use it to refer to the filesystem image that can be flashed onto an AP.

After learning about the popularity and level of support each chipset's device driver could offer, it is clear that Broadcom would be the chipset we are looking for. However, we would still want to evaluate other chipsets to see how they compare in terms of usability. We have a total of 9 different models of APs, 6 from Cisco LinkSys using Broadcom chipsets, 1 from D-Link using Ralink chipset and 2 from TP-Link using two different models of Qualcomm Atheros chipsets. 1 of the Cisco LinkSys APs was *bricked*[1] and another has certain unusable functionalities after flashing with our firmware.

One of the most important factors that allows us to determine which chipset to use is whether the chipset supports *monitor mode* natively. Monitor mode is needed for us to capture probe request frames, which are required for our chosen detection mechanism that we have mentioned under Design chapter to work. The Ralink chipset that we have does support monitor mode. However, once the AP's NIC is placed into monitor mode, it would not have network connectivity and could not function in AP infrastructure mode anymore, i.e., the AP cannot serves as an access point in 802.11 infrastructure mode. This would mean that even if we are able to capture probe request frames, there is a difficulty of getting network connectivity to transmit the collected data from the AP to a server for processing. As for Atheros chipsets, 1 model of the chipset allows us to put the AP's NIC into monitor mode but the other model does not. However, for the one that can be placed into monitor mode, we need to install several modules and drivers in order to do that.

Finally, Broadcom chipsets are the most usable out of the 3 different types of chipsets. This is because for Broadcom chipset, we could place the AP's NIC into monitor mode and at the same time, it also able to function in AP infrastructure mode. This is what we have found out to be unique about Broadcom chipset, which not many people have discovered and also not documented by Broadcom. Hence, we have decided to focus our implementation around Cisco LinkSys APs, which utilises Broadcom chipsets and NIC in most of their models. It should also be noted that even with Broadcom chipset, the types of WLAN NIC has a major impact in getting the monitor mode to work as well.

In this project, apart from having a suitable chipset, we need to use a custom AP firmware in order to run our program on the AP. This is because most AP manufacturers do not provide terminal access, such as *SSH* or *telnet*, to the AP's OS and it is extremely hard to modify the existing manufacturers' firmwares without their source code. Furthermore, even if we manage to get terminal access to the manufacturer's AP OS, we would not be able to run our program on the AP easily as well.

5.1.1 Choosing a Suitable Firmware

There are two types of firmwares, DD-WRT and OpenWrt, that we have mentioned in Section 2.3.1 under Background. Although we have explained and evaluated the advantages and disadvantages of each firmware in the aforementioned section, we still

[1]Damaged due to corrupted filesystem during flashing of the firmware, which usually relates to incompatible firmware version.

have to test them out on the actual AP to see what functionalities each firmware would offer as well as whether there are any compatibilities issues, in terms of NIC and chipset.

We have flashed OpenWrt firmware onto TP-Link and Cisco LinkSys APs. OpenWrt does not seem to be easy to use and configure. It is not easy to partition the flash storage space to support Journalling Flash File System (JFFS), which provides a re-writable space on the AP. Re-writable space is required for us to store our program so that even after we turn off the AP and turn back on again, the program still remains there.

As a result, DD-WRT is chosen as a custom firmware that we are going to work with since we can configure JFFS on it. Another reason why we choose DD-WRT instead of OpenWrt is that there are more available libraries that we can use in DD-WRT for our implementation. Furthermore, we discover that Broadcom has a proprietary "wl" device driver that is available for our use, which comes with most of the APs that use its chipset. After some experimentations, the "wl" device driver is found to work on DD-WRT firmware and not on OpenWrt. "wl" device driver is essential for us to set the AP into monitor mode and changing the AP's WiFi channels. This is essential for us to capture the probe request frames, which we have justified in Chaper 4 (Design) as the terminal detection mechanism we are going to implement.

5.1.2 Preparing Firmware

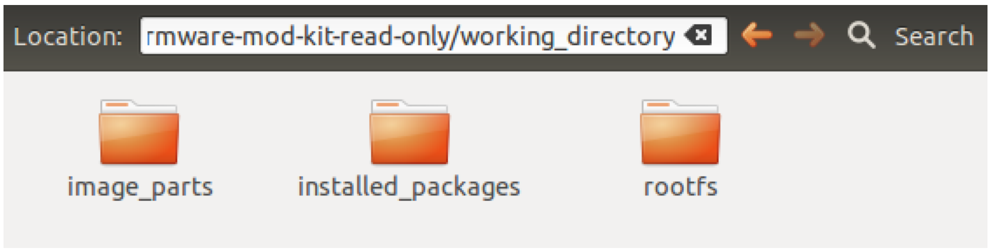


FIGURE 5.1: Top level of firmware image filesystem

Due to the constraint of limited space on an embedded device like the AP and since the original DD-WRT firmware already takes up much of the flash storage space that an AP would provide even using its minimal build with fewer features, there is a need for us to recompile the firmware. This is because DD-WRT does not expect other developers to install a custom program onto its OS, hence, it leaves very little flash storage space that is usable for storing other files. We use the Firmware Modification Kit [20], which allows us to make modification to the firmware image.

After using the kit to extract the firmware image, we get the different components that is shown in Figure 5.1 and 5.2. Figure 5.2 shows us that the internal filesystem of DD-WRT firmware looks a bit like the Linux OS filesystem. There is a *bin* folder which

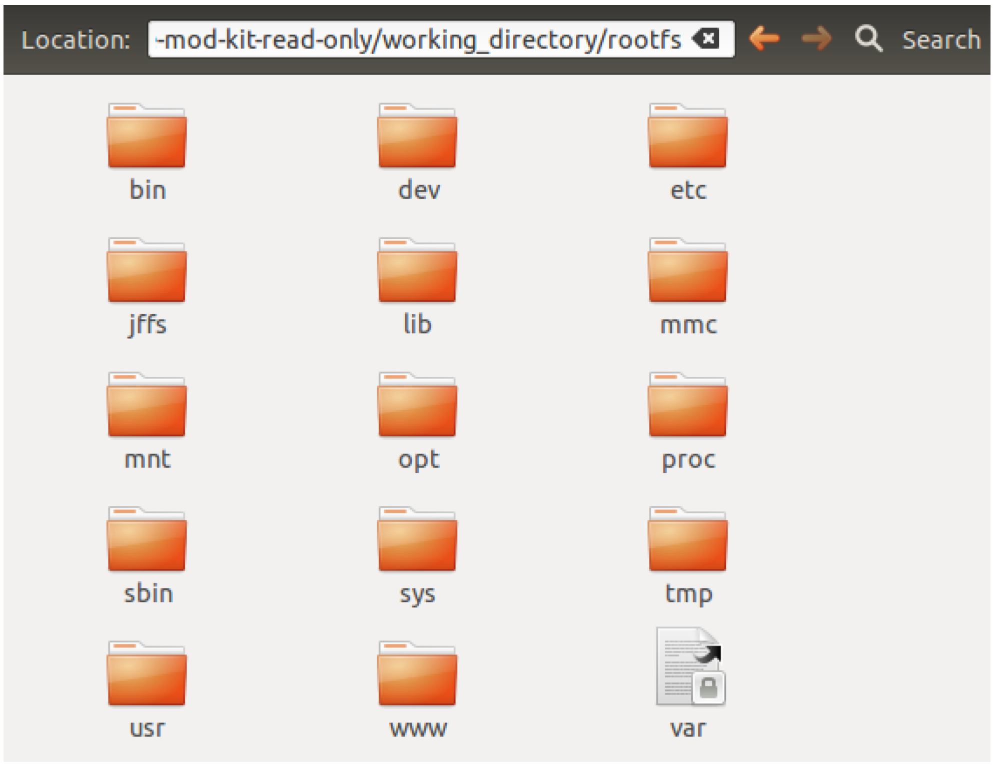


FIGURE 5.2: Root filesystem of firmware image

holds program such as *cp, mv, rm, umount, ls, ping, etc.* There is also a *jffs* folder which is a re-writable space when the AP is in operation.

Since our AP has limited flash storage space and we need space for our program with its libraries, we need to modify the firmware image. Our objective here is to reduce the firmware image size so that there are more space available for JFFS re-writable area. We need to extract irrelevant default programs from the original firmware to reduce the firmware size. We remove *pptpctrl, pptpd, xl2tpd* (a layer 2 tunnelling protocol not needed for this project), *bpalogin* (a bigpond login), *nas* (a Network Attached Storage module, which provides file server feature and is not needed in this project). After assembling back the DD-WRT firmware, we manage to reduce the overall firmware size from 3,490KB to 3,067KB. Since most of the APs that we have provide about 4MB of flash storage space, we could now have a little less than 1MB remaining for storing our program that also makes use of other libraries.

5.1.3 Flashing AP Filesystem

The embedded system is very sensitive to changes in firmware version according to what we have found out during our experimentation with a variety of different models of APs. We have to be extra careful when flashing the firmware on the AP such as not disconnecting the power cable when flashing is going on, waiting for appropriate amount of time during each stage of flashing and resetting the AP after it is flashed. However, even with such procedures taken, we still could not fully avoid bricking one of our APs. When an AP is bricked, it just became dead and does not respond to any ping anymore even we use an Ethernet cable to connect directly to the AP. The only way to *un-brick* it is to get a serial cable and use Trivial File Transfer Protocol (TFTP) to transfer the firmware image onto the AP and perform a re-flashing.

In this project, we spend a lot of time trying to find the right firmware version, as well as trying to fix some of the "semi-brick" conditions that we also face. This involves continuously *pinging* the AP with an ethernet cable connected from a computer and once we could detect a response from the AP, we could quickly use TFTP to transfer the firmware image across to perform re-flashing. This is an alternative to using serial cable but it only fixes AP in *semi-brick* condition.

5.2 Detecting, Transferring and Compiling

In this section, we will explain how we create a program to capture probe request frames, devise a data transfer protocol to transmit the collected data from AP to server and going through the painstaking cross compiling process to compile a 32-bit MIPS program on a 64-bit Intel computer.

5.2.1 Detection Program

Due to the time constraint of this project and the amount of emphasis we have in other parts of the project such as aggregating the collected data and designing a GUI for plotting graphs and drawing up charts, we have chosen to explore whether we could build on top of an existing tool for the capturing of probe request frames. There are two WLAN tools such as Kismet and Wiviz that we can look into. Both are open source tools [32, 37], which has a feature that involves the capturing of probe request frames.

Wiviz's code is easier to understand than Kismet although the code is outdated and would not work on some of the newer models of Cisco LinkSys APs. Kismet code base is very large, which spans to hundreds of files. It has some unnecessary modules such as the *drone* and *client* module that allows us to deploy an AP as a drone, which sends data to a *client* that reside on a computer. In the end, we decide to modify the Wiviz code to work according to our specifications and needs. We name our program as *analyticScan*, which can be run on the AP as a background process. We give details of how our program works below.

Calling Broadcom library functions

```
#define WLC_GET_MONITOR          107      /* When used with wl_ioctl, returned value of 1
                                             means monitor mode is On, 0 otherwise. */

#define WLC_SET_MONITOR          108      /* When used with wl_ioctl, pass in 1 as buf
                                              parameter would set monitor mode to On,
                                              otherwise 0 is Off. */

#define WLC_GET_AP               117      /* When used with wl_ioctl, returned value of 1
                                              means AP infrastructure mode is On, 0
                                              otherwise.  */

#define WLC_SET_AP               118       /*  When used with wl_ioctl, pass in 1 as buf
                                              parameter would set AP infrastructure
                                              mode to On, else 0 is Off. */

#define WLC_GET_CHANNEL          29       /* When used with wl_ioctl, channel number
                                              will be returned. */

#define WLC_SET_CHANNEL          30       /* When used with wl_ioctl, channel number
                                              is copied to buf parameter to set channel. */
```

LISTING 5.1: Identifiers for changing the configuration of the AP.

In order to start receiving probe request packets from the network interface, we need to set the NIC into monitor mode. This is done by calling `wl_ioctl(char * interface_name, int identifier, void *buf, int len)`, which is a function provided by Broadcom's device driver to allow the setting of AP with various configurations. From Listing 5.1, we can see that there are identifiers, which can be passed into `wl_ioctl` as one of the arguments to instruct it to change the configuration of the AP.

Before we start explaining the other parameters of `wl_ioctl`, we would like to explain about nvram. NVRAM is a non-volatile random access memory, usually for storing configuration settings. We can access the NVRAM simply by including `bcmnvram.h` and we can have access to two useful functions, namely `nvram_safe_get(char * name)` and `nvram_safe_set(char * name, char * value)`. The former is for getting the configuration value specified by the *name* and the latter is for adding new key-value pair to the NVRAM for storing.

Having explained about NVRAM, we know that we can get a configuration value from it by calling the provided function. In order to obtain the network interface name of AP, which could be different for different models of APs, we use the `nvram_safe_get(‘‘wl0_ifname’’)`. *wl0_ifname* is the key that we want to query for its associated value from NVRAM. The returned value is the network interface name. The *buf* parameter of the `wl_ioctl()` function allows any values to be returned to be copied to the buffer that is being allocated before the pointer to the buffer is passed into the function. *len* is the size of the buffer.

Opening a socket to the network interface and start receiving

After setting the NIC into monitor mode, we would need to open a socket to the network interface device driver to start receiving any packets that may come in through the interface. This is done by using the Linux socket interface, `socket(int socket_family, int socket_type, int protocol)`. We would pass in *PF_PACKET* as *socket_family* and *SOCK_RAW* as *socket_type*. *PF_PACKET* is needed because we want to receive raw packets at the device driver level. As for *SOCK_RAW*, it is specifying that we want to receive the the packets from the device driver without any modifications. We also pass in *ETH_P_ALL* as the protocol, which ensures that all incoming network packets are passed to the socket.

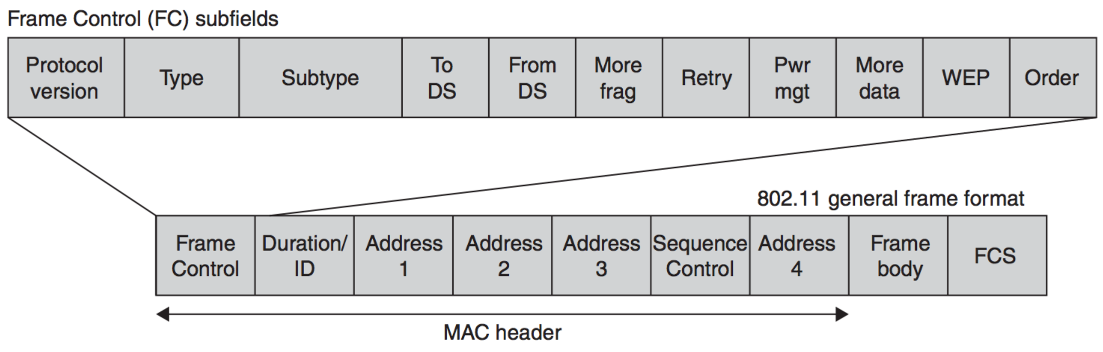


FIGURE 5.3: General IEEE 802.11 frame with Frame Control field highlighted [6]

After opening a socket, we use the Linux `recv` function to start receiving message from the socket. As we receive packets through the socket, we need to filter out the type of management frames[2] that we want. According to Table 2.3 that we have in Background chapter, which specifies the *Subtype value* in the Frame Control (FC) field of an IEEE 802.11 frame, we can use the *Subtype value* to distinguish between the types of packets. In Figure 5.3, we can see that there is a *Type* and *Subtype* field, which serve to determine the type of frame. What we want is a *Type* value of 00 for management frame and *Subtype* value of 0100 for probe request frame.

By filtering only probe request frames from all the packets we receive, we assume that only terminals would send out probe request frames and not any APs that are in *AP infrastructure mode*. We could capture probe request frames from an AP if it is operating in *Client mode*.

Checking for duplicates of terminals

Finally, we need to check whether the packets that we receive via the socket is coming

[2]Note that we are using the term *frames* and *packets* interchangeably to fit the condition that it involves.

from the same terminal or a different terminal. In Listing 5.2, it shows a hash function, which is being used to check whether we have already pick up probe request frame from the same terminal before.

```

    int hashedValue = (mac[5] + (mac[4] << 8)) % MAX_HOSTS;
```

Listing 5.2: A hash function.

Scanning different WiFi channels

Since we have learnt from Background that there are 13 channels allowed to be used in Europe, we need to set the NIC to the channel we want to monitor for packets. This is also done by using the function we have discussed earlier, `wl_ioctl`, using appropriate identifier. Since we know that Channel 1, 3, 6, 8 and 11 provide a continuous overlapping of all 13 channels as mentioned in Section 2.1.1 (Background), we could simply just monitor for packets in each of these channels for a short period of time. This period of time would be calibrated by some experimentations, which we discusses more in the next paragraph.

Duration to monitor for packets

We need to decide on how long we want to monitor for packets that the NIC is receiving before we transmit the collected data to the central server. We want to make sure that this *duration* would provide sufficient time for the AP to capture any probe request frames and detect any terminals that are nearby to it. After some experimentations to find the optimal duration, it was found to be 30 seconds. Hence, our AP will *scan* for any terminals nearby for 30 seconds before it transmit this information to a central server for processing.

Saving MAC addresses and RSSI information of detected terminals

After we have collected information about the presence of terminals near an AP, we need to save this data to a file for transmission to a central server. How we are going to serialise the data before transmission and how we are transferring it would be discussed in Section 5.2.2 and 5.2.4 below.

Since we decide to use a file transmission library to handle the transferring of data from AP to server, we would need to store the data to a file locally first. After experimentation with DD-WRT, we discover that it is possible to store file in the directory */tmp*, which actually uses up the RAM of the AP for storing the file. Once the AP is restarted, the file will be gone. This is quite an interesting discovery in that DD-WRT seems to *mount* the */tmp* directory using an area of the RAM. Since we also know that re-writing too many times on JFFS filesystem[3] would eventually damage the embedded

[3]To write to JFFS filesystem, we can save a file to the directory */jffs*.

device's flash storage space, it would be better to store our file using the space on the RAM in */tmp* directory. This actually fits our purpose directly since we are only keeping the file temporarily. We will overwrite over the file after every 30 seconds of scanning and completing transmission of the data file to the central server.

5.2.2 Data Serialisation

Since we need to transfer data, containing detected MAC addresses and its associated RSSI, from the AP to a server, we need to find an efficient way of serialising the data so that the serialised data is still small and secure for transfer.

Selecting a serialisation method

We have outlined the advantages and disadvantages of each available serialisation method that we could use for our project. We would like to briefly justify our final choice. Using tab-delimited to store our data is not very space efficient. Furthermore, this method of using tab to separate values requires us to use string functions extensively to concatenate values, which is computationally expensive and is not that fast as compared to something like Protocol Buffers. Protocol buffers provide a very fast parser for deserialising the data from raw bytes. As for JSON format, it takes too much space to store the key for each of its associated values. In contrast, Protocol Buffers do not need any key associated to a value in order to interpret the data. It simply uses an *Interface Definition Language* (IDL) file, which serves as a template for deserialising the data. In addition, there is a C-implementation of Protocol Buffers for embedded device, Nanopb, which we can use to serialise data on the AP and use the Java implementation of Protocol Buffers from Google on the processing server to deserialise the data.

The reason why we want to choose a serialisation method that results in a smaller serialised data is because we want to save the bandwidth of transferring the data from AP to server. This is even more relevant since our AP is sending data every 30 seconds, which means that we should try to reduce the amount of data to be transmitted as much as possible. As long as the AP could handle the serialisation process without requiring too much computing resources, we could employ a more efficient serialisation method like Protocol Buffers.

Defining Protocol Buffer IDL

An IDL file has an extension *.proto*. In Listing 5.3, we have shown how we choose to define the structure of how we are going to send the collected data. *ClientType* is a message type, which encapsulates the detail of each individual terminal, namely its MAC address and RSSI value. Since MAC address is made up of 48 bits, we choose to store it in hexadecimal, which takes only 6 bytes for each terminal we have. This

```
message ClientType
{
   required bytes mac = 1  [(nanopb).max_size = 6]; // 6 bytes for storing MAC address
   required int32 rssi = 2;                          // 4 bytes for storing RSSI
}

message APIdentity
{
   required string apMac = 1  [(nanopb).max_size = 18];     // 18 bytes for storing 17 bytes of
                                                             // AP's MAC with \0 ending character
   required string secretKey = 2  [(nanopb).max_size = 8];  // secret key used for securing transmission
}

message ScanResult
{
   repeated ClientType client = 1 [(nanopb).max_count = 300]; //Hold up to 300 of ClientType
   required APIdentity identity = 2;
}
```

Listing 5.3: IDL proto file defining how we serialise data for transfering from AP to server.

means that we are able to save 12 bytes of space since we need 18 bytes to store a MAC address in string with the colons and an ending null character as required in C. If we detect more than a 100 terminals, this means we would save a whopping 1200 bytes of space. Although 1KB might not seem to be a lot but if we consider the AP is sending information every 30 seconds, the saving would be quite great.

APIdentity is another message type, which encapsulates detail of the AP to allow the processing server to know where the collected data comes from. Since the *apMac* only has a single value, MAC address of the current AP, we simply just store it in full 18 bytes. The use of *secretKey* will be explained in the next section.

Finally, the message type *ScanResult* encapsulates up to 300 number of *ClientType* and the *APIdentity*. It should be noted that the variable name *mac, rssi, apMac, secretKey, client* and *identity* are used for our understanding only and Protocol Buffers will not include them in the serialised data. The serialised data will be compactly packed together, with each bytes side by side, and only a parser generated using the IDL file would be able to understand how to deserialise the data. This enhances the security of the data to a limited extent.

Using Nanopb to serialise data on AP and Protocol Buffers to deserialise
Nanopb as we have explained is a C-implementation of Protocol Buffers for embedded devices. Since it is quite a small project, it lacks a detailed documentation that fully explain how to use its various available functions to serialise the data. As we can see from the IDL file in Listing 5.3, we have a *repeated* ClientType message type, which

requires a different way of *putting* the message into *ScanResult* multiple times. Hence, we have to spend quite a great deal of time experimenting on how to write an *encoding* function to serialise this type of message. However, it is worth the time to get it to work because Nanopb is extremely fast in serialising data due to its optimisation with only essential features for embedded devices.

After serialising, deserialising would have to take place. However, this time round, it happens on the server side. We use the same *IDL proto* file to feed into Google Protocol Buffer generator to generate a parser. The parser allows us to deserialise the data and retrieve the pieces of information we want.

5.2.3 Securing Transmission

One of the major concerns that we, as software engineers, have is security. If a system is designed without security in mind, one day, it will be susceptible to attacks by *rogue* users. Hence, even though our project is only a prototype, we would like to add one layer of security into the prototype at this stage.

In order to prevent *rogue* APs that does not belong to us from sending garbage data to the central Processing Agent, we introduced something called *secret key*. Only APs that belong to us would know about this secret key and as you can see in Listing 5.3, the secret key will be serialised using the Protocol Buffers. Since it might be slightly hard to deserialise the raw bytes without having the IDL proto file, the secret key would appear just like any other kinds of data. Thus, it is not easy for someone to know that it is a secret key. When we are receiving the serialised data at the Processing Agent, we would deserialise it and compare the secret key with the one we have on the Processing Agent. Hence, this forms the basic level of security.

If we want to make sure that hackers would not be able to obtain the secret key from the serialised data at all, we could use a HTTPS connection for encrypting the data to be transmitted between AP and server.

5.2.4 File Transmission

After we have serialised the data at the AP, we need to decide on a way to transfer this data to the Processing Agent. We would have a pre-condition for this, i.e., the AP need to have an internet connectivity or be connected to a private network with a Processing Agent on the network. We will discuss more about Processing Agent later in Section 5.3. As for now, we would like to focus on the various ways that we can employ to transfer data from an AP to a server.

Approach 1 to file transmission
libcurl is a library for data transmission that supports a variety of application protocols such as HTTP, HTTPS, FTP and SFTP. It is available as open source and is a very robust library with proper error handling and exception. The only difficulty in using this library is to compile the source code into a library so that we can use it.

We can use the libcurl's HTTP POST feature to transfer a data file to the server. Libcurl also allows us to transfer more than one file at the same time but this is not required for us. By including the header file `curl/curl.h`, we would be able to invoke some of the functions that libcurl provides. However, we also need to link the libcurl library together with our program when we compile our program.

Throughout this project, we have to test each component separately to make sure each works as expected before we combine them together. Likewise, it also happens for file transmission. We write a simple code for file transfer and test it to work properly before we start to combine the file transfer component with our *analyticScan* program.

Approach 2 to file transmission
Apart from using a file transfer library, we could also use simple Linux-based mechanism to transfer our data from the AP to a server. This is done by instructing our *analyticScan* program to save the serialised data file to be transferred, containing MAC addresses and RSSI, in a temporary directory. Then we can write up a *Shell script* that uses *Secure File Transfer Protocol (SFTP)* to transfer the file across to the server. We would then set up a *Cron job*, a Linux built-in job scheduler that can schedule job at specific interval of times, to run the Shell script every minute. Cron can only schedule a job up to minute interval, hence, this would mean that we can only transfer the collected data every minute instead of the 30 seconds we have discussed earlier.

An advantage of this mechanism is that since we are using SFTP, the file is transmitted over a secure channel. However, we need to try to get SFTP functionality to work on the DD-WRT AP, which is possible but might take some time.

Final decision
We come up with the Approach 2 above as a backup or as an alternative to Approach 1 just in case we could not compile the libcurl library to work. However, we wants our *analyticScan* program to have control over the file transmission process so that we can build in extra error handling and exception, which we would explain more later. Using an external program to control the file transmission process is susceptible to failures that happen silently and since the APs are deployed in different locations, it is not possible or easy to fix program error easily on these devices. Hence, we decide to use a more robust approach, which is Approach 1.

Reducing the size of libcurl library
Since we are not going to use the libcurl file transfer library on a normal computer with plenty of disk space, we need to compile the library's source code with minimal features. We want to include only the features in libcurl that we need. For instance, we manage to compile the libcurl to include only essential feature such as HTTP protocol. We remove all other protocols such as *pop3, ftp, tftp, telnet, ipv6* and ssl and turn on the C optimisation flag, *CFLAGS='-Os'*, which optimises for size. We managed to reduce the compiled library size from 628.6kB to 256.0kB. This is 2.45 times size reduction, which is significant for our project since our AP only has a little less than 1MB for storing our *analyticScan* program as we have discussed earlier in Section 5.1.2 under Preparing Firmware.

It should be noted that at this point, we only want to focus on using HTTP for file transfer. However, we could easily adapt our program to use HTTPS in the future.

Error handling for transmission failure
Since we have limited RAM and flash storage space on our APs, we need a proper error handling to avoid causing the device to run out of memory or crashes just because of file transmission failure. We want our *analyticScan* program to continue capturing probe request frames and temporarily store the data on the AP. We would limit the number of copies of these data files on the AP to prevent it from running out of flash storage space or memory if we use the */tmp* directory[4] to store our files.

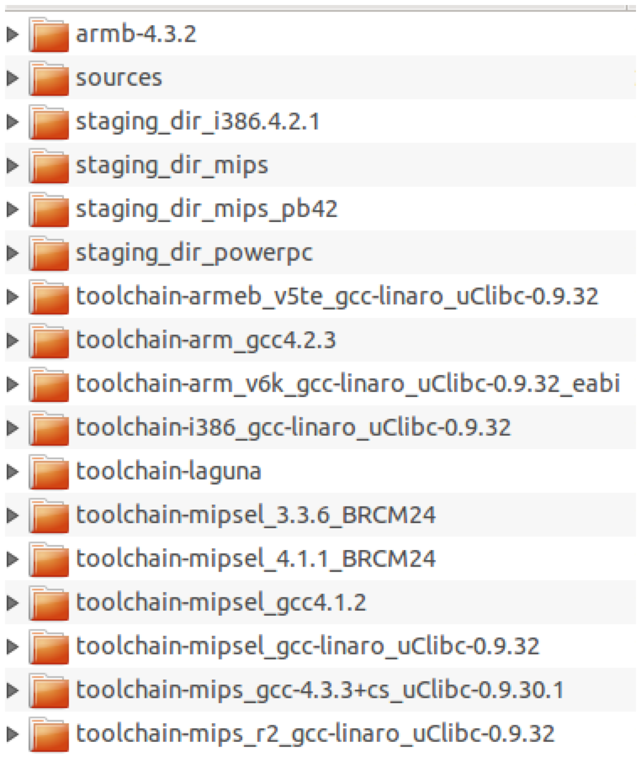
How this works is, if there is a transmission failure, we would check whether the number of failures has reach a maximum number of times. If it reaches the the maximum number of attempts, we would terminate the program and dump a log file of the details of failure to a directory which saves the file permanently and not in */tmp* directory. If an administrator do not see data sent from this AP after some time, at least he knows when this AP fails to send the data and why from the log file. In the future, we could possibly try to send an email to the administrator straight away too using some other libraries. If the file transmission failure has not reach maximum number of attempts, we would store the file locally.

After every 30 seconds of capturing probe request frames and ready to send the data, we would check a condition, a boolean, to see whether there are any backlog of data to be transmitted.

[4] */tmp* directory stores file in an area on the memory.

5.2.5 Cross Compiling Program

One of the main challenge of working with an embedded device such as an AP is to cross compile program to run on it. This is because an embedded device usually uses MIPS processor, which runs on a different Instruction Set Architecture (ISA) when comparing to our everyday computer. Furthermore, since the computing resources such as space, CPU speed and RAM on an embedded device are limited, we would not be able to compile our program on the device itself. Cross compiling means compiling a program on a build machine, could be a laptop with Intel processor, for running on another computer system with a different ISA. That would be MIPS in our case. This requires using a special toolchain for the cross compiling the program to run on a different ISA.



```
armb-4.3.2
sources
staging_dir_i386.4.2.1
staging_dir_mips
staging_dir_mips_pb42
staging_dir_powerpc
toolchain-armeb_v5te_gcc-linaro_uClibc-0.9.32
toolchain-arm_gcc4.2.3
toolchain-arm_v6k_gcc-linaro_uClibc-0.9.32_eabi
toolchain-i386_gcc-linaro_uClibc-0.9.32
toolchain-laguna
toolchain-mipsel_3.3.6_BRCM24
toolchain-mipsel_4.1.1_BRCM24
toolchain-mipsel_gcc4.1.2
toolchain-mipsel_gcc-linaro_uClibc-0.9.32
toolchain-mips_gcc-4.3.3+cs_uClibc-0.9.30.1
toolchain-mips_r2_gcc-linaro_uClibc-0.9.32
```

Figure 5.4: List of all toolchains provided by DD-WRT for cross compiling

There are a couple of issues that hinder our progress in cross compiling the program to successfully run on the AP. We highlight these issues below as well as give a brief explanation of how we address these issues.

1. DD-WRT does not promote the idea of developers creating program for running on its firmware, hence, there are very little detail on how to cross compile program for DD-WRT. Although there may be bits and bytes of documentation by some developers who tried to explain how they did it, following those instructions did

not always work for us. There are always problems here and there during the compilation when we follow others' instruction because their machine and ours are usually not running the same types and version of OS. Furthermore, the other developers' machine may have some *magical* libraries that are required to make the cross compilation work but we may not have them.

2. From Figure 5.4, we can see that there are 17 different toolchains provided by DD-WRT. Out of these 17 toolchains, there are 8 with the name *mips* in them. No matter how hard we try to find an answer online, we could not find the correct answer as to which toolchain to use. Hence, we have to experiment with compiling our program one by one and try to run it on the AP. The hardest part is, since our program uses some third-party and kernel libraries provided by the firmware, we are not sure whether a particular feature that is not working is because of cross compiling problem or there is something wrong with the libraries. Hence, we decide to focus on trying out each toolchain on compiling a file transmission test program to see whether cross compiling a program using a third-party library is working.

3. Just like what we have mentioned in the previous bullet points, we need to use other libraries, which could be dynamic libraries (end with .so extension) or static libraries (end with .a extension). If we compile our program using dynamic libraries, we need to share this libraries with other programs too and if these libraries are not available at program run-time, the functions provided by these libraries will not work. If we compile our program using static libraries, these libraries would be statically linked by the linker into the final executable of our program. This would increase the size of the program.

   However, the problem now is we need to find out how we can get the dynamic or static libraries that we need. This is achieved by downloading the whole source of DD-WRT, which is over 18GB in size, and attempt to cross compile the whole firmware to generate the libraries that we need to use. This process is challenging but also fun at the end when we are able to accomplish it. We believe not many people are able to cross compile the firmware as there are too many dependencies and issues to fix during the compilation process.

4. Another issue that we face is also the version of Linux kernel that we need to include in our Makefile since we also call some of the functions provided by the kernel. Hence, we have to test a few versions of the kernel as well.

In Figure 5.5, we have illustrated the whole compilation process. At the top of the diagram, we started off by cross compiling DD-WRT source code and *libcurl* source code to get the libraries that we need. Then, we cross compile our program and link

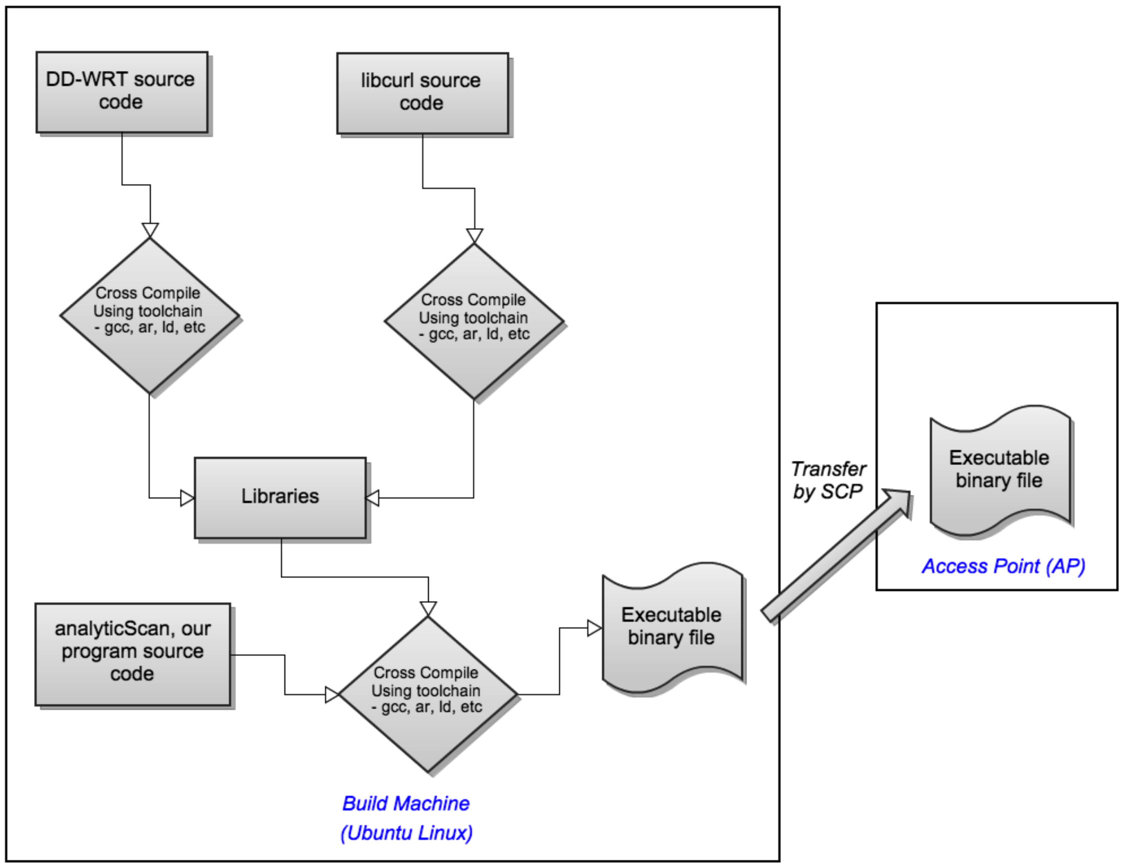
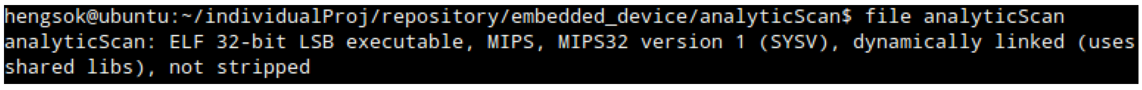

DD-WRT source code
libcurl source code
Cross Compile Using toolchain - gcc, ar, ld, etc
Cross Compile Using toolchain - gcc, ar, ld, etc
Libraries
analyticScan, our program source code
Cross Compile Using toolchain - gcc, ar, ld, etc
Executable binary file
Build Machine (Ubuntu Linux)
Transfer by SCP
Executable binary file
Access Point (AP)

FIGURE 5.5: The Cross Compiling process



```
hengsok@ubuntu:~/individualProj/repository/embedded_device/analyticScan$ file analyticScan
analyticScan: ELF 32-bit LSB executable, MIPS, MIPS32 version 1 (SYSV), dynamically linked (uses
shared libs), not stripped
```

FIGURE 5.6: Detail of the generated executable binary program file

the libraries with it. This generate an executable binary file, which we can transfer by Secure Copy (SCP) to the AP for executing. In Figure 5.6, it shows the detail of the executable binary file that we have generated. *LSB* means Least Significant Byte.

Means of transferring our program to AP

Finally, we would like to mention that since we are able to configure the AP to support SSH, we are able to use SCP to transfer our executable binary file to the AP. Initially, before we use SCP, we also try other alternatives such as uploading the binary file onto a server connected to the internet and use the Linux program *wget* to download the program back from the server since the AP has internet connectivity. However, we know that this is just a *quick* and *dirty* way and we use it initially because we are excited to test our compiled program on the AP. After that, we always use SCP for file transfer to the AP, which is much more convenient.

5.3 Building a Processing Agent

After we have completed the lower *stack* of our system, we need to implement the higher level *modules* to manage the data that is transmitted from the AP and attempt to process them. Ultimately, we want to convert the raw data that we have collected to something insightful and useful. In this section, we will explain how we implement the Processing Agent, which is a server with Java *web servlet* deployed using Tomcat[5].

5.3.1 Initialising Web Servlet

We want our servlet to respond to HTTP GET or POST request, hence, our `ProcessingAgent` class extends the `HttpServlet`. The `ProcessingAgent` class is the main servlet class that we have configured in a *web.xml* setting file to point to. This means that any HTTP GET or POST request to a url like *http://localhost/ProcessingAgent* would be directed to the `ProcessingAgent` servlet to handle.

When a servlet is created after we start Tomcat, the method `init()` will be invoked. Likewise when Tomcat is stopped, the method `destroy()` will be invoked. Since we are using HBase as our database choice, which we will explain more on it later, we need to create a pool of connections to the database that is available for usage when we want to transmit data to it. We will create this pool within the `init()` method and close any connections in the `destroy()` method. The pool of connections is needed because it is quite expensive to always having to set up a new connection to the database everytime each AP send in some data. However, having learnt that the HBase connections in the pool may become unusable after a long period of time, we choose to refresh[6] the pool every 3 hours. A *Check logic* has been implemented for this, which checks that if the pool has been established for 3 hours, we will refresh it.

5.3.2 Receiving and Deserialising Data

An HTTP request could be a GET or a POST. We implement two methods `doGet()` and `doPost()`, which override the existing methods in `HttpServlet`. Any HTTP GET request will invoke the `doGet()` method and any HTTP POST request will invoke the `doPost()` method.

[5]Tomcat is an open source web server that host a Java servlet.

[6]When we refresh the pool, we mean closing all existing connections in the pool and opening new ones and put back into the pool so that any instances of object could use the connection.

In order to receive file from a remote end via HTTP, we use the `ServletFileUpload` class that is available in the `org.apache.commons.fileupload.servlet.ServletFileUpload` package. We could then retrieve the content of the file being uploaded from the `InputStream`.

Apart from receiving the data, we also need to deserialise it. We use the Google Protocol Buffers generator together with our IDL proto template file to generate a parser, which also provides accessor methods for retrieving each of the information that we have serialised. One of the main concern that we have is how do we know how big is the data that is being uploaded by the AP so that we can allocate the right amount of memory space to hold it. This is because we do not want to store the data as a file first before we pass the file to the Protocol Buffer parser. However, it appears that we are able to pass the `InputStream` that is used to receive the data straight to the parser. Hence, there is no intermediate storing of temporary file before we parse the content of the file.

Checking authenticity of sender
After we deserialise the data, we would check the secret key that we have *packed* with the other kinds of data (MAC addresses and RSSI). We compare the secret key with the one we store on the Processing Agent to make sure the data sent from the AP is authentic.

5.3.3 Adding Timestamp

We want the time from all APs to be synchronised and agree with each other. If one AP's time is 5 minutes faster than another AP's time, then this will affect our aggregation of data very seriously. This is because we need to insert a timestamp for each record, which is make up of terminal's MAC address, RSSI and the AP MAC address that detects the terminal. We need the timestamp during the aggregation stage to determine at what time a terminal leaves a particular area. This is just one of the aggregations that uses timestamp. We will explain more later in Section 5.5 on aggregating data. There are two approaches to inserting timestamp and they are discussed below.

Approach 1 to adding timestamp
We can add a timestamp to each record at the AP using the AP's time. However, this would mean that we need to carry out clock sychronisation of the AP every now and then. We may use the Linux program *ntptime* which provides Network Time Protocol to sychronise computer clock. This program is available on the DD-WRT firmware but is unusable. After our testing, we discover that it is not possible to use it to synchronise or even set the AP's clock time. There appears to be some bugs with the *ntptime* program on DD-WRT firmware.

Approach 2 to adding timestamp
We can add the timestamp to each record at the Processing Agent using the server's clock time. This would provide an accurate timestamp for all the records. Even if we are going to deploy more than one Processing Agent by using load balancing solution, we could still sychronise the servers' clock time more easily than the APs' clock time.

There is one problem associated with this mechanism, that is, if there is any delay in the transfer of data from the AP to the agent, this would be a problem. However, we just want the timestamp of each records from different APs to agree with each other and not too particular about the precision. Previously, we have mentioned that we are going to retry file transmission up to a limit if the current transfer attempt fails. We do recognise that this is another case to address because if a file fails to be transmitted from an AP to the agent and after some time of retries, it succeed, the timestamp we are adding for the record would not be correct anymore.

Final decision
We have seen above that each approach has its advantages and disadvantages. However, for Approach 1, since DD-WRT does not allow us to set the clock of the AP to a correct time, Approach 1 would be ruled out completely. Hence, we are left with Approach 2. Although the case of failed transmission may cause the timestamp to be wrong, we know that it would not always be the case that our AP loses network connectivity to the Processing Agent and ends up with failed file transmission. Therefore, Approach 2 is the best choice that we can follow for now.

If we have more time to work on this, we could actually insert a notice (a time counter) at the AP for each of the files that fail to transmit and we can use the *time counter* to determine the actual time of each file. For example, if *file1, file2* and *file3* fail to be sent in this sequence, we will insert a time counter of 3, 2 and 1 to each file respectively. When we receive each file at the Processing Agent, we would check the time counter parameter. If it is 3, we will adjust the timestamp for all records from *file1* to 30s * 3, i.e., the actual timestamp for *file1* is 90s ago. This assumes that *file1* is the first that is failed to be transmitted and *file3* is the last.

Format of timestamp
We choose to use the *Unix time*[7], also known as POSIX time, as the format of our timestamp. This format is more reliable and is not susceptible to the problem of different timezones or daylight saving. In this project, we noticed that if we did not use Unix time format, the British Summer Time change would affect our timestamp if we stored

[7]Unix time is defined as the number of seconds that have elapsed since 00:00:00 Coordinated Universal Time (UTC), 1 January 1970[31]

it in the normal date format (DDMMYYYY HH:mm:ss). With the timestamp in Unix time format, Java would be able to interpret the correct time based on the timezone the server uses.

5.3.4 Pushing Data to Database

Finally, pushing the data to the database is the final stage on the Processing Agent. We push a record for each terminal that our AP has detected to the database. A *detection record* is defined as follows:

AP MAC address	Terminal MAC address	RSSI	Timestamp

Table 5.1: A Record

In Table 5.1, the AP MAC is the MAC address of the AP, which has detected that particular WiFi terminal. From now on, we shall refer to a *detection record* as having the structure above so that it is easier for us to explain about the aggregation process later on.

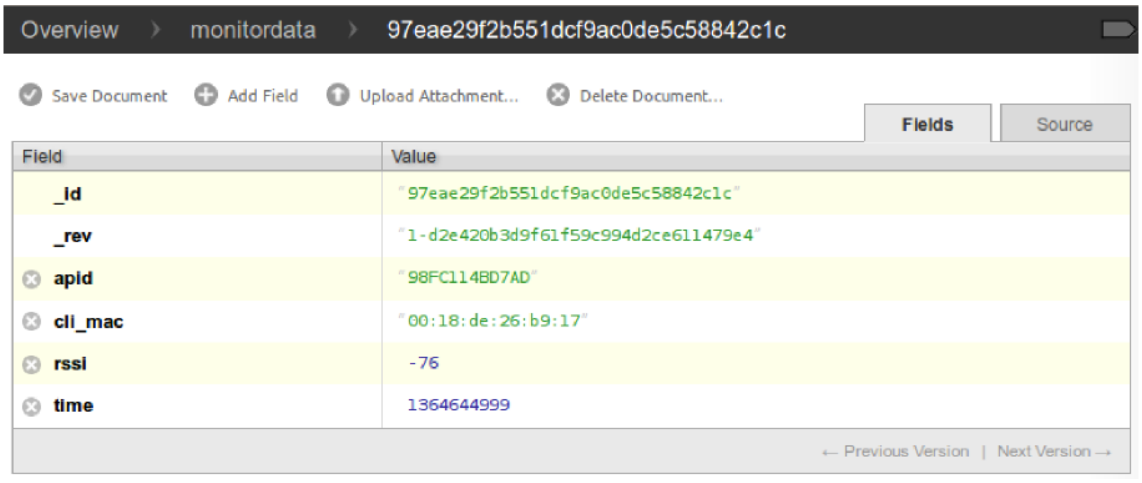
5.4 Storing and Managing Data

There are many ways that we can store data, but finding the best possible way to store it so that it fits our data access pattern requires some analysis. In our original objective, we want to find a database that is massively scalable to handle the continuous stream of data from all APs, we want to have flexible data types and schema and we do not need the time critical transaction feature of relational database. This is because we are not talking about high frequency trading in Banks, in which each of the trade orders need to observe strict consistency. In order to maintain strict consistency, the database management system would have to sacrifice read and write performance of data. Hence, since we do not need such feature, it is clear that we should try out the next generation database, NoSQL, which becomes more and more popular recently due to the emergence of different NoSQL databases such as HBase, CouchDB, MongoDB and Cassandra. NoSQL has very fast write performance, which is good for us to *push in* more data simultaneously collected from each AP. Even if we have a thousand of APs, this would be no sweat for NoSQL database.

The best thing that these NoSQL solution provides would be their tight integration with MapReduce, which is a powerful framework to process huge amount of data in parallel and across many machines. An alternative to MapReduce would be to use the Online analytical processing (OLAP) feature of relational database. However, this work slightly different from MapReduce because it requires us to write up a specific query statement to obtain the aggregated results that we want from the database. OLAP results are usually generated when the query is executed and the results are usually not stored. This would be quite expensive if we have many users who want to see the same results and the database have to execute that many times. Furthermore, MapReduce is more flexible in allowing us to put in more logic into the Map and Reduce functions than the OLAP queries. The results from one MapReduce job could be passed on to another MapReduce job for further processing or stored as tab-separated values in a text file or stored directly to a database.

5.4.1 Comparison between HBase and CouchDB

After much analysis and reading up of the books written for some of the NoSQL databases, we have narrowed our choice down to two. We attempt to analyse the performance of HBase and CouchDB and their features. We attempt to gives the rationale behind our choice below:



Field	Value
_id	"97eae29f2b551dcf9ac0de5c58842c1c"
_rev	"1-d2e420b3d9f61f59c994d2ce611479e4"
apid	"98FC114BD7AD"
cli_mac	"00:18:de:26:b9:17"
rssi	-76
time	1364644999

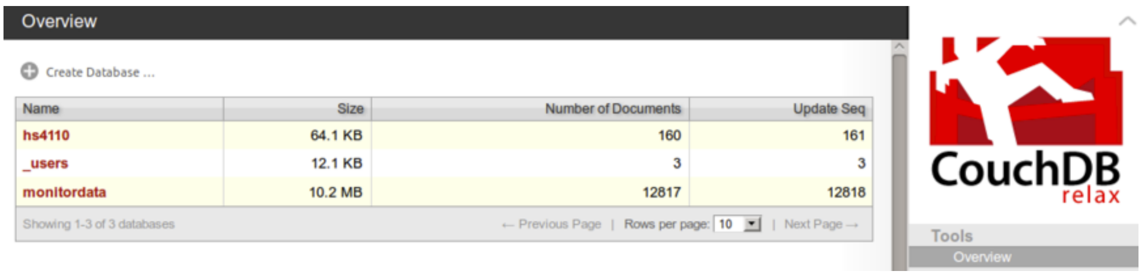
Figure 5.7: Illustration of *Documents* in CouchDB

- **Storage:** In HBase, data is stored as key-value pair and we have complete control over what data types the key or value should be stored in. This is because HBase stores the key and value in bytes and provides a Java Bytes Utility package for us to do the conversion between bytes and the actual data types (String, Long, Integer and others). Before we want to store the data in HBase, we will have to convert it to bytes first, which is really fast with HBase Bytes Utility. In CouchDB, data is stored in separate *documents*. For example, in Figure 5.7, we can see that a detection record[8] is stored as a document. CouchDB relies on JSON basic data types and we have less control on instructing what data types CouchDB should

[8]We have defined what a detection record means earlier in Section 5.3.4

store for each value. In HBase, each detection record can be stored as a row with multiple columns.

- **Access:** Data can be inserted into HBase using its Java Client package, which uses Remote Procedure Call (RPC) in its implementation. However, CouchDB allows us to insert data into the database by using HTTP via its REST API. Using HTTP is a little slower and is not that efficient.
- **MapReduce:** HBase allows us to *chain* multiple MapReduce jobs, i.e., the result from the first MapReduce job can be passed as an input to the second MapReduce job. However, CouchDB has a built-in MapReduce feature, which allows only one job to be executed. Usually, we require executing a few MapReduce jobs to achieve a final aggregated results that we want.

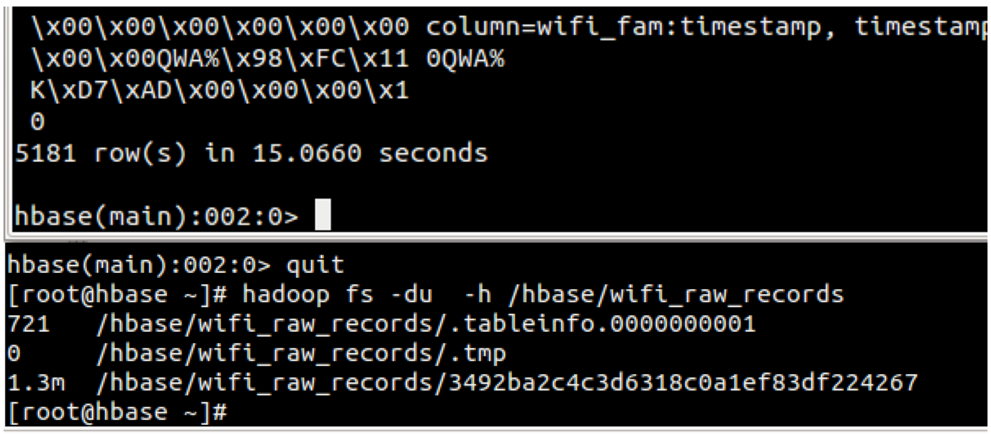

Overview

Create Database ...

Name	Size	Number of Documents	Update Seq
hs4110	64.1 KB	160	161
_users	12.1 KB	3	3
monitordata	10.2 MB	12817	12818

Showing 1-3 of 3 databases ← Previous Page | Rows per page: 10 | Next Page →

FIGURE 5.8: Storage size for 12817 *Documents* in CouchDB


```
 \x00\x00\x00\x00\x00\x00 column=wifi_fam:timestamp, timestamp
 \x00\x00QWA%\x98\xFC\x11 0QWA%
 K\xD7\xAD\x00\x00\x00\x1
 0
5181 row(s) in 15.0660 seconds

hbase(main):002:0> 
```

```
hbase(main):002:0> quit
[root@hbase ~]# hadoop fs -du  -h /hbase/wifi_raw_records
721   /hbase/wifi_raw_records/.tableinfo.0000000001
0     /hbase/wifi_raw_records/.tmp
1.3m  /hbase/wifi_raw_records/3492ba2c4c3d6318c0a1ef83df224267
[root@hbase ~]#
```

FIGURE 5.9: Storage size for 5181 rows in HBase

Storage size comparison

In Figure 5.8, we can see that for 12817 documents, each storing a detection record with details shown in Figure 5.7, the total size that is used is 10.2 MB. This is about 834 bytes per detection record. In Figure 5.9, we have attempted to use the HBase facility to print out all values of each row and we can see that for 5181 rows, only 1.3 MB is required for storing those rows. This is about 263 bytes per detection record. This is 3.17 times better than how CouchDB stores the data. The reason behind this is that

CouchDB has a few extra metadata, which uses up quite a bit of space and CouchDB does not allow us to control the data types of the value being stored.

Although we have make use of *Restlet*, a REST client library, to implement the mechanism to push data into CouchDB from the Processing Agent, we choose to abandon the code we have written in favour of using HBase.

5.4.2 Setting up of HBase, HDFS, MapReduce and Zookeeper

Setting up HBase is time consuming and with a level of uncertainty. This is because most of HBase users are corporate users such as Facebook, StumbleUpon and Twitter, and these companies have active development teams to setup, maintain and write their applications to make use of HBase. If there are more ordinary users, there would be more documentations and instructions shared by other users like us. Hence, a large portion of our time was also spent on setting HBase, HDFS, MapReduce and Zookeeper. Since HBase makes use of Hadoop Distributed Filesystem for storing its data, it also can make use of Hadoop MapReduce functionality. We also need to install a Zookeeper, a distributed coordination service, which is required as part of HBase deployment.

We attempt to use the Cloudera distribution[9] for the installation of HBase and other components. However, even using Cloudera distribution and following its instruction, we still could not get HBase to work due to a number of problems, which take us a long time to fix. We have briefly summarised these problems below.

- **Incompatible Versions:** Since HBase requires a few other components of Hadoop to be installed, there are incompatible versions. To make things worst, since we needed to use Hadoop and HBase Java client packages, some versions of the client packages are not compatible with the version of Hadoop and HBase server components. Although we installed HBase 0.94.2 on the server, its associated Java client package version 0.94.2 is not compatible with it. After we wrote our MapReduce code making use of the Java client package version 0.94.2, the execution throws a *weird* exception, which we could not understand and searching through the internet yield minimal help. It took us a long time before we realised that using an older version of the HBase Java client package 0.92.1 works with the HBase server 0.94.2. We have raised this issue to the HBase development community.
- **Heap size:** Since HBase is built for massive scalability, its memory requirement is huge as well. For HDFS, there are a few different components such as *Datanode* and *Namenode*. Within HBase, there are *Hbase Master*, *Hbase RegionServer* and *REST server*. There are also *MapReduce TaskTracker* and *JobTracker* as well

[9]Cloudera provides hosting of some HBase and Hadoop versions that we can download and install.

as *Zookeeper*. Since we choose to setup HBase and Hadoop in Pseudo-distributed Mode for this project, the whole setup requires huge amount of memory on a single server. In Pseudo-distributed Mode, each of the components we have mentioned would exist as a separate process on the computer system. We need to find the different configuration files, which are located in many different locations, to alter the JVM Max Heap size allowance to limit the amount of memory each process uses. We also have to decide on a value that would not cause some of the components to run out of memory.

- **IpV6:** Currently, HBase is reported to cause some issues with IpV6. We discovered this after our code threw up some exceptions and we found out that it was related to IpV6. Hence, we disable the IpV6 support in CentOS, which is the Linux OS we use for our HBase setup.
- **Reverse DNS Lookup:** HBase requires that we properly configure the Reverse DNS Lookup in order for it to function properly.

5.4.3 Data Schema Design

	packet_details			
	ap_mac	terminal_mac	rssi	timestamp
row_key1	01:02:03:04:05:06	22:22:22:AS:BB:CC	-65	1369908231
row_key2	...	...	...	...
row_key3	...	...	...	...

TABLE 5.2: HBase Table Structure for Detection Records[10]

Although HBase is flexible on schema, we still need to know how we define our row key, so that it allows us to query for our data. Designing a good row key structure is very important in HBase. This is because it will provide ease of access to the data that we want and for performance purposes. We have reproduced the same table example that we have given in Chapter 2 (Background) so that we can easily refer to it in this chapter. In Table 5.2, *row_key1* is a row key, *packet_details* is a column family and *ap_mac, terminal_mac, rssi* and *timestamp* are column qualifiers. *ap_mac* is the MAC address of the AP, which detects the terminal. *terminal_mac* is the MAC address of the terminal being detected. *rssi* is the received signal strength. *timestamp* gives the time at which the AP detects the terminal.

We have explained before in Background that HBase might store column families on different RegionServers (servers that host small chunks of HBase table) for high availability and scaling purposes. However, HBase also relies on the row key to decide which rows go to which RegionServers. Hence, if we do not design a good row key, this may affect the performance of data read and write.

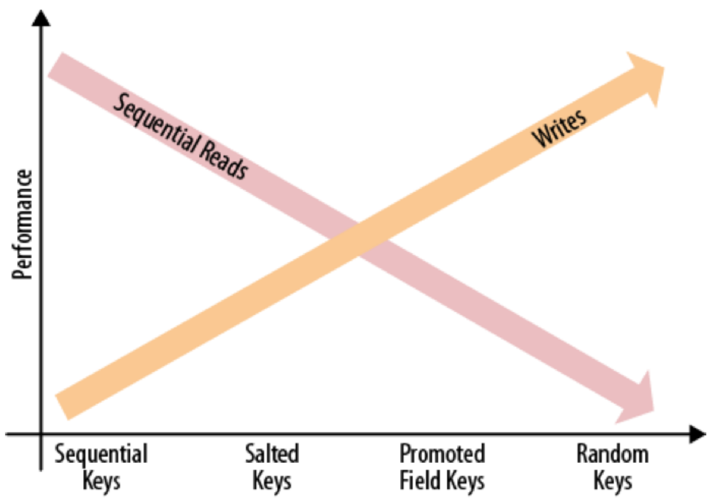


FIGURE 5.10: Balance between *sequential read* and *write performance* [18]

In Figure 5.10, *sequential key* refers to a row key that follows a sequence such as 1,2,3 ... 100. *Random key* refers to a key that is generated randomly. Using a sequential key, it would be faster for us to select detection records that fall within a range of time.

We have defined our row key to have the following structure.

$$\langle cluster\_id \rangle - \langle timestamp \rangle - \langle ap\_mac \rangle - \langle incremental\_count \rangle$$

The row key shown above is a composite row key, which is make up of different pieces of information that we combine together for ease of querying the row from the table. It should be noted that the *precedence* increases from left to right. We design the key this way with consideration of the way we are going to select a range of rows for input to MapReduce jobs later. We provide explanations for the row key design below:

- **cluster_id** We may have many clusters of APs deployed in different location, for example, 20 APs in *Shopping Mall 1* and 30 APs in *Shopping Mall 2* and 50 APs in *Shopping Mall 3*. The *cluster_id* would serves to segregate the records that belong to different clusters.
- **timestamp** Next, we have the *timestamp*. HBase provides a feature to *scan* for a range of rows in order to fetch them. The timestamp contributes the sequential portion of the key so that we can specify a *scan start key* and *a scan end key* to select rows that have their timestamp portion of the key falling in between the start and end key. We will explain this more later as we start explaining about our aggregation logic.
- **ap_mac** As for *ap_mac*, we want to include it in the row key so that we know which AP the particular record belongs to.

- **incremental_count** Finally, since an AP may detect more than one terminals with the same timestamp (remember that we are inserting timestamp for each detection record at the Processing Agent), we need to differentiate between the records by introducing the *incremental_count* component, which has a range of 0 up to n depending on how many terminals an AP would detect within the 30 seconds of scanning.

It should be noted that the row key structure that we have discussed above would be used for storing a detection record (*ap_mac, terminal_mac, rssi, timestamp*).

HBase Scan feature

One of the beautiful feature of HBase is that it has a *scan* feature, which allows us to specify the range of rows we want to retrieve. The performance of the scan is subjected to how well we design the row key too. That is why row key design that we have explained earlier is important.

```
//clusterid always start from 0
byte[] clusterStartID= Bytes.toBytes(CLUSTER_START_ID);

// the starting timestamp we want to start retrieving
byte[] startTimestamp = Bytes.toBytes(startTime);

//construct byte arrays for making the startRowKey
byte[] startRowKey = new byte[clusterStartID.length  + startTimestamp.length];
int offset = 0;

//put the clusterStartID and startTimestamp into the byte arrays we have initialised
offset = Bytes.putBytes(startRowKey, offset, clusterStartID, 0, clusterStartID.length);
Bytes.putBytes(startRowKey, offset, startTimestamp, 0, startTimestamp.length);

// padding the tail of row key so they are all zeros with no cardinality
startRowKey = Bytes.padTail(startRowKey, APMAC_LENGTH + INCRE_COUNT_LENGTH);
...
...
// endRowKey is constructed in about the same way as startRowKey but using
// an endTimestamp
endRowKey = ...
...
...
Scan s = new Scan(startRowKey, endRowKey);

//specify what columns we want to retrieve
s.addColumn(WIFI_RAW_RECORD_FAM, APMAC_COL);
s.addColumn(WIFI_RAW_RECORD_FAM, RSSI_COL);
...
...
```

Listing 5.4: A simple example to illustrate scanning for a range of rows by specifying the start and end key.

In Listing 5.4, we have shown an example of how we construct the start and end row key in order to retrieve the range of rows that we want. This is important because if we want to aggregate records that fall between 10AM and 2PM of today , we would use the Unix time format of 10AM (1371117600) as the *startTime* and that of 2PM (1371132000) as the *endTime*. Since we have chosen to include the timestamp in the row key structure, this would allow us to retrieve the detection records that fall within this range for aggregation simply by creating the *scan* object like the one we have in Listing 5.4.

From Listing 5.4, we can see that we pad the tail of the rest of the row key on Line 16. This means that only the *cluster_id* and *timestamp* would take precedence.

5.5 Aggregating Data

In this section, we will explain the logic behind our MapReduce functions, which are powerful in localising a terminal, counting the number of terminals near each AP and tracking how long each terminal stays near an AP. The great thing about using Hadoop MapReduce together with HBase is the native support from HBase for MapReduce. This is because HBase's data is stored on HDFS in a distributed fashion, hence, the MapReduce component of Hadoop can also be carried out on the HBase's data in parallel. The good thing about this is that we can use data that is stored in HBase's table as both the *source* and as a *sink*. We can specify which table will provide the data as the input of the Map function and which table will be responsible for storing the output results from the Reduce function. The *scan* feature that we have discussed earlier is extremely useful here for MapReduce. It allows us to specify which range of rows we want to retrieve and pass as input to the Map function.

```
import org.apache.hadoop.hbase.mapreduce.TableMapReduceUtil;
import org.apache.hadoop.hbase.mapreduce.TableMapper;
import org.apache.hadoop.hbase.mapreduce.TableReducer;
...
...
TableMapReduceUtil.initTableMapperJob(WIFI_TABLE_NAME, scan, Mapper1.class,
        ImmutableBytesWritable.class, Put.class, job);
TableMapReduceUtil.initTableReducerJob(WIFI_AGGRE_TABLE_NAME, Reducer1.class, job);
...
```

Listing 5.5: Importing relevant packages and setup MapReduce jobs.

In Listing 5.5, it shows the packages that we need to import in Java in order to use the Hadoop MapReduce with HBase's table, in which we create to store data.

The `initTableMapperJob()` function is called to run the Map task by specifying the table that is used as input, in this case, *WIFI_TABLE_NAME* holds the raw detection records of terminals that we have collected. *scan* is an object, which we have created according to the code in Listing 5.4 earlier. *Mapper1.class* gives the Map function, which we need to implement. *ImmutableBytesWritable.class* and *Put.class* are the data structures of the output key and value of the Map function respectively. *job* is just the MapReduce job we want to run.

The `initTableReducerJob()` function is called to run the Reduce task by specifying *WIFI_AGGRE_TABLE_NAME* as the table that is used to store the output aggregated results from the Reduce phase. *Reducer1.class* gives the Reduce function, which we need to implement.

Apart from using HBase table that is specified like above as input to a Map function, we could also access other tables in HBase in both Map and Reduce function when needed. For example, we may have an HBase table that can be used as a lookup table within the Map or Reduce function. We could even insert or delete data in any HBase tables within the two functions. This feature becomes handy when we are dealing with the New versus Returning WiFi users aggregation, in which we store a history of users we have detected before in order to infer whether they are new or returning and access this *history* table within the Reduce function.

Finally, before we zoom into each types of aggregation, we would like to mention that aggregating data requires getting our *hand dirty* with the data itself, analysing each stages step by step to verify that we are aggregating the right thing. This also involves printing out the data at both the Map and Reduce function to check whether our logic is right and the output is what we want. We also defined some unit tests that use specific test suites based on some scenarios and cases we have come up with to check our aggregation logic.

5.5.1 Overview of Aggregation Process

In our project, a terminals may be detected by a few APs nearby to it, hence, we need to use the RSSI information to localise a terminal to determine which AP is the terminal closer to. This corresponds to the *MapReduce Job 1* in Figure 5.11. After we have localised all the terminals, we would have the data available in the *Localised Terminal Records* table. The MapReduce job for this localisation process only happens once and all other types of aggregation can make use of the data in *Localised Terminal Records* table. Storing the results is a good approach because we will not waste computing

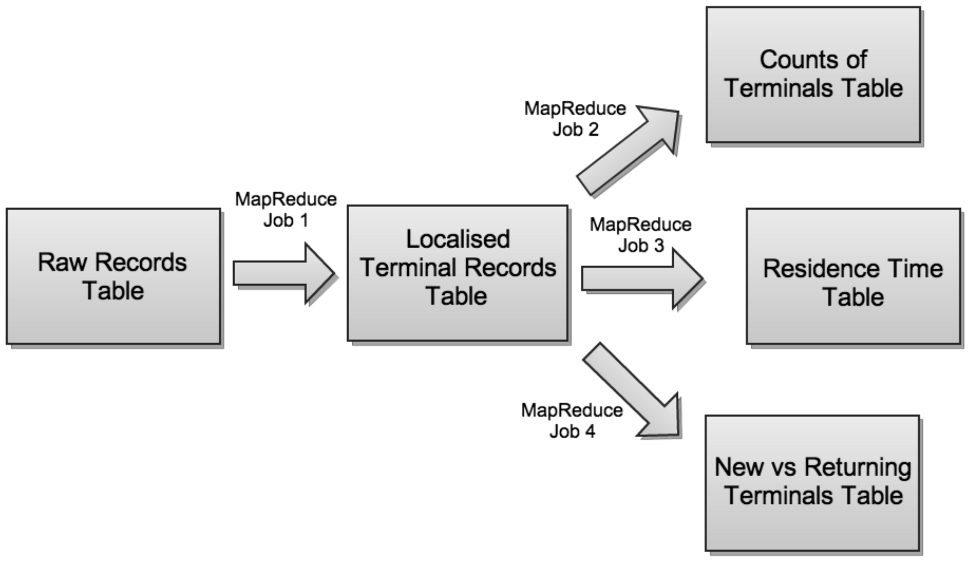


FIGURE 5.11: MapReduce work flow

resources localising again and again. After localising the terminals, we would carry out the following aggregations:

- We want to count the number of terminals that are close to each AP. This is handled by *MapReduce Job 2*. The *Counts of Terminals* table stores the aggregated results, which we can query from the GUI for plotting graphs or drawing charts.
- We want to determine how long each terminals stay close to each AP, i.e. their *residence time* at each AP. This is done with *MapReduce Job 3* and the results are stored in *Residence Time* table.
- We want to determine the number of new and returning terminals for each AP. We do not use unique terminals but terminal sessions in our counting, i.e., a terminal may come close to an AP in the morning (count as new) and again in the evening (count as returning). This aggregation is done with *MapReduce Job 4* and the results are stored in *New vs Returning Terminals* table.

Now, we should already have a rough idea of how MapReduce works from discussion above and in Section 2.6.3 of Background, which we attempt to explain how MapReduce framework works. From here on, we will focus on how we are implementing our Map and Reduce functions in order to obtain the type of aggregation results that we want.

5.5.2 Localising Terminals

The *Localised Terminal Records* table that we have in Figure 5.11 would be using the same row key structure as *Raw Records* table. This is because *MapReduce Job 1* just attempts to localise each terminal by associating it to its nearest AP by using RSSI information, thus, it seems like we are just removing some of the *extra* detection records from the *Raw Records* table. We will use the HBase *scan* feature to select the range of rows that we want to pass into the Map function as input.

$$\underbrace{\text{row\_key}}_{\text{row key}} \; \underbrace{\text{ap\_mac} \;|\; \text{terminal\_mac} \;|\; \text{rssi} \;|\; \text{timestamp}}_{\text{columns}}$$

Table 5.3: A Row Representing a Detection Record in *Raw Records* table and *Localised Terminal Records* table. Both tables have the same structure. The row key has the structure that we explained earlier under Data Schema Design section.

Map function

Input key: $\langle row\_key \rangle$
Input value: $\langle ap\_mac, terminal\_mac, rssi, timestamp \rangle$
Output key: $\langle terminal\_mac \rangle - \langle time(yyyyMMddHHmmss) \rangle$
Output value: $\langle row\_key \rangle - \langle ap\_mac, terminal\_mac, rssi, timestamp \rangle$

The input key shown above is the row key of a record as illustrated in Table 5.3 and the input value is a collection of columns within the row. Each row, representing a detection record, that falls within the range of time we have selected using the HBase *scan*, would be passed into the Map function one at a time. The Map function would be executed once for each input key and value.

Within the Map function, we will use the timestamp that is passed in as input value and convert it to another format that is usable such as yyyyMMddHHmmss (yearMonthDayHourMinuteSecond) (1). During the conversion, since we are using Unix time format, Java would take care of any daylight saving or timezone issue for us by using the timezone of the server this MapReduce job is execute on. With the format mention in (1), we will round off the time to the previous 0 seconds or 30 seconds. For instance, a terminal that is detected at a time of 2013-05-25-14-56-33 would be rounded to 2013-05-25-14-56-30 and at a time of 2013-05-25-14-56-22 to 2013-05-25-14-56-00. We would then emit out the *output key* as a concatenation of *terminal_mac* and *time* using the format in (1). What we are trying to achieve here is to classify together the records for the same terminal, which is generated within the same 30 seconds of time. Then, we simply pass the input value as the output value.

By emitting the records this way, those records representing the same terminal detected by multiple APs within the same time interval of 30 seconds would be grouped together under the same key ⟨*terminal_mac* and *time*⟩. This group would then be passed as an input to the Reduce function.

Reduce function

Input key: $\langle terminal\_mac \rangle - \langle time(yyyyMMddHHmmss) \rangle$
Input value: $[\{\langle row\_key \rangle - \langle ap\_mac, terminal\_mac, rssi, timestamp \rangle\}]$ (2)
Output key: $\langle row\_key \rangle$
Output value: $\langle ap\_mac, terminal\_mac, rssi, timestamp \rangle$

The output of the Map phase would becomes the input of the Reduce phase. After the Map phase, those output values sharing the same key would be grouped together. The input value of the Reduce function is a list of records sharing the same key. We would iterate over this list and find out the record with the highest RSSI value. We would then output the row key of that record, which can be obtained from (2), and the columns for that record also from (2).

Minimise "Ping Pong" effect

After conducting an experiment, which we will cover in Chapter 6 (Evaluation), we notice that there is a "Ping Pong" effect happening. "Ping Pong" effect happens when the received signal strength becomes unreliable at times leading to a WiFi terminal being associated with one AP at one time and to another at subsequent time although the terminal has not moved. This effect is most commonly observed when a terminal is located directly in between two APs.

In order to fix this problem, we sort the list of records from the input value of the Reduce function using natural ordering on the *ap_mac* from each record. We would then introduce a *RSSI_DIFF_THRESHOLD* when comparing the RSSI value between two records. If one record has RSSI value higher than another record by 5, we will choose the former one. But if a record has RSSI value higher only by 3 than another one, we will not consider choosing the former. The natural ordering introduce a *precedence* or *favour* for a record detected by a particular AP. The *RSSI_DIFF_THRESHOLD* serves to break this *precedence* or *favour* for a record with RSSI that is distinctively higher. This would slightly reduce the effect of "Ping Pong", in which we end up localising a terminal to one AP at one time and to another at subsequent time, just because there is a small improvement in RSSI value for the latter.

Object reference error

During the time we worked on this localisation algorithm, there was one particular bug, which caused us to spend a lot of time in trying to debug. This is because we do not know whether the error happens in the way HBase execute our Map and Reduce functions or there is error in our code. From Listing 5.6, we can see that everything seems

```
1
2       //Put is an object representing a row in an Hbase table
3       Put closestRecord = null;
4       int bestRssi = −300;
5
6       for (Put p : values) {
7           int rssi = ... //Get RSSI encapsulated in p
8
9           int rssiDiff = rssi − bestRssi;
10          if(rssiDiff > RSSI_DIFF_THRESHOLD){
11              bestRssi = rssi;
12              closestRecord = p;
13          }
14      }
15      ...
```

Listing 5.6: Illustrating a bug in object reference.

to look *fine*. However, on Line 12, when we store the reference of p, a row (representing a record) with the highest RSSI so far, to *closestRecord*, this reference is not persistent. What we discover is although we reference to the p in the current iteration, Java still discard that p object for that iteration. The final result of *closestRecord* actually always reference the p from the last iteration of the *for loop*. In order to solve this problem, we realise that HBase client package provides a method for *cloning* a Put object by constructing a new object with the same state as the existing one. In Listing 5.7, we replace Line 12 in the previous listing with the new code to fix the problem.

```
Put tempPut = new Put(p);
closestRecord = tempPut;
...
```

Listing 5.7: Illustrating a bug in object reference.

5.5.3 Count Statistics

After localising the terminals by associating them to their closest AP, we would have the aggregated results in *Localised Terminal Records* table. From here on, all our aggregations, namely *counting, residence time* and *new versus returning*, would make use of data from *Localised Terminal Records* table. For this section on Count Statistics, our objective is to count the number of terminals that are close to each AP. After this aggregation, we would store the results in *Counts of Terminals* table, which we have mentioned in Figure 5.11. It should be noted that we are counting the number of terminals that are close to each AP during a 1 minute interval.

Map function

Input key: $\langle row\_key \rangle$
Input value: $\langle ap\_mac, terminal\_mac, rssi, timestamp \rangle$

$$\underbrace{\langle ap\_mac \rangle - \langle time(yyyyMMddHHmm) \rangle}_{\text{Map output key}} \quad \Big| \quad \underbrace{\langle terminal\_mac \rangle}_{\text{Map output value}}$$

Table 5.4: Count Statistics Map Function Output Key and Value

The input key shown above is the row key of a row (representing a record) in *Localised Terminal Records* table and the input value is a collection of columns within the row. Table 5.4 shows the output key and value of the Map function.

Within the Map function, we will use the timestamp that is passed in as input value and convert it to another format that is usable such as yyyyMMddHHmm (yearMonthDayHourMinute) (3). We position the year portion to the far left of the format in (3) since it has higher precedence. Notice that this time round, we *chop off* the *second* part of the time format when compared to previous section on Localising Terminal. This is because we want to count only those records for different terminals[11] that are generated within the current minute. For example, a terminal is detected at 2013-05-25-14-**56-22** (at 2:56:22PM) and another terminal is detected at 2013-05-25-14-**56-51** (at 2:56:51PM), we would consider counting both terminals for the time interval 2013-05-25-14-**56** (at 2:56PM) by *chopping off* the seconds part of the time. Hence, we will emit out an *output key* from the Map function as $\langle ap\_mac \rangle - \langle time(yyyyMMddHHmm) \rangle$, e.g. $\langle AA : BB : CC : DD : EE : FF \rangle - \langle 201305251456 \rangle$, since we want all records detected by the same AP within the same time interval to be grouped together. The *output value* is the *terminal_mac*. We choose to emit out this value for a reason that we will explain under the Reduce function below.

Reduce function

Input key: $\langle ap\_mac \rangle - \langle time(yyyyMMddHHmm) \rangle$
Input value: $[\{terminal\_mac\}]$ (4)
Output key: $\langle ap\_mac \rangle - \langle time(yyyyMMdd) \rangle$
Output value: $\langle no\_counts \rangle$

Within the Reduce function, we would be receiving all the MAC addresses of terminals that are being detected by an AP specified by the *ap_mac* input key. This means

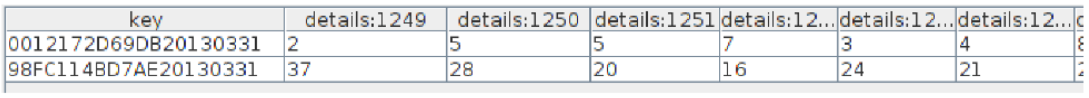
[11]Note that we have already done the localising of terminals and we are using the aggregated results in Localising Terminal table.

that after the Map phase, all the terminals that are being detected by the same AP would be grouped together under the same key and this would be passed to the Reduce function as a group of terminals' MAC addresses. In (4), we receive as input value a list of MAC addresses.

Since we are scanning every 30 seconds and within a 1 minute interval, 2 detection records for the same terminal are pushed to the server, there is a possibility that we detect a terminal at say 12:50:13PM and again at 12:50:45PM. The time is not 12:50:43PM (after 30 seconds elapsed) because we consider that there could be a few seconds of transmission delay[12] and in this example, we just take that as 2 seconds. We would not want to count the terminal twice, which contributes to the *double counting* problem. Hence, we use a `HashMap` and add each terminal MAC address to the map data structure, using MAC address as the key of the map and simply use integer value of 1 as value. Note that HashMap does not allow duplicate keys, which is what we want.

Then, we can obtain the total counts of terminals close to an AP by getting the size of the HashMap as that would indicate how many key-value elements are there in the map. This would tell us the number of unique terminals we have detected within the 1 minute interval.

Improvement to how we store the results



key	details:1249	details:1250	details:1251	details:12...	details:12...	details:12...
0012172D69DB20130331	2	5	5	7	3	4
98FC114BD7AE20130331	37	28	20	16	24	21

FIGURE 5.12: Structure of *Counts of Terminals* table

In Figure 5.12, we have illustrated how we are storing the results from the Reduce function in *Counts of Terminals* table. The row key is a composition of *ap_mac* and *date*. *details* is the column family and the column qualifier indicates the time interval (HHmm) corresponding to the number of counts for that interval, e.g. there are 2 counts for the interval *1249* which represents the period from 12:49:00PM to 12:59:00PM for the example in Figure 5.12.

Initially, we do not store the data like the one shown in the figure. We make use of a different row key design using $\langle ap\_mac \rangle - \langle time(yyyyMMddHHmm) \rangle$. We include the *HHmm* in the row key instead but this means the we will end up having many rows, which is not that practical in the long term and also hard for us to query the results from the front-end GUI.

[12]Remember that we are adding timestamp at Processing Agent.

5.5.4 Residence Time

In order to find out how long each WiFi terminal, indirectly the user, stays close to an AP, we need to write a much more sophisticated algorithm in the Reduce function than the one we have before. We would be analysing the *traces* of a terminal for the whole day across all our deployed APs.

Since we have the records of a terminal being detected by any of our APs across the day in the *Localised Terminal Records* table, we could project out the *traces* of a terminal within the day by sorting the detection records according to the timestamp of each record as illustrated in Figure 5.13. If we have more time for this project, from these *traces*, we could even attempt to analyse how a user move within the environment we are monitoring. This could be combined with the Residence Time MapReduce job.

Map function

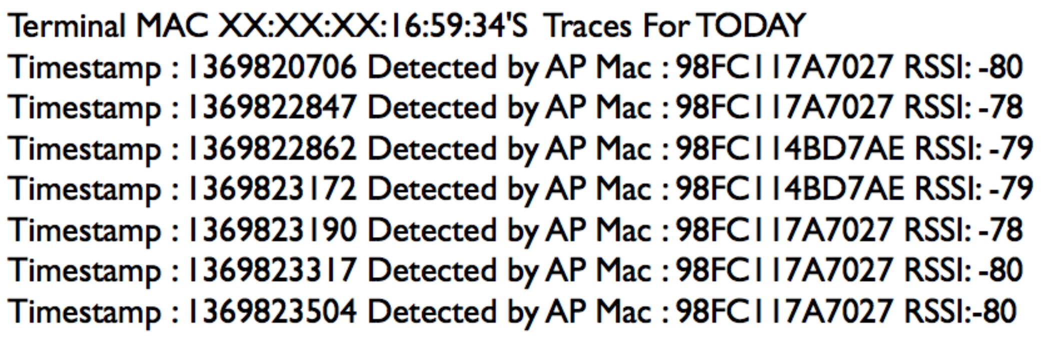
$$\underbrace{\text{terminal\_mac}}_{\text{Map output key}} \quad \underbrace{\text{ap\_mac, terminal\_mac, rssi, timestamp}}_{\text{Map output value}}$$

TABLE 5.5: Residence Time Map Function Output Key and Value

Each row (representing a record) from the *Localised Terminal Records* table would be an input to the Map function. In other words, the Map function would be applied to each row in *Localised Terminal Records* one by one. In the Map function, we will emit out the *terminal_mac* as the output key and the whole record (ap_mac, terminal_mac, rssi, timestamp) as output value as illustrated in Table 5.5.

Reduce function

After the Map phase, since we have emitted out *terminal_mac* as the Map output key, all the detection records belonging to a terminal would be grouped together under the same key, *terminal_mac* in this case. Hence, we will receive *terminal_mac* as an input key in the Reduce function and a list of records ([{*ap_mac, terminal_mac, rssi and timestamp*}]) as input value. We will iterate over this list of records and attempt to sort these records according to the timestamp, by ascending order of time. Figure 5.13 shows an example illustrating part of the traces of a terminal's presence across the day, sorted by the *timestamp* and show information such as which AP detects the terminal and what is the RSSI associated.



```
Terminal MAC XX:XX:XX:16:59:34'S  Traces For TODAY
Timestamp : 1369820706 Detected by AP Mac : 98FC117A7027 RSSI: -80
Timestamp : 1369822847 Detected by AP Mac : 98FC117A7027 RSSI: -78
Timestamp : 1369822862 Detected by AP Mac : 98FC114BD7AE RSSI: -79
Timestamp : 1369823172 Detected by AP Mac : 98FC114BD7AE RSSI: -79
Timestamp : 1369823190 Detected by AP Mac : 98FC117A7027 RSSI: -78
Timestamp : 1369823317 Detected by AP Mac : 98FC117A7027 RSSI: -80
Timestamp : 1369823504 Detected by AP Mac : 98FC117A7027 RSSI:-80
```

FIGURE 5.13: Part of the traces of a terminals presence across the day

Criteria for our algorithm in Reduce function

1. What we want to find out here is a *collective* residence time of all terminals for each AP, i.e., how many terminals stay for 5 minutes, 10 minutes, 15 minutes and so on near *AP1*.
2. Within a day, a terminal maybe detected by several of our APs, depending on how they move within an environment and how long they stay at each place. For example, a terminal may be detected by *AP1* for the whole 15 minutes, *AP3* for 30 minutes and *AP6* for 10 minutes when the terminal stays close to these APs for the respective amount of time. Hence, what we are considering here is counting the number of terminal sessions and not a unique terminal. Our algorithm must be able to handle this case.
3. Due to the fact that a terminal may not send out probe request frames that often as we can see from Section 6.3 (Frequency of Probe Request Frames under Evaluation), an AP may detect a terminal from 12:00PM to 12:10PM and from 12:15PM to 12:30PM. There is a gap of 5 minutes between 12:10PM and 12:15PM. However, we do not know whether the terminal actually move away to another place and come back at 12:15PM or the terminal did not send out probe request frames during that period of time. Hence, we need to introduce a threshold duration,x, in which we would consider the terminal already have left a place if the AP that used to detect that terminal no longer detects it for more than x minutes. If x here is 10 minutes, that means our algorithm would consider the terminal to have stayed for a residence time of 30 minutes from 12:00PM to 12:30PM.
4. Due to the fact that there is a "Ping Pong" effect, in which an AP may detect a terminal for 10 minutes and suddenly, the terminal is detected by another AP for 30 seconds, we need to decide whether we should ignore the record showing an AP detecting the terminal for just 30 seconds. Hence, we also introduce a threshold to counter this problem.

```
public static class Reducer1 extends TableReducer<ImmutableBytesWritable,
                                                  Put, ImmutableBytesWritable> {
    private HTable durationStayTable;
    private HTable returnClientTable;
    private HTable historyTable;

    /**
     * Setup is called only once for all groups that need to be reduced
     */
    protected void setup(Context context) {
        Configuration conf = HBaseConfiguration.create();
        conf.set("hbase.zookeeper.quorum", ZOOKEEPER_QUORUM);

        try {
            //Open connection to two table instances,
            //one for storing durationStay stats and another for ReturnTerminal lookup
            durationStayTable = new HTable(conf, WIFI_DURATION_TABLE_NAME);
            returnTerminalTable = new HTable(conf, WIFI_RETURN_TABLE_NAME);
            historyTable = new HTable(conf, WIFI_RETURN_LOOKUP_TABLE);
        } catch (IOException e) {
            e.printStackTrace();
        }
        ...
        ...
    }

    protected void reduce(ImmutableBytesWritable key, Iterable<Put> values, Context context)
                throws IOException, InterruptedException {

        /**
         * Algorithm for Reduce function here
         */
         ...
         context.write(key, value); //Output value to HBase table
    }
}
```

Listing 5.8: Reduce class that we pass to HBase MapReduce for executing.

Accessing a cell in HBase table multiple times

Apart from projecting the traces of a terminal, there is one more special thing about our Reduce function for Residence Time. For a particular terminal within a day, we may detect multiple sessions of it. For example, a terminal may stay at a place for 30 minutes, move off for 2 hours and come back later to stay for another 1 hour. This means within that day, there are 2 residence time for that terminal, namely 30 minutes and 1 hour.

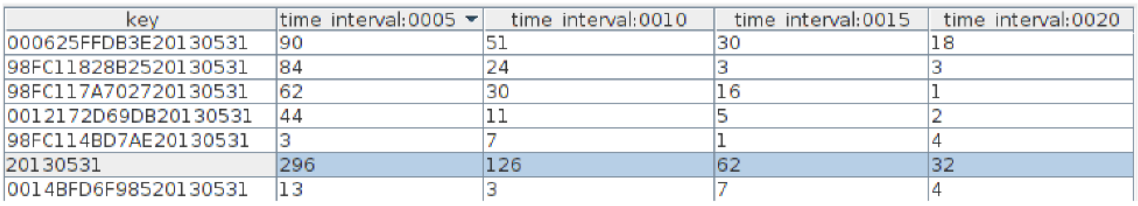
The `context.write(key, value)` method [13] provided by Hadoop MapReduce would not be able to insert value into different cells of the table multiple times but this is what

[13]`context.write()` method is used for emitting out a key and value from a Map or Reduce function. If it is used in a Reduce function, it will output the value to an HBase table if we have configured using a table as a sink for storing the results.

we need. Hence, after consulting the HBase community mailing list, a suggested solution is to open connection to the HBase table within the *Reduce class* once in the `setup()` method as shown in Listing 5.8.

Then we use the `Increment` object provided by HBase to increment a value in a cell in an HBase table. Thus, we can access multiple cells now in the Reduce function. To illustrate why we need to access multiple cells, we will look at the table structure of *Residence Time*, which stores the aggregated results for residence time. In Figure 5.14, each row represents the number of terminal, which has residence time of 5, 10, 15, 20 minutes and so on. For example, an AP with MAC address *000625FFDB3E*, has 90 terminal sessions that last for 5 minutes, 51 for 10 minutes, 30 for 15 minutes and so on, for the date 20130531 (31/5/2013)[14].

While analysing a typical terminal's traces for the day, we may find that a terminal may have a residence time of 10 minutes at *AP1*, another 20 minutes at *AP1* and 10 minutes at *AP2*. Hence, after we have this information, we need to access the different cells in the table shown in Figure 5.14 to update the value by incrementing the count.



key	time interval:0005	time interval:0010	time interval:0015	time interval:0020
000625FFDB3E20130531	90	51	30	18
98FC11828B2520130531	84	24	3	3
98FC117A702720130531	62	30	16	1
0012172D69DB20130531	44	11	5	2
98FC114BD7AE20130531	3	7	1	4
20130531	296	126	62	32
0014BFD6F98520130531	13	3	7	4

FIGURE 5.14: Structure of *Residence Time* table

In Listing 5.8, it also shows that we also open connection for other tables too such as *WIFI_RETURN_TABLE_NAME* and *WIFI_RETURN_LOOKUP_TABLE*. These extra connections are for New versus Returning aggregation, which we will discuss later in the next section. In Listing 5.8, it also shows the `reduce()` method, which represents the Reduce function that we have always been talking about.

5.5.5 New Versus Returning

The idea of deriving this type of analytic is inspired by the Google Analytic feature of tracking the percentage of new and returning visitors to a website. The idea is to track what percentage of the visitors[15] who come into contact with a particular AP today has also come into contact with it before, which could be the day before or weeks or months.

[14]It should be noted that we are considering terminal sessions here and not a unique terminal as explained in our algorithm criteria earlier.

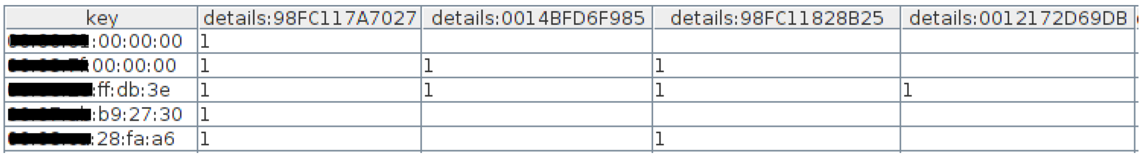
[15]We will use visitors to refer to the WiFi users owning a WiFi terminal. This is easier for business owners or administrator to understand later when we use this term in our Web GUI.

In order to implement this aggregation, we will use the records of terminal being detected from *Localised Terminal Records* table. We have tried our best to simplify the way *New versus Returning* aggregation is done. This is achieved by thinking along the line of using the *traces* of a terminal across the day. This would sound familiar to us because that is what we have been mentioning in the Residence Time aggregation section earlier.

Our objective for *New versus Returning* aggregation is to determine the number of new visitors that are close to an AP and the number of returning ones. We will count the number of visitor sessions rather than unique visitors and we will do this for each AP.

Keeping history of the Past

For this part of aggregation, although it is not entirely similar, we are partly inspired by the idea of *Free space bitmap* implemented by some filesystem to track free available sector. Since HBase table allows us to access a cell value by row and column, we can use a table like a bitmap. In Figure 5.15, each row represents a terminal's MAC address[16] and each column represents an AP's MAC address (the AP that detects the terminal). We will use this *History Lookup* table to determine whether a terminal session is new or returning one for each AP.



key	details:98FC117A7027	details:0014BFD6F985	details:98FC11828B25	details:0012172D69DB
[redacted]:00:00:00	1			
[redacted]00:00:00	1	1	1	
[redacted]:ff:db:3e	1	1	1	1
[redacted]:b9:27:30	1			
[redacted]:28:fa:a6	1		1	

FIGURE 5.15: Structure of *History Lookup* table

Factors to consider for implementing and maintaining History Lookup table

Below shows some of the questions that would come to our mind.

1. How often do we want to flush the History Lookup table? Do we flush the whole table at the same time or just individual cell value corresponding to a terminal session close to an AP?
2. Why use terminals' MAC addresses as rows and APs' MAC addresses as column?

Now, let us decide how to address those questions and explain further in detail our implementation of History Lookup table below.

[16]We have masked part of the terminals' MAC address so that it is not distinguishable.

1. Fortunately and coincidentally, HBase provides a feature called Time-To-Live (TTL) that we can set at a column family level. This means that if we specify 18,000 seconds as TTL value for a column family x, any cells that are under x will expire after 18,000 seconds has elapsed starting from the time each cell is created. Hence, we can flush history on a cell by cell basis, which is really beautiful by setting the TTL.
2. We store a terminal's MAC address as the row key and AP's MAC address as the column qualifier because HBase has the capability to allow us to have billions of rows and millions of columns. Since we may detect massive number of MAC addresses from terminals that come across any of our APs (assuming for commercial deployment) and only not more than a few thousands of APs, we can safely store the data this way.
3. History is stored per AP and not system wide. A visitor that have been to *AP1* but not *AP2* would be a returning visitor for *AP1* but treated as a new visitor to *AP2*.
4. HBase stores free null values. If a cell has no value, there is no allocation of space for the cell in HBase. In contrast, relational SQL explicitly stores the null value or allocate a space for it. This feature of HBase makes using a History Lookup table like what we have done an ideal choice.

5.5.6 Summary

We have been discussing a lot about aggregation and it is really a painful and headache process to go through the raw data when something goes wrong. This is one of the most challenging part of this project too since we have no experience before in data analytic of such scale.

As we can see from all types of aggregations so far, the design of the row key for *Raw Records* table and *Localised Terminal Records* table is very important since we make use of them extensively during the MapReduce process in each types of aggregation we have discussed above.

MapReduce concept might be easy to understand but the algorithms involved in each of the functions might require some time to digest. Hence, we hope that we have at least given the gist of how we are aggregating the data without going too much into the deep detail of the actual implementation.

5.6 GUI Design and Implementation

After we have implemented the bottom and middle layers of our system's *stack*, we finally reach the top layer. This layer is about querying aggregated data from the middle layer to display beautiful graphs and charts so that it is easier for human to comprehend the meaning behind the data we have collected. In our Web GUI, we have used some open source libraries such as Twitter Bootstrap, Smarty PHP Template Engine, jQuery and jqPlot. We have implemented quite a number of different statistical representations of the data collected, namely LiveCounts, CountStatistics, ResidenceTime, ResidenceTime Overall and New Vs Returning visitors. Figure 5.16 shows how the dashboard of our Web GUI looks like. We would explain the key challenges in implementing some of these features. In Chapter 6 (Evaluation), we will explore more of our Web GUI when we attempt to look through the trends that we have observed from our experiment conducted in the laboratory.

Our dynamic Web GUI is powered by PHP and MySQL in the backend as well as Javascript and HTML in the frontend. MySQL database is only used for storing business owners and administrators login account information only. We make use of *PHP sessions* to implement the login and logout features.

Please login into our Web GUI and try out our app-like web interface, in which the selection of each option in the dropdown menu would present a graph *live* without

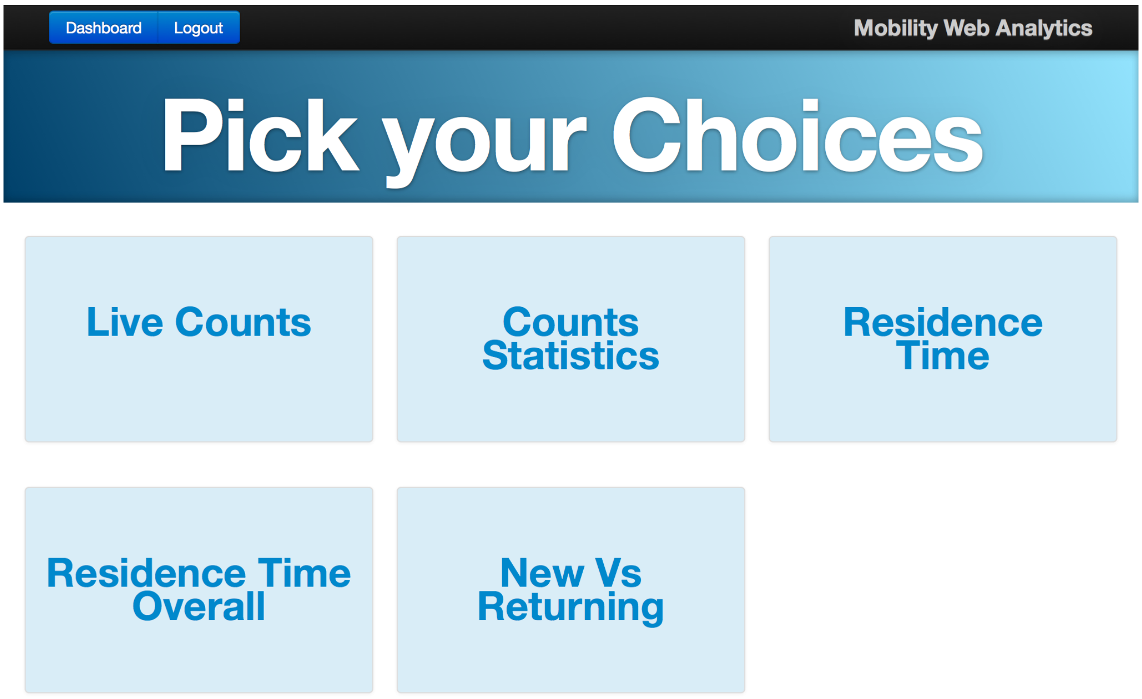


FIGURE 5.16: Dashboard of our Web GUI

reloading of webpage. The details of the URL, username and password are below. If you would like, you can even visit *http://fyp.console.magagram.com/signup.php* to sign up for an account of your own since we have configured in the backend for this to happen just for this demonstration. If there are any issues with the Website, please contact the author at *hs4110@doc.ic.ac.uk*.

- **Web GUI URL:** http://fyp.console.magagram.com
- **Login Username:** demo
- **Login Password:** 123456
- *This website is optimised and work correctly according to our testing on Chrome Browser. When copying and pasting the URL into the address bar of the browser, ensure that the URL is exactly the same as above and no extra spacing is added.*

5.6.1 Retrieving Data from HBase

HBase may provide all the exciting features and capabilities that we have seen along the way, however, it also has its downside. This would be the inconvenience of retrieving data from the database if the platform we are working on is not using Java. Since we are using PHP, Javascript and HTML for our Web GUI, we need to find another way to retrieve data from HBase. HBase currently provides a good Java client library for accessing the data stored in the table but not for other languages. Although HBase does provide a REST API, its functionality is limited, which requires some extension in order to allow us to query the set of data that we want.

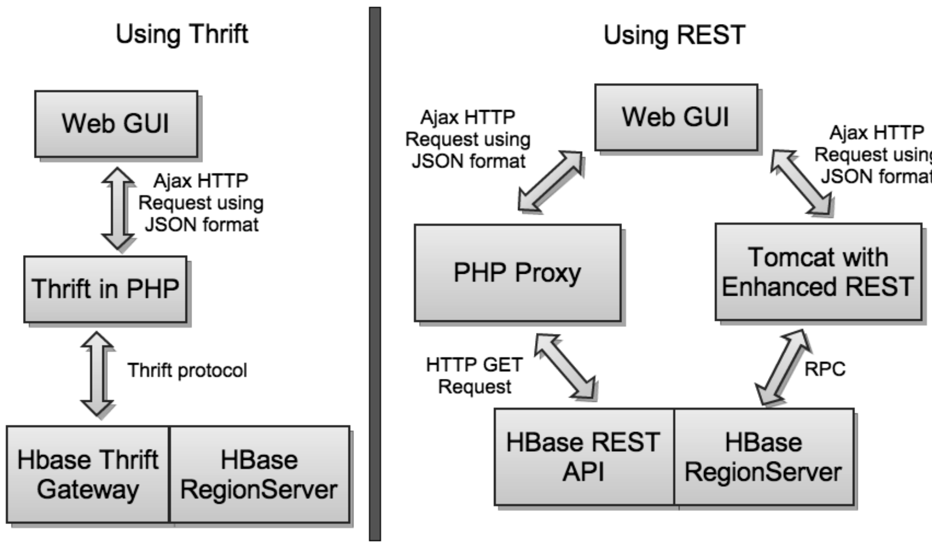


FIGURE 5.17: Two proposed ways of retrieving data from HBase to Web GUI

In Figure 5.17, we have proposed two ways of retrieving data from HBase.

1. **Using Thrift:** Thrift is a RPC software framework for scalable cross-language communication [30]. Thrift has support for many programming languages but it requires us to define an Interface Definition Language (IDL) to create a Thrift service in a language we are working on. In our case, the language is PHP. HBase has a Thrift Gateway module that can be installed on the same server as Region-Server (server that stores small chunks of the table). However, we are required to use the Thrift IDL file for HBase to generate a Thrift service for PHP. The current documentation for doing this is not very clear and after spending some time studying the feasibility of using Thrift, we think that it would not worth the effort since we do not have enough support for this method.
2. **Using REST:** HBase provides a REST[17] API that allows us to query for data in some way. We can query for a whole row from an HBase table by specifying the row key in a URI, e.g. http://hbase-rest/table_name/row_key. However, although on HBase wiki, there is a *scan* feature which we can specify a range of rows we want to query, the feature does not seem to work after much effort. Hence, we decide to implement this *scan* feature in Java by utilising the HBase Java client package and deploy this module on Tomcat. We call our module HBaseEnhance-dREST, which is shown in Figure 5.17 as Tomcat with Enhanced REST.

Since we want to use Javascript extensively to create an *app-like* effect for our Web GUI, we need to make jQuery Ajax HTTP GET request[18] directly in Javascript. However, there is a *cross-domain restriction* policy imposed by all browsers for security reason, which state that any direct Ajax HTTP GET request to a server requires that the server respond with *Content Header* set to includes “Access-Control-Allow-Origin: *”. This means that the server allow access from any origin, hence, the browser would trust that the server permits it to make Ajax HTTP GET request to it. If no such Content Header is set, the browser will not accept the server’s response.

HBase REST API does not set Content Header to include “Access-Control-Allow-Origin: *”, hence, we cannot directly make Ajax GET request to HBase REST API in Javascript. The only work around is by setting up a PHP Proxy as

[17]REST is a software architecture that involves client-server, in which the server provides a standardised application programming interface for accessing and modifying data.

[18]jQuery Ajax HTTP GET request is a method provided by jQuery Javascript library to get data from a server on a client-side using HTTP.

shown in Figure 5.17. We use the open source Simple PHP Proxy [15]. This proxy basically just accepts Ajax HTTP GET request from the Web GUI in Javascript and forward that using *PHP cURL* module to the HBase REST API. Since *PHP cURL* does not requires the server's response Content Header to include "Access-Control-Allow-Origin: *", it can interact with HBase REST API without any problems. When the data returns from HBase, the proxy would pass it to the Web GUI with proper Content Header set. It should be noted that the Thrift in PHP shown in Figure 5.17 would have to do the same thing of setting proper Content Header.

After some analysis and experimentations, we decide to use the second approach above, *Using REST*. This is because the Thrift approach does not promise a working solution while we know the REST approach is much more feasible in terms of implementation. Thus, if we want to retrieve a whole row or any rows from HBase, we will use the default HBase REST API via our PHP Proxy. If we want to use the *scan* feature to query a range of rows from HBase, we will use our HBaseEnhancedREST API, which we have implemented.

Javascript Bytes Utility and REST wrapper

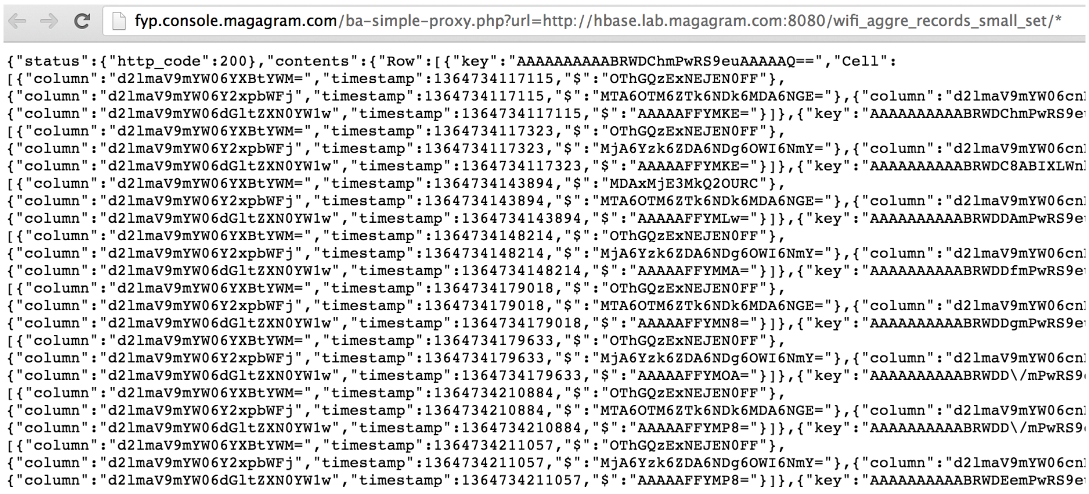
HBase REST has another problem, which we need to overcome. However, this is a common problem for everyone and if we manage to solve it, it would bring great benefits to the whole HBase community. Currently, if anyone wants to use the HBase REST, the data type for each cell in the table can only be *string*, which opposes the original idea of HBase being flexible on data types and schema.

Let us explain why this is happening. HBase stores the value of the cell in *bytes* and this value could be of any data types. If the developers can retrieve these bytes from HBase table, they would have known how to decode it since they know what data types these bytes represent. Since HBase REST uses JSON format to transmit the queried data to a client-side, it is not possible to represent bytes in JSON. Hence, the bytes have to be encoded somehow before it is transmitted to the client-side. However, HBase REST is just like a *middle man* who does not know what the bytes for these cell represent, hence, it could not *autonomously* interpret the data types of these cell values and convert them to their corresponding data types. Therefore, HBase basically states that if we want to use HBase REST, we must store the content of each cell in the table in string so that HBase REST knows that the bytes represent string. HBase REST converts the cell value in bytes to string first and then use *Base64*[19] to encode

[19]Base64 is a scheme used to represent binary data in ASCII string standard.

the string value before transmission to client-side. On the client-side, we use Base64 to decode the data into string.

However, we think that by doing that, we would waste a lot of space used to store *integer, long* and *short* data types in string. Hence, we write a *Mini Javascript Bytes Utility for HBase* and licensed it under the Apache License Version 2.0 for anyone who faces the same situation like us to use. We are sure that other developers would not want to be forced to store other data types as string in HBase table just because of the above problem. In this utility, we make use of some byte shifting techniques in Javascript to do conversion between bytes and string, integer, long or short.


fyp.console.magagram.com/ba-simple-proxy.php?url=http://hbase.lab.magagram.com:8080/wifi_aggre_records_small_set/*

```
{"status":{"http_code":200},"contents":{"Row":[{"key":"AAAAAAAAAABRWDChmPwRS9euAAAAAQ==","Cell":
[{"column":"d2lmaV9mYW06YXBtYWM=","timestamp":1364734117115,"$":"OThGQzExNEJEN0FF"},
{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734117115,"$":"MTA6OTM6ZTk6NDk6MDA6NGE="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734117115,"$":"AAAAAFFYMKE="}]},{"key":"AAAAAAAAAABRWDChmPwRS9e
[{"column":"d2lmaV9mYW06YXBtYWM=","timestamp":1364734117323,"$":"OThGQzExNEJEN0FF"},
{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734117323,"$":"MjA6Yzk6ZDA6NDg6OWI6NmY="},{"column":"d2lmaV9mYW06cn
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{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734143894,"$":"MTA6OTM6ZTk6NDk6MDA6NGE="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734143894,"$":"AAAAAFFYMLw="}]},{"key":"AAAAAAAAAABRWDDAmPwRS9e
[{"column":"d2lmaV9mYW06YXBtYWM=","timestamp":1364734148214,"$":"OThGQzExNEJEN0FF"},
{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734148214,"$":"MjA6Yzk6ZDA6NDg6OWI6NmY="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734148214,"$":"AAAAAFFYMMA="}]},{"key":"AAAAAAAAAABRWDDfmPwRS9e
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{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734179018,"$":"MTA6OTM6ZTk6NDk6MDA6NGE="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734179018,"$":"AAAAAFFYMN8="}]},{"key":"AAAAAAAAAABRWDDgmPwRS9e
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{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734179633,"$":"MjA6Yzk6ZDA6NDg6OWI6NmY="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734179633,"$":"AAAAAFFYMOA="}]},{"key":"AAAAAAAAAABRWDD\/mPwRS9
[{"column":"d2lmaV9mYW06YXBtYWM=","timestamp":1364734210884,"$":"OThGQzExNEJEN0FF"},
{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734210884,"$":"MTA6OTM6ZTk6NDk6MDA6NGE="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734210884,"$":"AAAAAFFYMP8="}]},{"key":"AAAAAAAAAABRWDD\/mPwRS9
[{"column":"d2lmaV9mYW06YXBtYWM=","timestamp":1364734211057,"$":"OThGQzExNEJEN0FF"},
{"column":"d2lmaV9mYW06Y2xpbWFj","timestamp":1364734211057,"$":"MjA6Yzk6ZDA6NDg6OWI6NmY="},{"column":"d2lmaV9mYW06cn
{"column":"d2lmaV9mYW06dGltZXN0YW1w","timestamp":1364734211057,"$":"AAAAAFFYMP8="}]},{"key":"AAAAAAAAAABRWDEemPwRS9e
```

Figure 5.18: Illustration of return query from HBase REST API

We also write a *Javascript wrapper functions for HBase REST API*, which we also release under the same license as above. We make use of `window.atob()` to decode Base64 encoded values. In Figure 5.18, we can see that the returned data from HBase REST API is a great mess in which we need to understand and do appropriate conversions. This is when our Bytes Utility and REST wrapper comes in handy. This utility and the one we mentioned earlier are released on the popular open source repository, GitHub, at github.com/hengsok/hbase.

5.6.2 Making Asychronous Ajax Request

Within our Web GUI, we make extensive number of HTTP Ajax GET request to REST interface. All of these requests can only be done by using jQuery `$.ajax()` function, which is asynchronous in nature. Asynchronous in this context means when we make a HTTP request to the server, the Javascript code will not wait for the server to response but continue executing. This creates quite a challenge for us because we have to write our code to handle *asynchronous* call carefully.

For instance, after a user chooses a date amongst the options of a dropdown menu, we make an asynchronous HTTP GET request to the server to fetch the data for that date. However, how would we know when the data comes back from the server so that we could start plotting the graphs. This is done using a beautiful feature in Javascript called *promise*. *Promise* is a programming construct that have been introduced since 1976 [33].

```

var promise = REST.getAllRowsAllCols(restEndpoint,"TABLE NAME");

promise.success(function (data) {
        if(data.status.http_code == 200){
                //use data safely here
        }
});
```

LISTING 5.9: Using Javascript promise to manage asynchronous function call.

In Listing 5.9, `REST.getAllRowsAllCols()` is an asynchronous function call. We make this call and store the promise that it returns. In `REST.getAllRowsAllCols()` function, we return a promise. Then we have the handler `promise.success()`, which will be invoked when the asynchronous call succeeds. We could then call any other functions or do something within this handler.

5.6.3 CountLive and CountStatistics

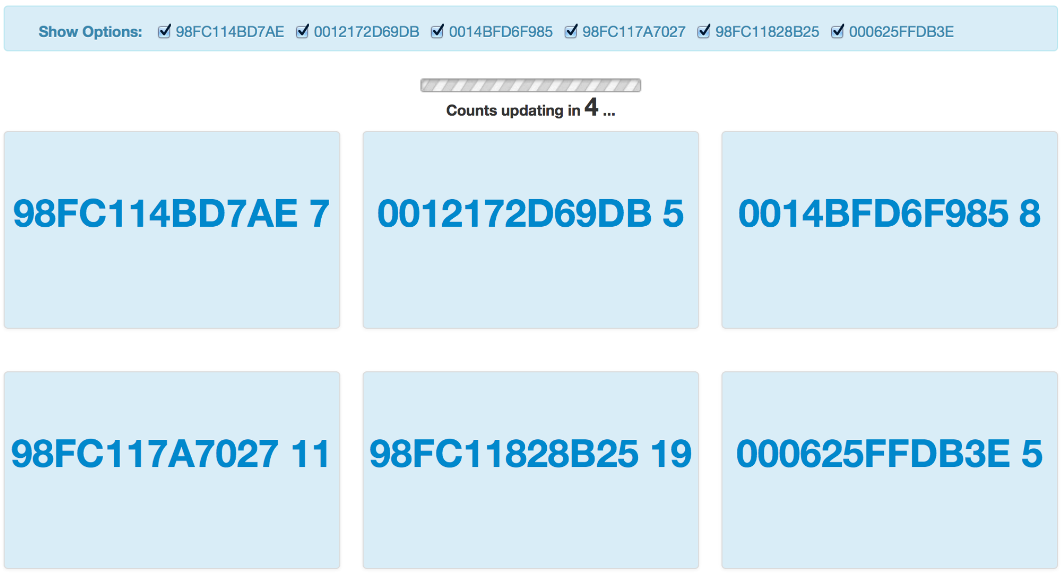


FIGURE 5.19: Illustration of CountLive page in Web GUI

A CountLive feature is great to reflect the number of terminals that are *currently* close to each of our deployed APs. Although we use the word *currently*, our implementation has a delay of 1.5 minutes from actual statistics of the real environment. This is because the MapReduce job for localising terminals and counting them requires some time to run.

In order to know when data is available for querying, we need to run a *count down clock*, which will attempt to query the server for data every 60 seconds. The time is 60 seconds because we run the MapReduce job for localising terminals and counting them every minute. We also need to carry out some error handling here in the case that data is not available, i.e., the APs are offline and not deployed.

In CountLive webpage, we also provide the checkbox option as shown in Figure 5.19 to select only the APs that we are interested to view. Whenever a check-box is changed, we will redraw the *div* HTML element in order to reorganise the thumbnails (blue rounded corner box).

In Figure 5.20 and 5.21, we show how our CountStatistics webpage looks like, which is a different webpage from CountLive.

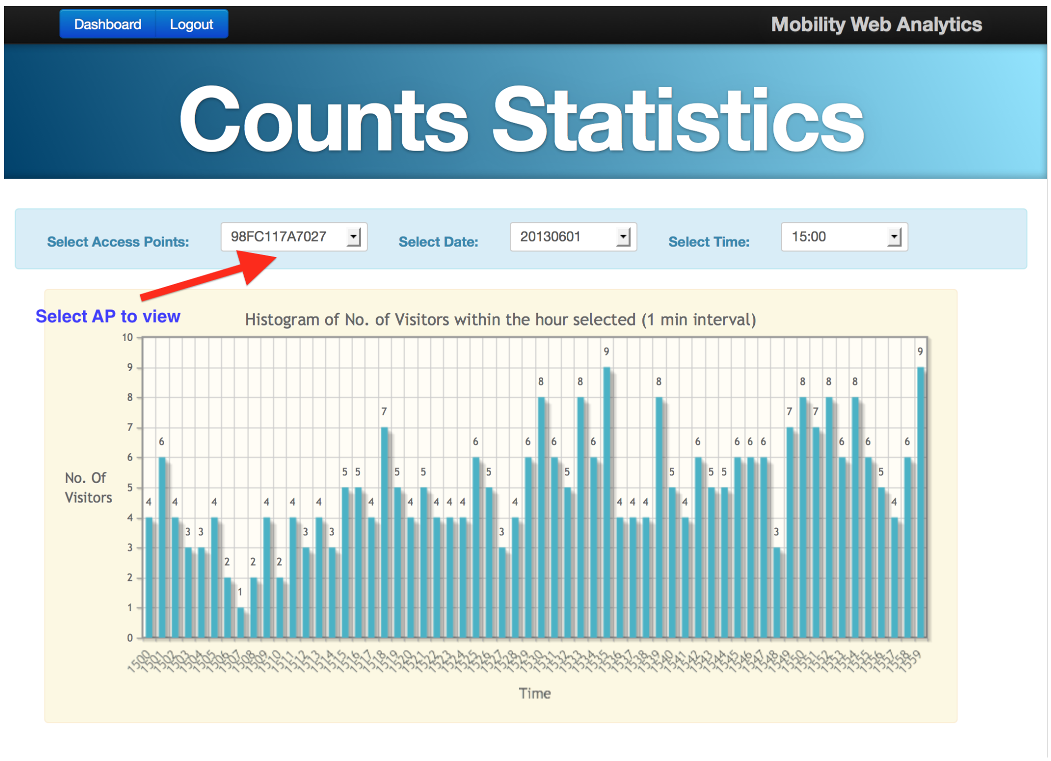


FIGURE 5.20: Illustration of histogram on CountStatistics page in Web GUI

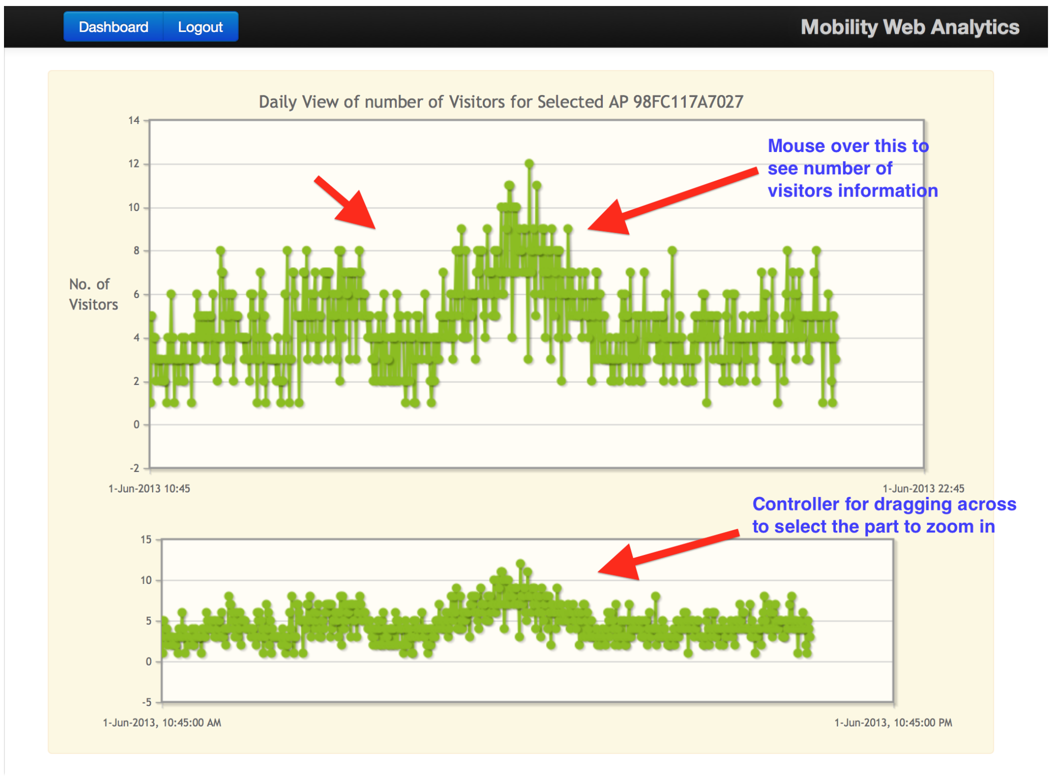

Dashboard
Logout
Mobility Web Analytics
Daily View of number of Visitors for Selected AP 98FC117A7027
No. of Visitors
1-Jun-2013 10:45
1-Jun-2013 22:45
Mouse over this to see number of visitors information
Controller for dragging across to select the part to zoom in
1-Jun-2013, 10:45:00 AM
1-Jun-2013, 10:45:00 PM

FIGURE 5.21: Illustration of Daily View with controller on CountStatistics page in Web GUI

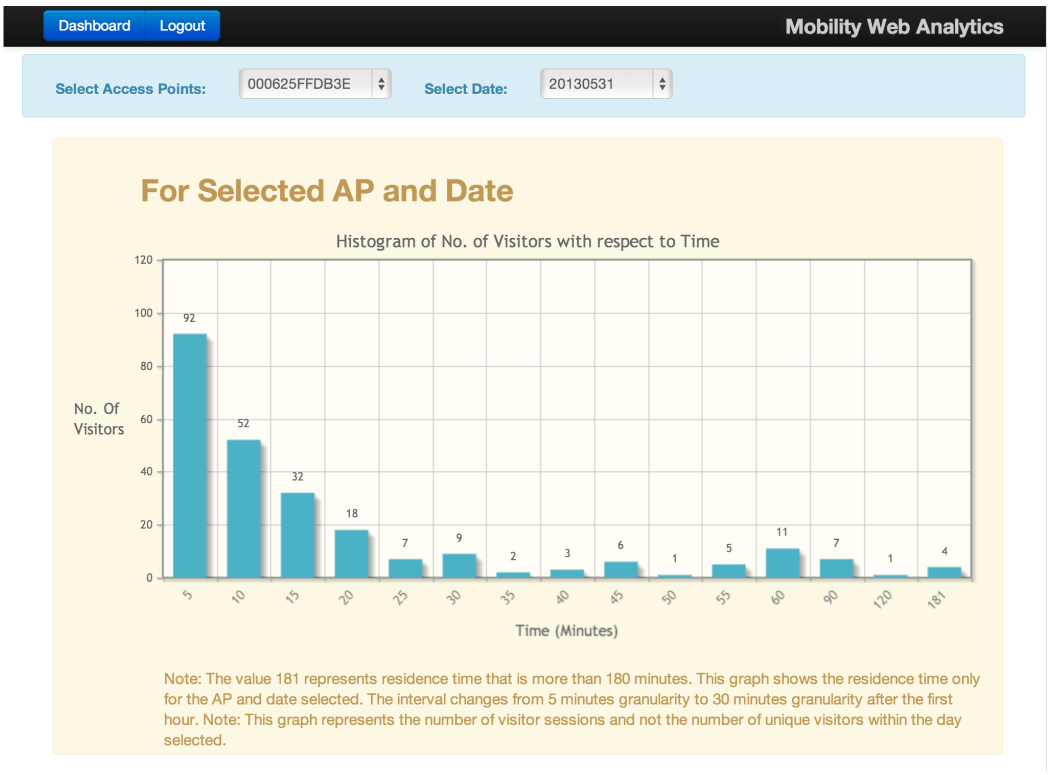
5.6.4 ResidenceTime and ResidenceTime Overall

For ResidenceTime webpage, we show only histogram of residence time for one AP across a day as illustrated in Figure 5.22.

For the ResidenceTime Overall page, we have attempted to draw up a probability density distribution across all APs for each day. This distribution is an approximation from a histogram for the residence time data. We also attempt to normalise the distribution in order to generate a better approximation. Furthermore, we make use of the *smoothing* algorithm of jqPlot, a Javascript graph plotting library, to *smoothen* out the curve.

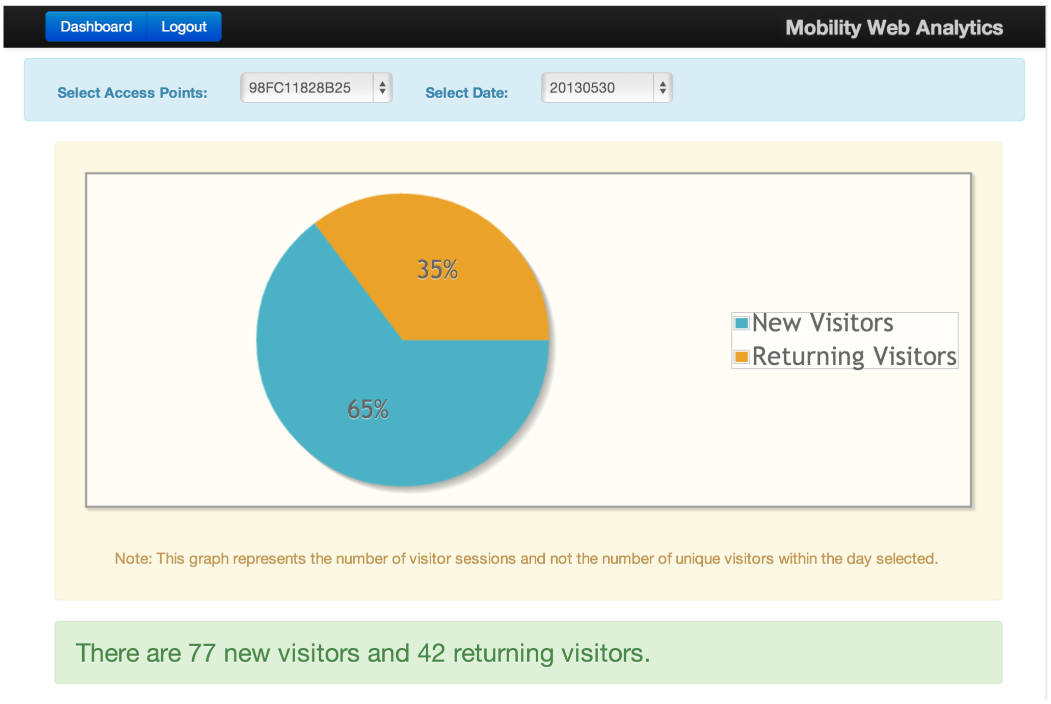
5.6.5 New and Returning Visitors

For New and Returning Visitors webpage, we decide to draw a piechart to better illustrate the percentage of each type of visitors (Figure 5.23).



Note: The value 181 represents residence time that is more than 180 minutes. This graph shows the residence time only for the AP and date selected. The interval changes from 5 minutes granularity to 30 minutes granularity after the first hour. Note: This graph represents the number of visitor sessions and not the number of unique visitors within the day selected.

FIGURE 5.22: Illustration of ResidenceTime page in Web GUI showing histogram of residence time for one AP across one day



Note: This graph represents the number of visitor sessions and not the number of unique visitors within the day selected.

There are 77 new visitors and 42 returning visitors.

FIGURE 5.23: Illustration of New and Returning Visitors page in Web GUI

Chapter 6

Evaluation

6.1 Setting up of Experiment in Laboratory

After implementing a system to track WiFi terminals, we should put it to a good test. There is a couple of issues that almost prevent us from conducting an experiment in the Department Of Computing laboratory successfully.

Firstly, our university's network and security team was concerned that our APs might interrupt the experience of using wireless internet access by individual students in the laboratory. These include radio signal interference and some students may unexpectedly connect to our APs. To solve part of these problems, we disable the broadcast of SSID across all our APs. Even if a terminal knows our SSID, we use WEP as a simple protection to prevent it from connecting to our APs.

Secondly, our department was concerned that it would be hard to wire our APs to the department's existing network. In order to solve this problem, we had decided to setup our own private network by linking up all our APs wirelessly by setting some APs into *client bridge* mode and some into *repeater bridge* mode. We used another AP, which really worked in AP infrastructure mode but not connected to the university's network, as the main AP that other APs would connect to and extend the network. This allows us to have a wireless private network in which each of the APs can communicate with each other easily. Our main objective is to allow each AP to have access to a central Processing Agent so that it could sent the collected data to it.

Finally, since our university's network and security team was concerned that our APs may exist in *AP infrastructure* mode, our APs are not allowed to connect to the school's network to gain internet access. Hence, we could not send the data collected to the database, which is hosted somewhere else on the internet. To solve this problem, we attempted to buy a 3G Dongle from O_2 in order to provide internet access via one of our APs. This could be done since we have a *Mini 3G AP* from *TP-Link*, which allows us to connect the 3G Dongle to it and there is a *RJ-45* port on the *Mini 3G AP* that provides internet access via Ethernet. Hence, we can connect one of our APs using this port and all our other APs would be configured to receive the internet connectivity as well.

After successfully tested out this idea, we realised that everything works according to what we expected. However, there was one issue with high latency caused by the unstable 3G connection. Sometimes, the 3G connection would lose internet connectivity for a short period of time before regaining. This means that if we use this method of providing internet access to our APs, there may be period of time where there are interruptions. Even after we have implemented the error handling, which we have explained in Implementation chapter, we believe this mode of providing internet connectivity is too unreliable.

Therefore, we thought again of other alternatives. We came up with an alternative, which promised to allow us to run the experiment in the laboratory successfully. We connected a laptop to the main AP, which we have mentioned before, to provide the laptop access to the private network that we had set up. We bought an extra USB WiFi adapter and plugged into the laptop to provide a second network interface for the laptop. Then, we changed the priority of the network cards/interfaces on Windows 8, which our laptop had installed so that the laptop could still have internet access via one interface and access to our private network via another. If we do not do this, we would not be able to get internet access on the laptop (running Windows) when another interface is connected to a private network.

The laptop served as a central Processing Agent in which we deployed our *servlet* on it using Tomcat. All APs had network access to this agent and they would *push* all collected data to it. Then, this agent would process the data, insert timestamp and establish a connection to the database to push the processed data to the database hosted on the internet.

Ideally, in the future, we require that all our APs would have internet connectivity, which should be the case since they are APs.

6.1.1 Deployment Overview

In Figure 6.1, it shows an overview of our deployment in the laboratory. Since we do not want to publish the map of our laboratory, we have shown only the locations, which we deployed our APs. We purposely deployed AP3 and AP2 close together to see whether our aggregation algorithm is working correctly. Indeed, we did observe a strong "Ping Pong" effect from the data we collected between these 2 APs, which prompted us to alter our Localising Terminal algorithm to introduce a threshold. This serves to indicate that our Localising Terminal aggregation is working properly after the change to our algorithm. In the figure, it also could be seen that AP2 is placed very close to the corridor. This is because it acts as a repeater bridge in which AP1 can connects to

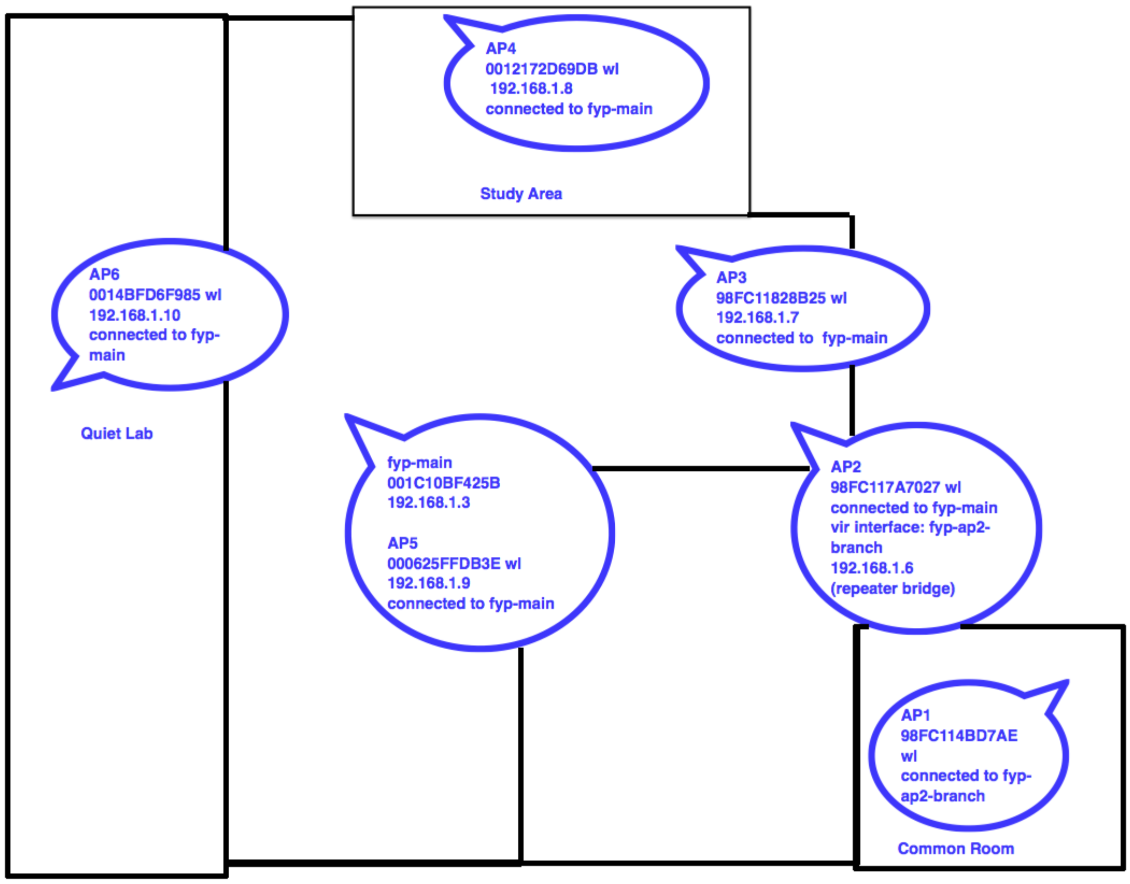
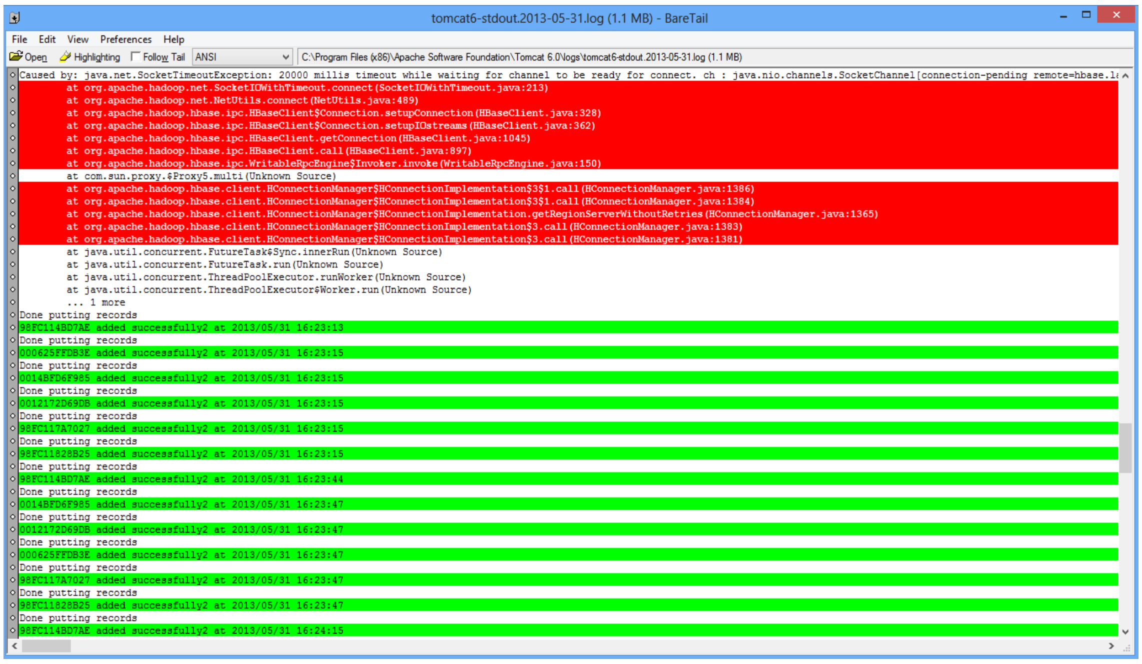


Figure 6.1: Overview of deployment

and since AP1 is in the common room, we need to keep AP2 within the range at which AP1 can connect wirelessly.

6.1.2 Monitoring APs' Heartbeat

In order to monitor the progress of our experiment and to ensure that everything was running as expected with no AP offline, we have written a simple code in our Processing Agent to output a progress statement to the Tomcat log file. Then, we used the *BareTail* program to follow the tail of the log file. The software would show green colour highlighting if the APs are adding detection records to the Processing Agent successfully and red if something wrong is happening. Everything was live updated and this is shown in Figure 6.2.


tomcat6-stdout.2013-05-31.log (1.1 MB) - BareTail
File Edit View Preferences Help
Open Highlighting Follow Tail ANSI
C:\Program Files (x86)\Apache Software Foundation\Tomcat 6.0\logs\tomcat6-stdout.2013-05-31.log (1.1 MB)

```
Caused by: java.net.SocketTimeoutException: 20000 millis timeout while waiting for channel to be ready for connect. ch : java.nio.channels.SocketChannel[connection-pending remote=hbase.la
        at org.apache.hadoop.net.SocketIOWithTimeout.connect(SocketIOWithTimeout.java:213)
        at org.apache.hadoop.net.NetUtils.connect(NetUtils.java:489)
        at org.apache.hadoop.hbase.ipc.HBaseClient$Connection.setupConnection(HBaseClient.java:328)
        at org.apache.hadoop.hbase.ipc.HBaseClient$Connection.setupIOstreams(HBaseClient.java:362)
        at org.apache.hadoop.hbase.ipc.HBaseClient.getConnection(HBaseClient.java:1045)
        at org.apache.hadoop.hbase.ipc.HBaseClient.call(HBaseClient.java:897)
        at org.apache.hadoop.hbase.ipc.WritableRpcEngine$Invoker.invoke(WritableRpcEngine.java:150)
        at com.sun.proxy.$Proxy5.multi(Unknown Source)
        at org.apache.hadoop.hbase.client.HConnectionManager$HConnectionImplementation$3$1.call(HConnectionManager.java:1386)
        at org.apache.hadoop.hbase.client.HConnectionManager$HConnectionImplementation$3$1.call(HConnectionManager.java:1384)
        at org.apache.hadoop.hbase.client.HConnectionManager$HConnectionImplementation.getRegionServerWithoutRetries(HConnectionManager.java:1365)
        at org.apache.hadoop.hbase.client.HConnectionManager$HConnectionImplementation$3.call(HConnectionManager.java:1383)
        at org.apache.hadoop.hbase.client.HConnectionManager$HConnectionImplementation$3.call(HConnectionManager.java:1381)
        at java.util.concurrent.FutureTask$Sync.innerRun(Unknown Source)
        at java.util.concurrent.FutureTask.run(Unknown Source)
        at java.util.concurrent.ThreadPoolExecutor.runWorker(Unknown Source)
        at java.util.concurrent.ThreadPoolExecutor$Worker.run(Unknown Source)
        ... 1 more
Done putting records
98FC114BD7AE added successfully2 at 2013/05/31 16:23:13
Done putting records
000625FFDB3E added successfully2 at 2013/05/31 16:23:15
Done putting records
0014BFD6F985 added successfully2 at 2013/05/31 16:23:15
Done putting records
0012172D69DB added successfully2 at 2013/05/31 16:23:15
Done putting records
98FC117A7027 added successfully2 at 2013/05/31 16:23:15
Done putting records
98FC11828B25 added successfully2 at 2013/05/31 16:23:15
Done putting records
98FC114BD7AE added successfully2 at 2013/05/31 16:23:44
Done putting records
0014BFD6F985 added successfully2 at 2013/05/31 16:23:47
Done putting records
0012172D69DB added successfully2 at 2013/05/31 16:23:47
Done putting records
000625FFDB3E added successfully2 at 2013/05/31 16:23:47
Done putting records
98FC117A7027 added successfully2 at 2013/05/31 16:23:47
Done putting records
98FC11828B25 added successfully2 at 2013/05/31 16:23:47
Done putting records
98FC114BD7AE added successfully2 at 2013/05/31 16:24:15
```

Figure 6.2: Monitoring progress of experiment

6.2 Measuring Performance of Terminals Detection

In this section, we analyse the results that we have observed from the experiment in the Department Of Computing Laboratory. In order to evaluate the performance of our system in detecting the number of WiFi users, we carried out ground truth observation of the number of students within a confined area in the laboratory, which we had two of our APs deployed around that area. The two APs have MAC addresses 98FC11828B25 (AP3) and 000625FFDB3E (AP5).

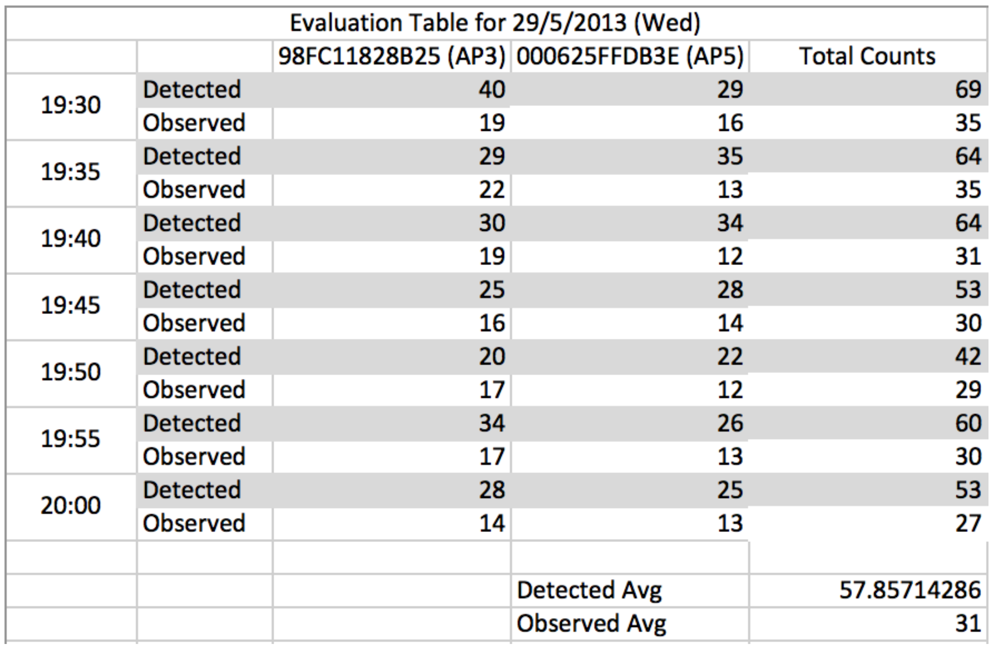
6.2.1 Procedure to Prepare Evaluation Graphs

We conducted our experiment on 5 days in the laboratory. Each day, we carried out a ground truth observation of the number of students in the laboratory and record it down. In order to calibrate and determine which values of RSSI we should set on our APs to filter out, we changed this parameter on different days of our experiment. This is because if we do not filter out detection records with their associated RSSI values, our APs might even detect terminals that are outside the laboratory and across the street. Hence, on 29/05/2013 and 30/05/2013, we set the *filtered RSSI* parameter[1] to

[1]We would use the term *filtered RSSI* parameter from now on to refer to the RSSI that we have set to filter only those detection records with RSSI value higher than the specified amount. Note that RSSI is in dBm, which means that the less negative the value, the better.

-80, which means that we will only accept those terminals that our APs have detected with RSSI more than or equal to -80. We have summarised this detail below:

- 29/05/2013 (Wed), filtered RSSI parameter: -80.
- 30/05/2013 (Thurs), filtered RSSI parameter: -80.
- 31/05/2013 (Fri), filtered RSSI parameter: -70.
- 01/06/2013 (Sat), filtered RSSI parameter: -65.
- 03/06/2013 (Mon), filtered RSSI parameter: -60.



Evaluation Table for 29/5/2013 (Wed)				
		98FC11828B25 (AP3)	000625FFDB3E (AP5)	Total Counts
19:30	Detected	40	29	69
	Observed	19	16	35
19:35	Detected	29	35	64
	Observed	22	13	35
19:40	Detected	30	34	64
	Observed	19	12	31
19:45	Detected	25	28	53
	Observed	16	14	30
19:50	Detected	20	22	42
	Observed	17	12	29
19:55	Detected	34	26	60
	Observed	17	13	30
20:00	Detected	28	25	53
	Observed	14	13	27
			Detected Avg	57.85714286
			Observed Avg	31

Figure 6.3: Evaluation Table showing details of number of terminals detected and students observed

By changing the filtered RSSI parameter, we want to see whether this would helps to increase the accuracy of our detection. In Figure 6.3, it shows that we have carried out 7 instances of observation at a 5 minute interval. We chose 5 minutes to allow sufficient time for the environment to evolve. *Detected* represents the number of terminals we have detected and *Observed* represents the number of students we have counted in the predefined area of observation. We compute the total *Detected* counts for the two APs and the total *Observed* counts for the corresponding areas. *Detected Avg* takes the average of the total number of terminal counts across the 7 instances. *Observed Avg* takes the average of the total number of student counts across the 7 observations.

To view all the evaluation tables, please refer to Appendix A.

Minimising the problem of infrequent probe requests sent by terminals
Within the 5 minutes interval, a terminal may choose to send out probe request frames at the first minute or the last minute of the 5 minutes interval. If we simply just take the

number of counts of detected terminals on the dot at each time interval, 19:30, 19:35, 19:40, etc, we may miss out some terminals from being detected. Since we can see that the number of observed students do not fluctuate that much within the confined area, we choose to use the counts of the number of unique terminals within the 5 minutes interval, i.e., at 19:30, we would include the number of unique terminals detected between 19:25 and 19:30 by our APs and compare this to the number of students we count at 19:30.

We have written a code to find out the number of unique terminals that fall within each 5 minutes interval.

6.2.2 Factors Affecting Accuracy of Detection

Before we start discussing the results of our observations and detections, we would like to explain what are the factors that would influence the accuracy in our results. In particular, these factors would cause the number of terminals that we have detected to deviate from the number of students we have counted.

1. Firstly, in our evaluation of the frequency of probe request being sent out by terminals later in Section 6.3, we would notice that the frequency varies according to different brands and models of devices due to their difference in OS implementations. Most devices do not send out probe request that often and this would serve to decrease the number of terminals that we detect.
2. Secondly, since our experiment is conducted in a university computing laboratory, each student usually carries more than one WiFi terminals with them such as a laptop, a smartphone and a tablet. This would increase the number of terminals that our APs would detect when compared to the number of students we observe in the laboratory.
3. Finally, our APs may pick up radio signal from terminals that are not physically in the the room under observation but adjacent to it. There may also be people walking by the room along the corridor, which may be detected by our terminals. This would increase the number of terminals that our APs detect.

Although the factors above may affect the accuracy of our evaluation, we would still want to know how our system performs by analysing the number of terminals detected by our APs and the number of students we have observed. In particular, we would calculate an average of the number of terminals detected and number of students observed and we draw a line for each in the same graph. By keeping the scale of the axis constant, we want to see how close the two line would be. The closer they are on the graph, the more accurate is our system in detecting the number of WiFi users.

6.2.3 Discussion of Results

Across from Figure 6.4 to Figure 6.8, we can observed some trends from the graphs plotted. It should be noted that the scale for *x-axis* and *y-axis* remains unchanged across all the graphs. This would allow us to visually observe the change in trend across all graphs.

First, let us compare the graph in Figure 6.4, which shows the count of the number of terminals for 29/05/2013 (Wed) and Figure 6.5, for 30/05/2013 (Thurs). On these two days, we keep the *filtered RSSI* parameter the same, i.e., at -80. What we can see from the graphs of *Detected Avg* and *Observed Avg* reflects that *filtered RSSI* parameter is crucial since this parameter causes these two graphs to shift up and down. The ratio of *Detected Avg* to *Observed Avg* is 1.866 (calculated by 57.857/31) for 29/05/2013 and 1.887 (calculated by 52.285/27.714) for 30/05/2013. The ratios for both days remain almost unchanged, which indicates that by keeping the *filtered RSSI* parameter unchanged, the accuracy of our detection would remain about the same too. Hence, it also gives a good indication that no matter how the environment changes, as long as the factors we have mentioned in Section 6.2.2 remain unchanged, our mechanism would work as expected in detecting the number of terminals within the environment monitored. Thus, it injects a great level of confidence that our aggregation process correctly localises and counts the number of terminals.

Another very interesting trend that we observe across all graphs is as *filtered RSSI* parameter increases from -80 to -70 and to -65, the *Detected Avg* and *Observed Avg* lines become closer and closer, which indicates that our estimation of the actual number of students in the confined area becomes more accurate up to this point. However, it should be noted that on 01/06/2013, in which the *filtered RSSI* parameter was set at -65, it was a Saturday and there were fewer number of students who came to the laboratory.

As the *filtered RSSI* parameter increases further to -60, which means that we basically filter out terminals with associated RSSI less than -60, we have reduced the coverage that our APs would detect terminals. This actually has a negative effect and does not bring the *Detected Avg* and *Observed Avg* lines close together.

There is one more trend which we can also observe across all graphs. From Figure 6.4 (29/05/2013) to Figure 6.7 (01/06/2013), the graphs of *Detected* and *Detected Avg* are always above the graphs of *Observed* and *Observed Avg*. However, at one point when we set the *filtered RSSI* parameter to -60, the opposite of what we have seen happens, i.e., the graphs of *Observed* and *Observed Avg* are above the graphs of *Detected* and *Detected Avg* as shown in Figure 6.8 instead. We know that *filtered RSSI* parameter of -65 is actually the value that is suitable for our environment in the laboratory. From this, we know that there must be some values of *filtered RSSI* that can be calibrated for each different environment in order for us to get a good approximation of the number of WiFi users in each environment. Each environment has its own unique profile. By tweaking the *filtered RSSI* parameter, we essentially minimise other factors affecting our counts of terminals, such as detecting terminals that are located far outside the monitored environment. This allows our system to approach a good approximation of the number of WiFi users within the environment under monitored by our APs.

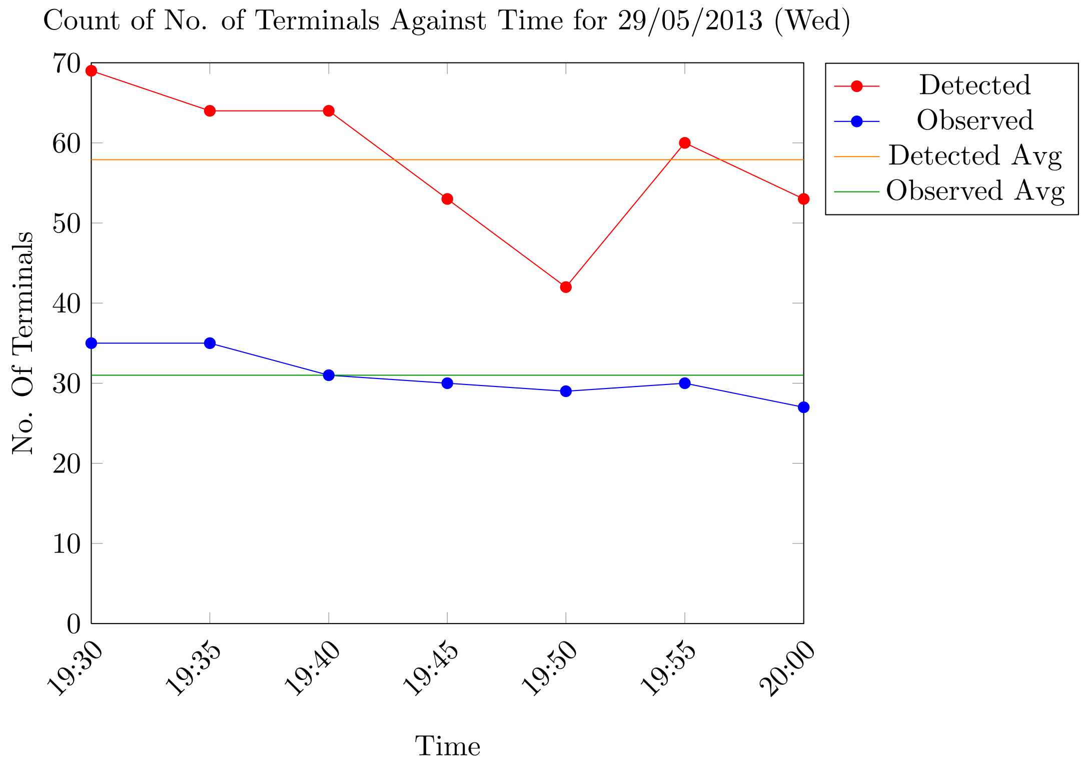


FIGURE 6.4: Comparing number of terminals being detected and observed near AP3 and AP5 on 29/05/2013 filtering out RSSI less than -80. Notice that *Detected Avg* is a little higher than *Observed Avg*.

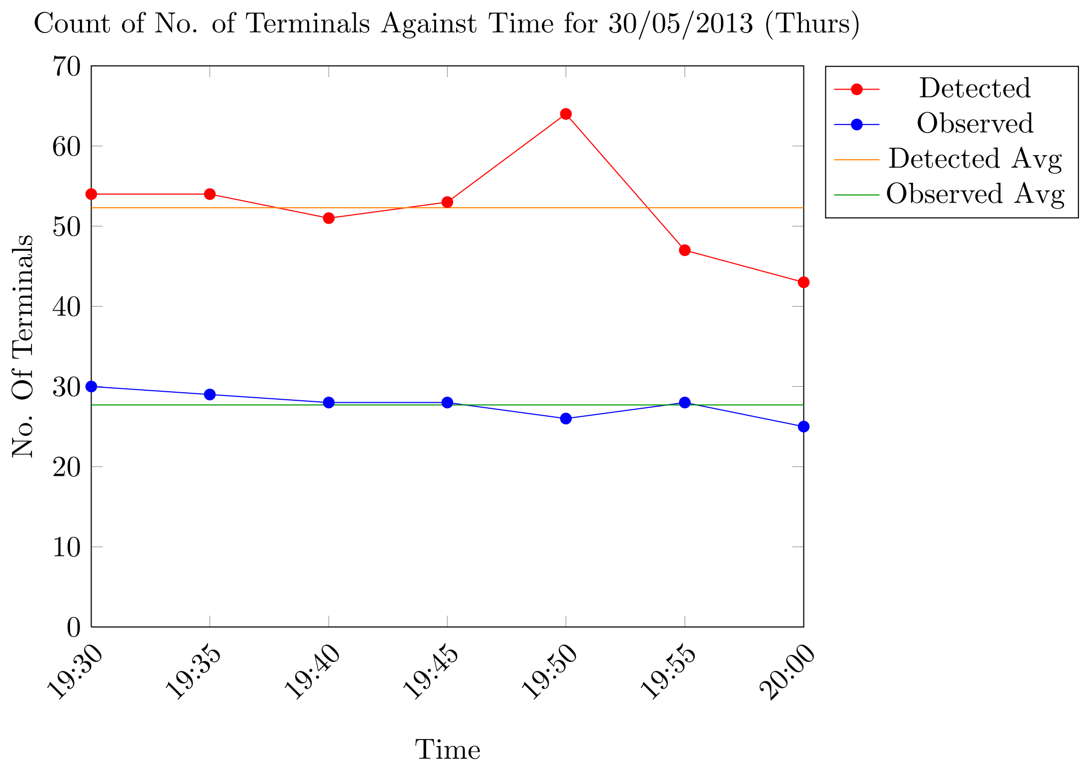


FIGURE 6.5: Comparing number of terminals being detected and observed near AP3 and AP5 on 30/05/2013 filtering out RSSI less than -80. Notice that *Detected Avg* is still a little higher than *Observed Avg*.

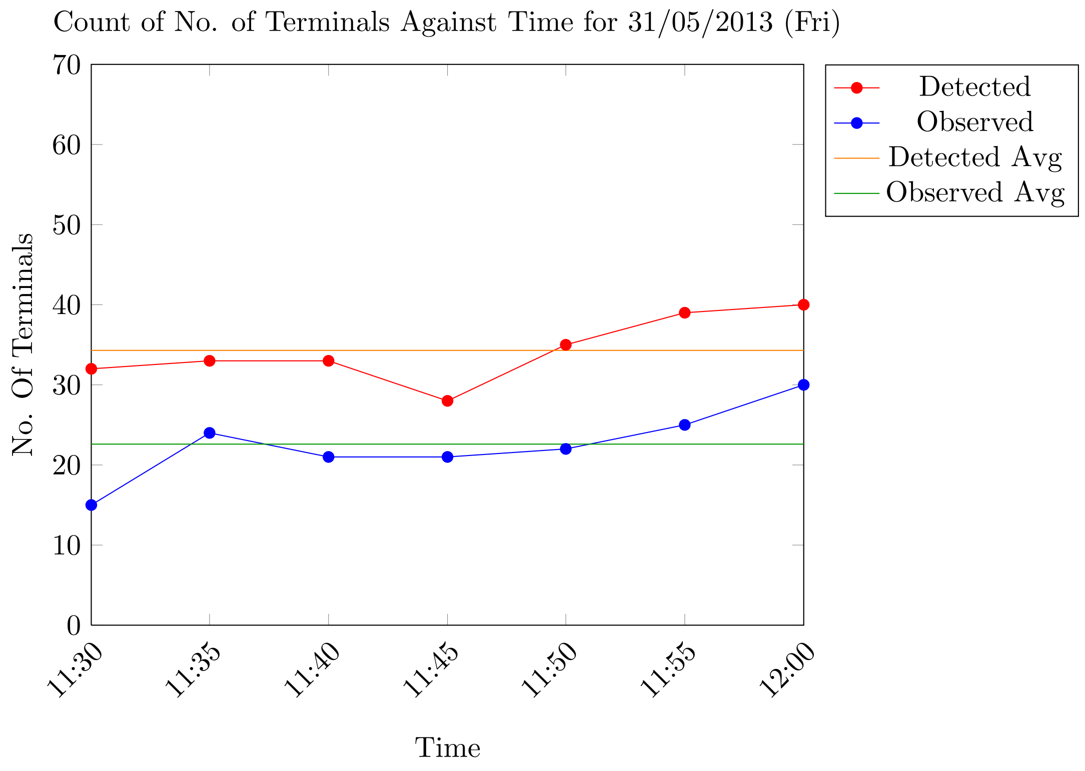


FIGURE 6.6: Comparing number of terminals being detected and observed near AP3 and AP5 on 31/05/2013 filtering out RSSI less than -70. Notice that *Detected Avg* is getting closer to *Observed Avg*.

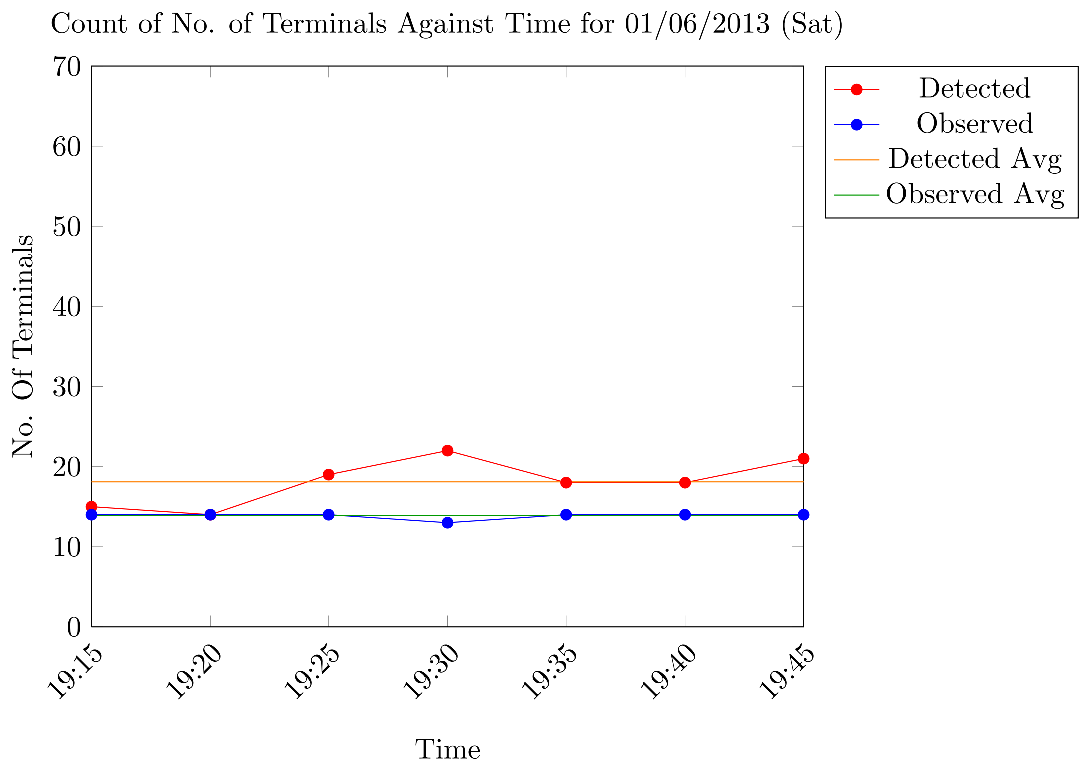


FIGURE 6.7: Comparing number of terminals being detected and observed near AP3 and AP5 on 01/06/2013 filtering out RSSI less than -65. Notice that *Detected Avg* is closest to *Observed Avg* amongst all other graphs.

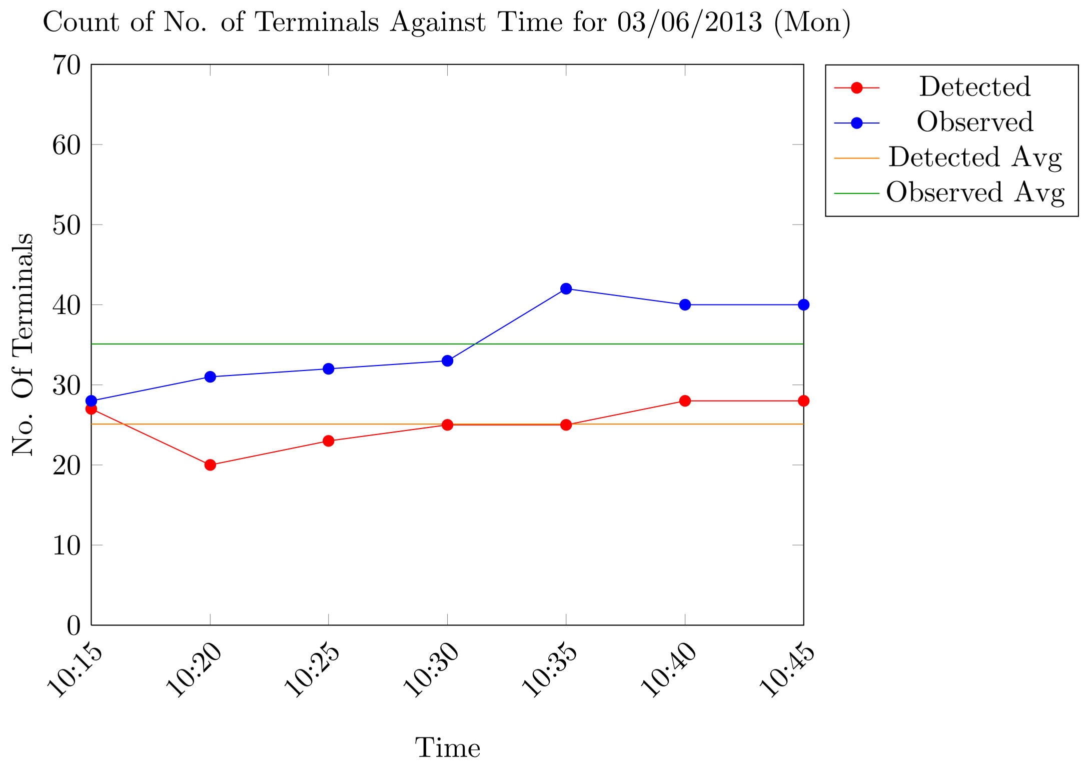


FIGURE 6.8: Comparing number of terminals being detected and observed near AP3 and AP5 on 03/06/2013 filtering out RSSI less than -60. Notice that *Detected Avg* is now lower than *Observed Avg* instead.

6.2.4 Analysing Trends from Web GUI

In Figure 6.9, we can observe a trend of the number of visitors in the laboratory. We can see tht at around 12:45 and from 14:30 to 15:15, the number of visitors drop. This indicates to us that these two periods are the most common periods that students go out to have lunch. The peak of the histogram happens between 15:45 and 17:45, indicating the peak period of the laboratory. This is true since we normally observe that the laboratory is very packed around that time. Please note that the histogram in the figure only shows the result for one AP. In the Web GUI, we can choose any AP to view the statistics for it. Please refer to Section 5.6 for the URL and login details.

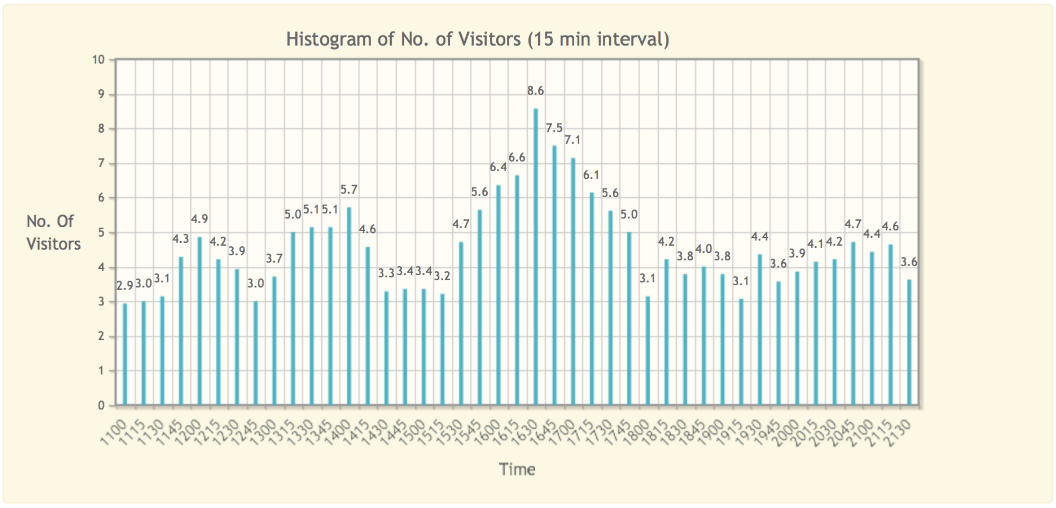
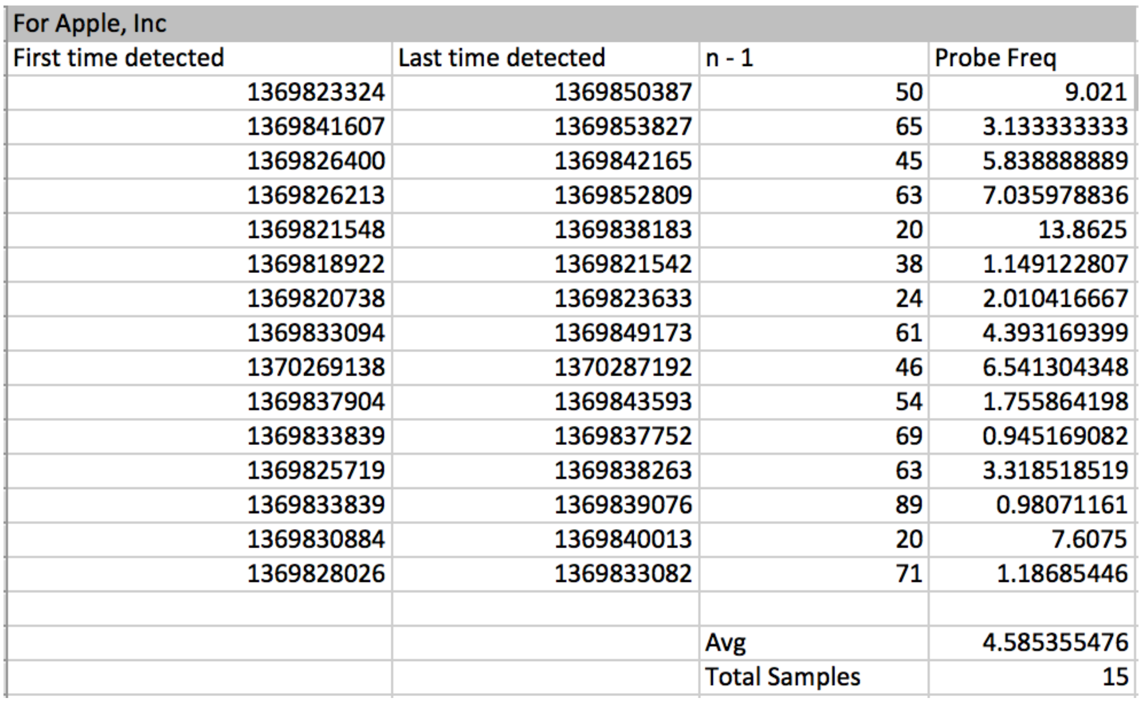


FIGURE 6.9: Trend of number of students in laboratory

6.3 Frequency of Probe Request Frames

Since we have collected so much data about WiFi devices, we could put it to good use. We attempt to find out the average probe request frequency of major brands. We want to know how often WiFi devices from each brand send out probe request frames. This is probably the largest compilation of the frequency of probe request by carrying out random sampling across the population of each brand. Previously, researchers would measure the frequency of probe request of specific devices. This might not be a good representation of a population of WiFi devices under each brand. We do recognise that our results might not fully reflect the probe request frequency of each brand. However, the results at least give us an idea of the general trend, in which we will analyse further below.

6.3.1 Compiling Process



For Apple, Inc			
First time detected	Last time detected	n - 1	Probe Freq
1369823324	1369850387	50	9.021
1369841607	1369853827	65	3.133333333
1369826400	1369842165	45	5.838888889
1369826213	1369852809	63	7.035978836
1369821548	1369838183	20	13.8625
1369818922	1369821542	38	1.149122807
1369820738	1369823633	24	2.010416667
1369833094	1369849173	61	4.393169399
1370269138	1370287192	46	6.541304348
1369837904	1369843593	54	1.755864198
1369833839	1369837752	69	0.945169082
1369825719	1369838263	63	3.318518519
1369833839	1369839076	89	0.98071161
1369830884	1369840013	20	7.6075
1369828026	1369833082	71	1.18685446
		Avg	4.585355476
		Total Samples	15

FIGURE 6.10: Calculations of probe request frequency

In Figure 6.10, we have shown the table that we used to calculate the frequency of probe request for each brand. First, we sort the detection records according to the timestamp in ascending order and we only include those that we believe the terminal still stay at the place it is being detected, i.e., our Residence Time algorithm has not considered the terminal to have moved away somewhere else. Then we take the time the terminal is first detected and the last time is it detected as shown in Figure 6.10. We then count the number of records that exist between these two timestamps, n.

We use the formula below to determine the probe request frequency of each device.

$$\frac{last\ time\ detected - first\ time\ detected}{n\ \ - 1}$$

After this, we take the average across the number of samples we have for each brand. We do recognise that the larger the number of samples, the better our representation of the population. However, some brands of WiFi devices that we have detected have a small population, hence, the sample size for each brand is different. This should be fine since we classify each brand of devices as different population while we do our random sampling, i.e., we randomly select devices for each brand.

We would like to thank MACVendorLookup [12] for providing the list of Organizationally Unique Identifier (OUI) that belongs to each manufacturer.

6.3.2 Discussion of Results

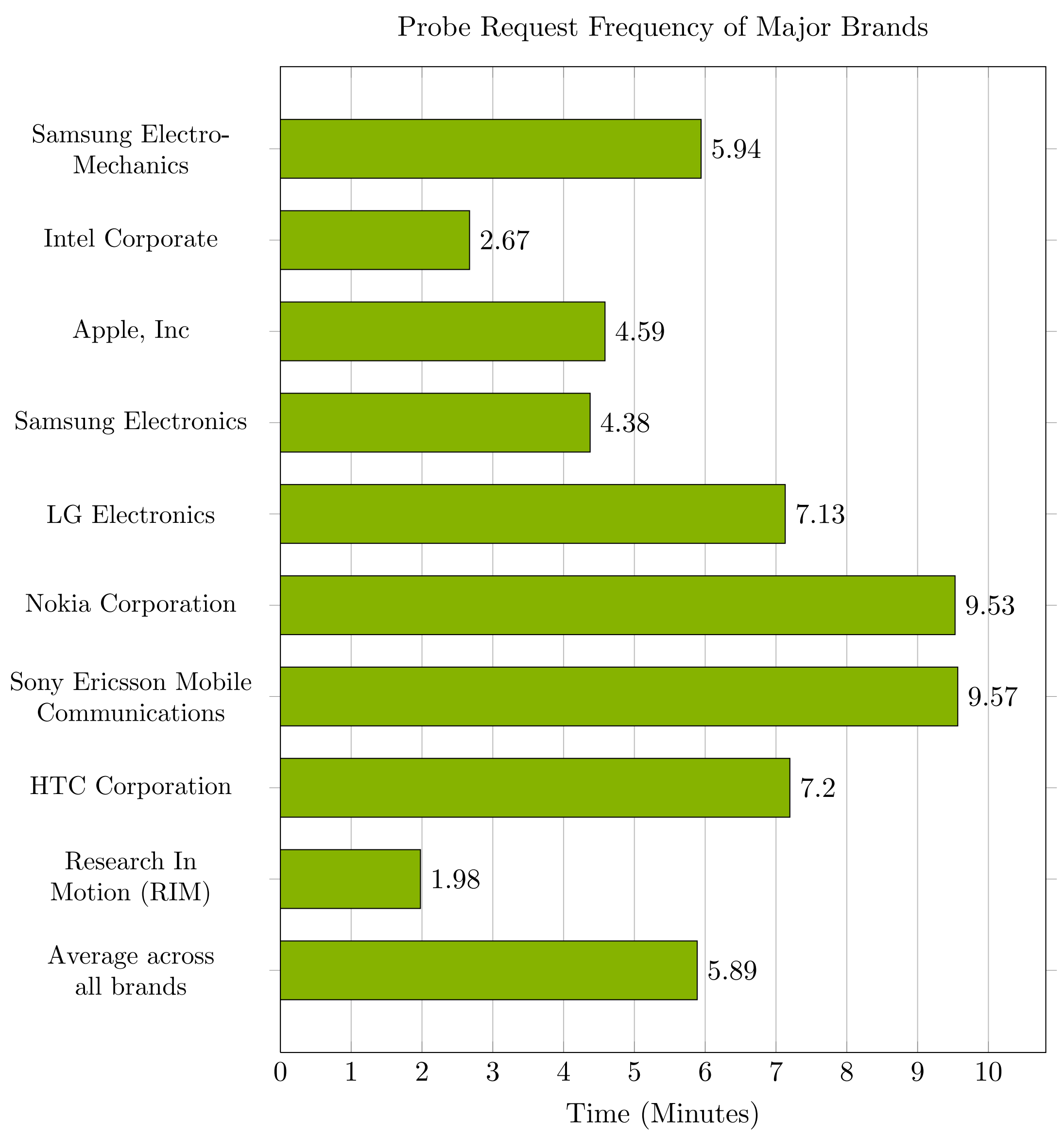


FIGURE 6.11: Probe request frequency of major brands

In Figure 6.11, we present our chart of the frequency of probe request for each brand we have selected. We hope this would be useful for other academics too.

From the figure, we could see that *Intel Corporate*'s WiFi devices has a higher frequency of sending out probe request than many other brands. This could be because the samples for this brand come mostly from laptop computers of the students in the laboratory. We could then infer that laptop send out probe request more frequently than mobile devices since we could see that other major mobile devices' brands have lower frequency of sending out probe request. From the same figure, we have two *Samsung* brands but the OUIs they own are registered under different company names. Due to the limited further information we can obtain, we could only guess that each of the brands is used for different types of devices.

We also can derive that for all the brands we have studied, their probe request frequency falls below 10 minutes. We could be quite confident that this might be true for majority of WiFi devices since most of the brands we have covered are either major laptop or smartphone manufacturers.

6.4 Microbenchmark

In order to understand how effective our chosen mechanism performs in detecting the terminals, we set up a micro-benchmark experiment. This experiment measures the performance and accuracy of our detection mechanism in different environments. We had carried out 2 experiments in the laboratory and 2 experiments in open space.

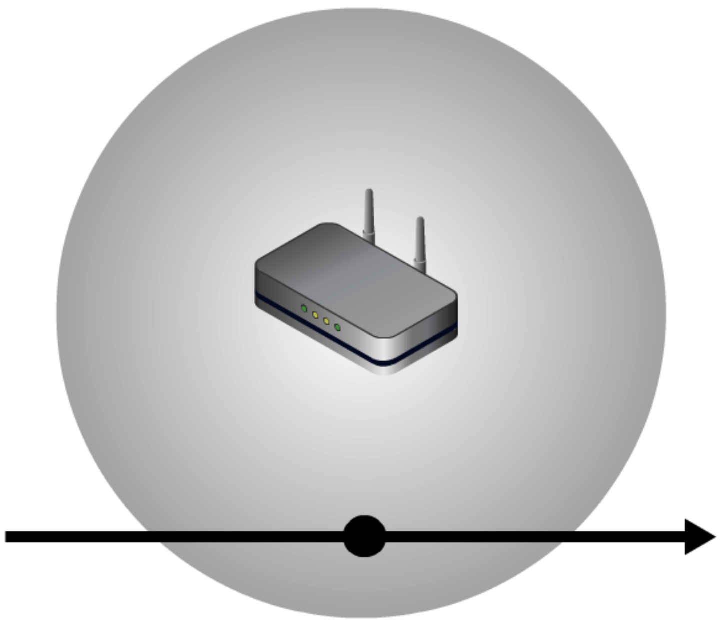


Figure 6.12: Illustration of how students move for Mobility experiment

For each environment, we conducted a *static* and *mobility* experiment. For the *static* experiment, we sought the help of 5 friends, each carrying two WiFi terminals, and they would stand at different distance intervals from an AP that we set up. We then configured our AP to filter out only those MAC addresses of terminals that had been registered for this experiment. We wanted to understand out of 10 terminals, as the terminals move further and further away from AP, how many we could still detect reliably. For the *mobility* experiment, we also had 5 students carrying 2 terminals each. We asked the 5 students to carry out different mobility movement such as walk, jog and run across a point that is at a fixed distance from the AP and is perpendicular to it. This is illustration in Figure 6.12, in which the students would move at different speed in a group along the arrow line.

We have shown our results of findings in the graphs from Figure 6.13 to Figure 6.16. From the graphs, we have noticed that mobility does not really affect the accuracy of our detection mechanism that much. However, as the group of students moves further and further away from the AP, for *static* experiment, the number of terminals detected drops. This could be due to the fact that radio signal becomes weaker as distance from AP increases.

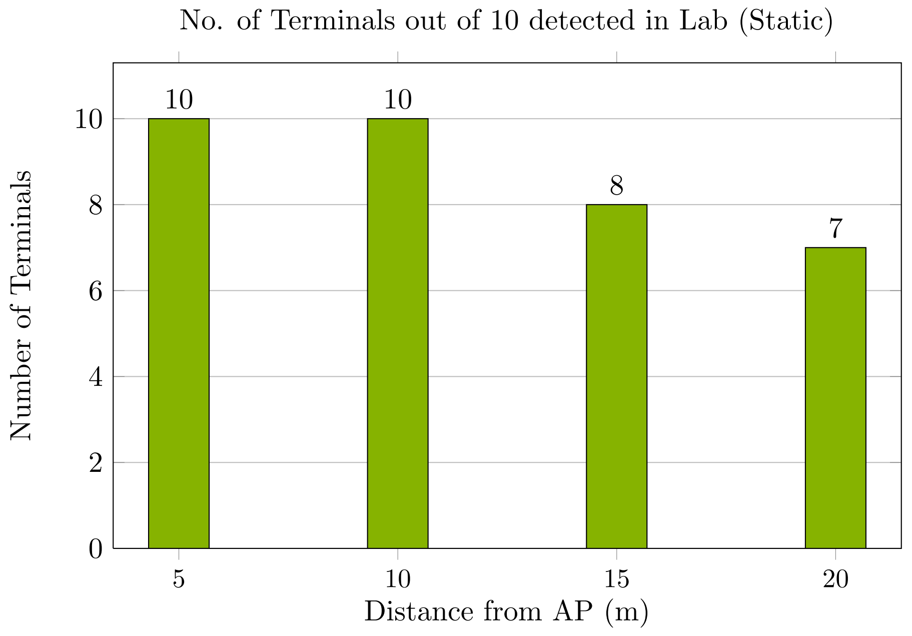


FIGURE 6.13: Number of terminals out of 10 detected in Lab (Static)

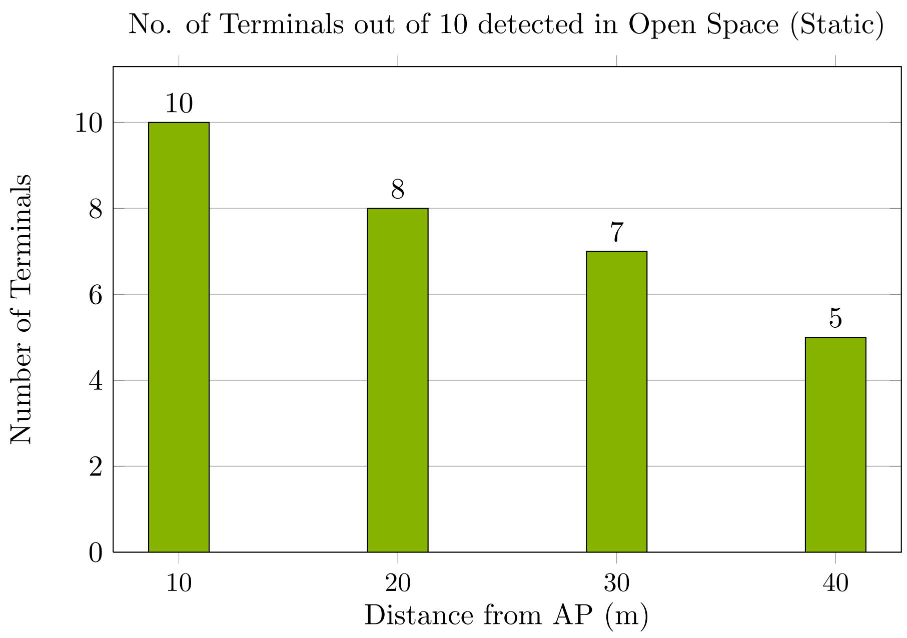


FIGURE 6.14: Number of terminals out of 10 detected in Open Space (Static)

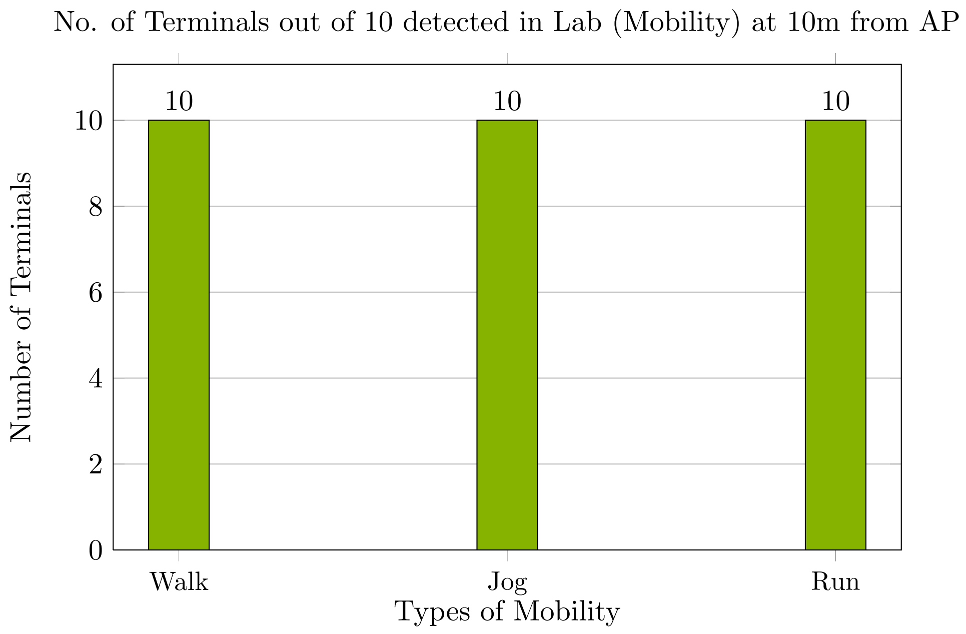


FIGURE 6.15: Number of terminals out of 10 detected in Lab (Mobility) at 10m from AP

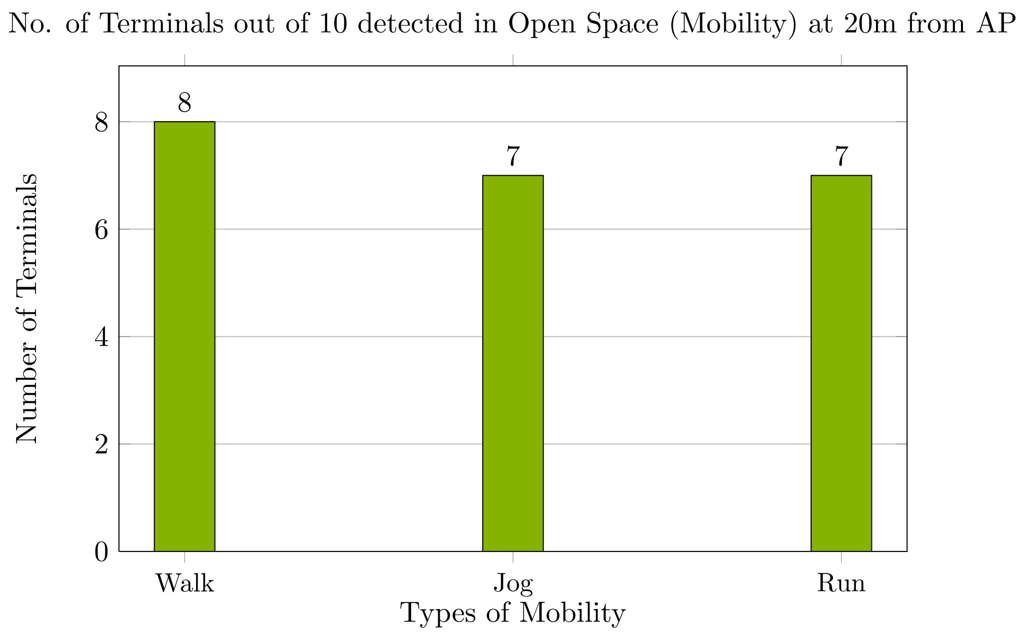
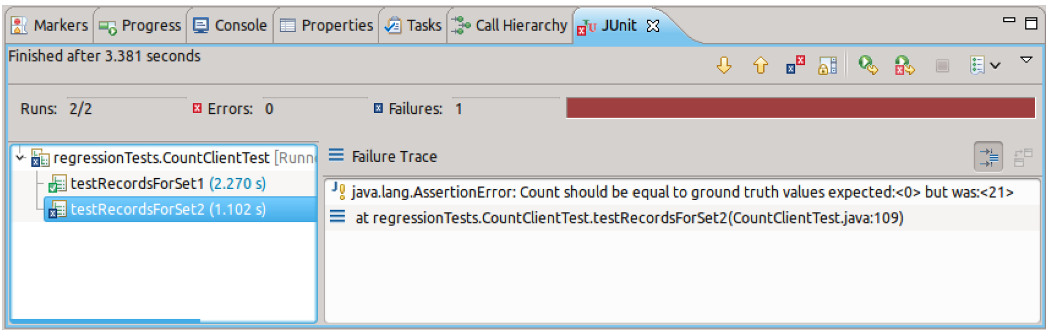


FIGURE 6.16: Number of terminals out of 10 detected in Open Space (Mobility) at 20m from AP

6.5 Unit Tests

In order to verify that our aggregation algorithms are working correctly, we have written some unit tests for them. This is done by having test sets, which contain detection records for specific cases that we want to test out. We have shown some screenshots in Figure 6.17 and 6.18.



Finished after 3.381 seconds

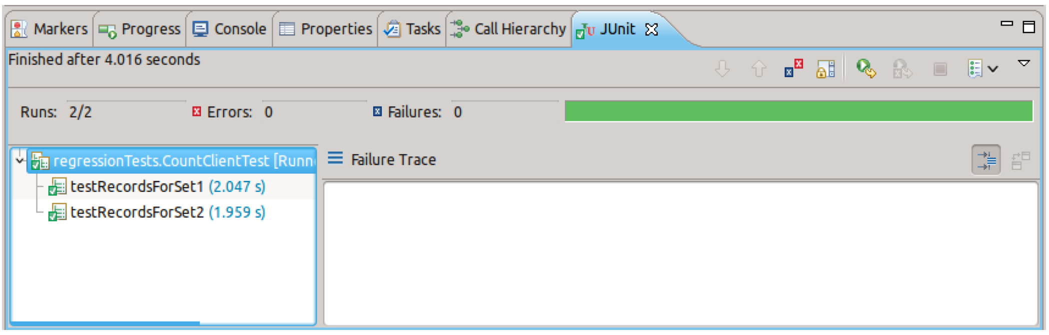
Runs: 2/2 Errors: 0 Failures: 1

regressionTests.CountClientTest [Runn
testRecordsForSet1 (2.270 s)
testRecordsForSet2 (1.102 s)

Failure Trace

```
java.lang.AssertionError: Count should be equal to ground truth values expected:<0> but was:<21>
at regressionTests.CountClientTest.testRecordsForSet2(CountClientTest.java:109)
```

FIGURE 6.17: Unit Test showing a test with error



Finished after 4.016 seconds

Runs: 2/2 Errors: 0 Failures: 0

regressionTests.CountClientTest [Runn
testRecordsForSet1 (2.047 s)
testRecordsForSet2 (1.959 s)

FIGURE 6.18: Unit Test showing a successful test

6.6 Summary

From the evaluation results that we have above, it shows that we have managed to detect the presence of terminals, processed the collected data with the right logic and displayed the results on a webpage. We have noticed that when we changed one of the parameter of the experiment such as the *filter RSSI* value, this causes the ratio of the number of terminals counted to the number of users observed to change as well.

The random sampling of probe request frequency as shown in Figure 6.11 gives us a very good indication of the performance of our detection mechanism. The average probe request frequency across all brands is 5.89 minutes, which suggests that our mechanism has a tracking accuracy of around 5 minutes. This is good enough since we are not really into tracking a specific user's whereabouts but to track collective mobility of WiFi users to understand a general trend and behaviour.

Finally, our micro-benchmark experiment put the sensitivity of our detection mechanism to test. The experiment indicates that our detection mechanism has a 100% accuracy of detecting terminals that are 10m away from the AP, 80% for 20m, 70% for 30m and 50% for 40m in open space. As for the laboratory environment, which has more interference, we have a detection accuracy of 100% for up to 10m of distance from AP and 70% at a distance of 20m.

Chapter 7

Conclusion and Future Extensions

7.1 Conclusion

From detecting to aggregating and to displaying, each stage enables us to learn many different aspects of computer science. We have dived into the lower level implementation of a program to run on an embedded device, employed the use of modern analytic framework, MapReduce, and new breed of database, NoSQL, which has become ever more popular due to the rise of Bigdata, and finally make use of the latest web technology, HTML5, together with Javascript to create an app-like web interface experience. Throughout the whole process, we learn and evaluate the suitability of each piece of technology as well as understand their usage in big organisations by analysing relevant case studies. This allows us to learn the best practice from these companies.

There are three main phases in this project. We began first by studying how different WiFi components under the umbrella of IEEE 802.11 operate and communicate with each other. Then we proposed a few different mechanisms that could be used to detect the presence of WiFi terminals. We chose the best one, the detection of probe request frames, that requires no actions to be taken from the users of the terminals while allowing us to detect them passively. This mechanism was proven to work effectively in our evaluation, in which we observed distinctive trend in the number of terminals detected across the day in the laboratory, where we observed the period when students went out for lunch break and the peak hours of the laboratory. Furthermore, the average number of detected terminals were not too far away from the average number of students we observed in the confined area. We provided reasons to explain the difference in the number of terminals detected and number of users observed, as there are still limitations in our project, which we could look into to extend in the future. This is discussed later under Future Extensions.

While implementing the mechanism to detect terminals, we faced issues of flashing the right firmware onto the AP and also the limitations in the computing resources of an embedded device in terms of RAM and flash storage space. The cross compiling process was the most rewarding one since it allowed us to successfully run our program on the

AP. If the compiling step did not succeed, we would have to look into alternative device for implementation such as using a laptop with its NIC to simulate an AP.

In the second phase, we picked the most suitable method of aggregating the data collected from each AP. At this phase, we managed to learn a lot about how to build a collective representation of the mobility of WiFi users in a wireless network environment, using just the detection records we have, which compose of AP and terminal MAC addresses, RSSI information and timestamp. These records are the fuel for our aggregation engine, which makes use of the logic we have built into it to turn all this little information into some meaningful statistics. It was also at this phase that we managed to learn a lot more about the phenomenon we are faced with such as the "Ping Pong" effect and the infrequent probe request broadcast. These phenomenons prompted us to think further on how to fine tune our algorithms so that we could minimise the effect of such problems. However, we do recognise that there is no easy way to increase the frequency of probe request of terminals since that is dependant on the implementation of the OS of the terminals.

In our final phase, although our aggregation engine could generate useful values, we still have the task of visualising these values into something that human can comprehend. We decided to build a web interface, which is the current most convenient way to browse through information. Graphs and charts are plotted and drawn with colours and symbols to explain what are going on at each AP. We managed to determine the number of *visitors* located close to each AP, their residence time and the number of new and returning visitors. Although this number does not actually represent the true number of visitors, they give a good approximation to it since we could assume that most users bring only one WiFi terminal either in their pocket or handbag when they are out in shopping mall, supermarket or stadium. These are the places that our APs would most likely be deployed in for a commercial roll-out.

7.2 Future Extensions

During our experiment, we observe a few phenomenons, which are real and need to be addressed if we can extend this project further.

7.2.1 A More Reliable Way of Localising Terminal

We recognise that using just RSSI information to localising a terminal is not accurate enough, which leads to the "Ping Pong" effect that we have mentioned earlier. After reading through research papers and reviewing them under Related Work, we noticed that there are various localisation techniques that could be employed to improve the accuracy of localising a terminal. One such technique is triangulation, which requires the use of 3 or more APs to detect and determine the position of a terminal.

7.2.2 Enclosing the Environment Under Monitored

Another issue that we noticed from our experiment is that, our APs are detecting terminals that are outside the area that we are supposed to track. This contributes to the inaccuracy that we may have in our statistics. In order to track the collective mobility of users within a confined environment, we could develop techniques to ignore users that are outside the confined space.

7.2.3 Ignoring Static Terminals

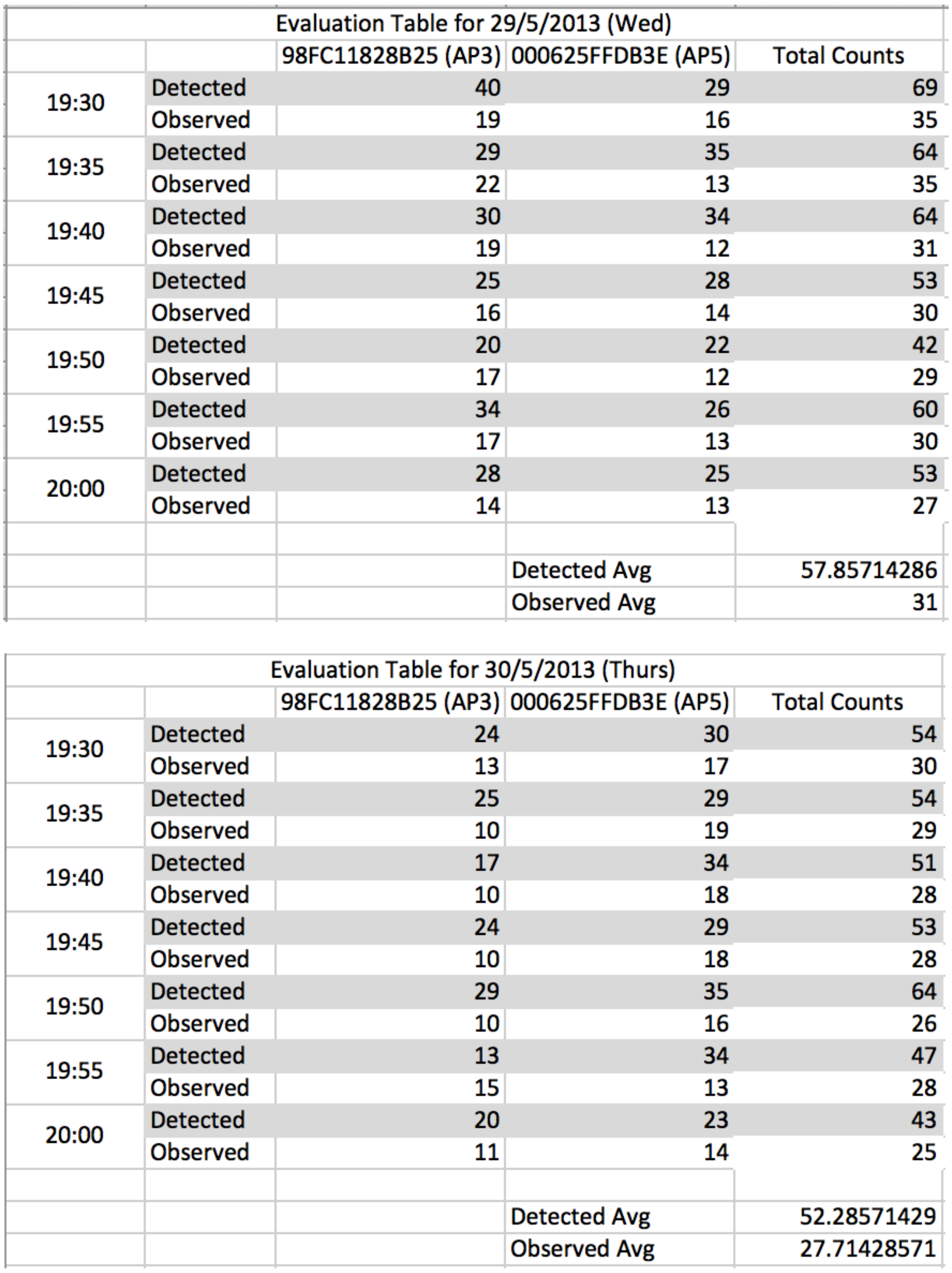
After our experiment, we also realised that there are WiFi terminals that just sit there for hours and hours and there are no human carrying them. These terminals were most likely be placed in the Computing Support Group room, which is located next to the Common Room in which we have one AP deployed there for tracking terminals. Furthermore, we also discovered a beautiful MAC address, *00:00:01:00:00:00*, which belongs to a Xerox brand, suggesting that it could be a printer having WiFi capability. These devices should be ignored using appropriate technique.

7.2.4 Protecting Privacy of Individuals

Finally, throughout this project, we have been observing many different MAC addresses. Although we could not really pinpoint a MAC address to a person, unless the person reveal this information, we would still like to enhance the privacy of individuals that our system is tracking. This could be done by making use of a strong one-way hash function with a salt to encrypt the MAC addresses. Whenever we detect a terminal's MAC address, we would hash it according to the hash function we have chosen and we could still identify a unique terminal that we have detected before by comparing this hashed values with the one we store in our database.

Appendix A

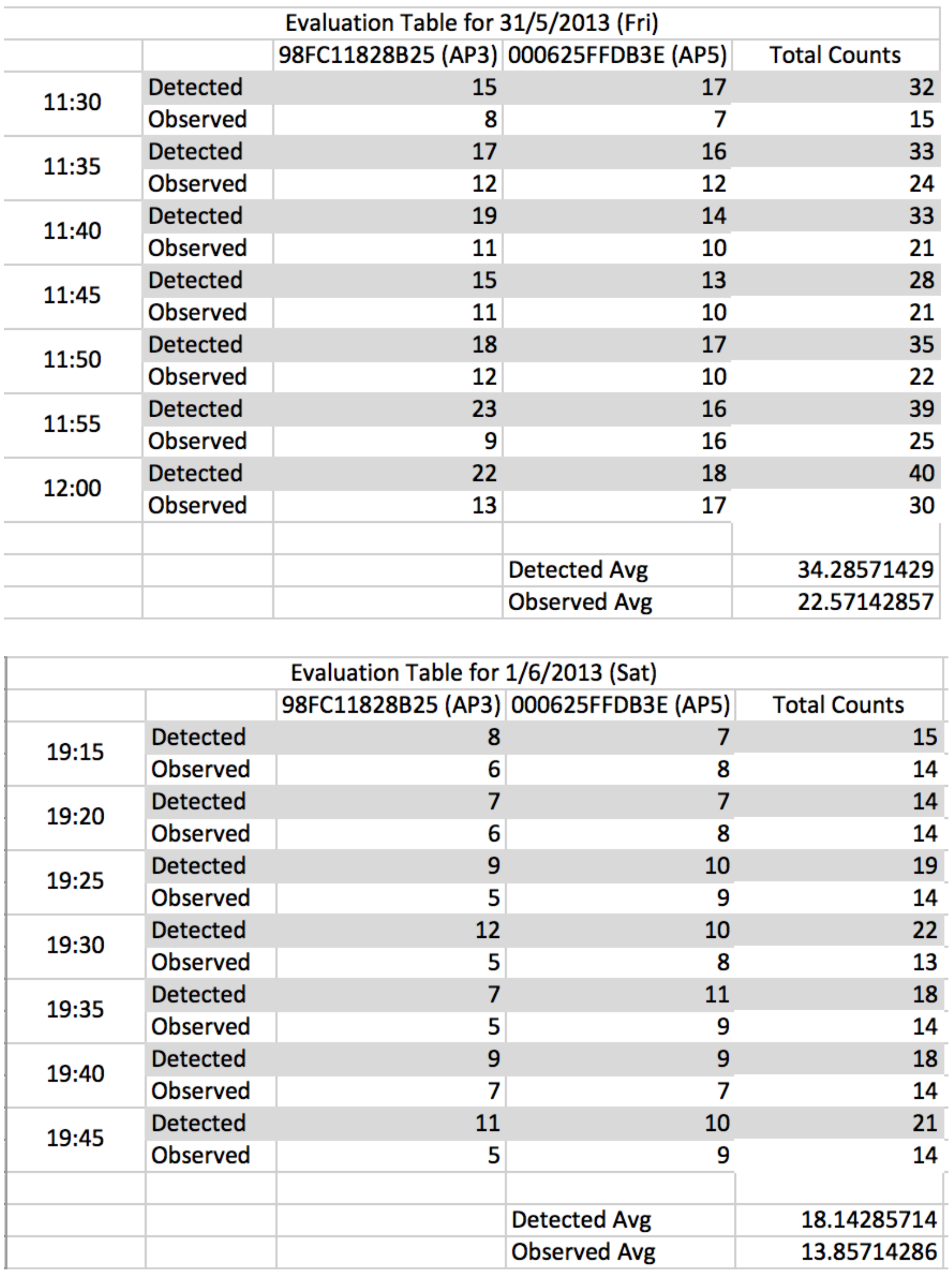
Evaluation Tables



Evaluation Table for 29/5/2013 (Wed)				
		98FC11828B25 (AP3)	000625FFDB3E (AP5)	Total Counts
19:30	Detected	40	29	69
	Observed	19	16	35
19:35	Detected	29	35	64
	Observed	22	13	35
19:40	Detected	30	34	64
	Observed	19	12	31
19:45	Detected	25	28	53
	Observed	16	14	30
19:50	Detected	20	22	42
	Observed	17	12	29
19:55	Detected	34	26	60
	Observed	17	13	30
20:00	Detected	28	25	53
	Observed	14	13	27
			Detected Avg	57.85714286
			Observed Avg	31

Evaluation Table for 30/5/2013 (Thurs)				
		98FC11828B25 (AP3)	000625FFDB3E (AP5)	Total Counts
19:30	Detected	24	30	54
	Observed	13	17	30
19:35	Detected	25	29	54
	Observed	10	19	29
19:40	Detected	17	34	51
	Observed	10	18	28
19:45	Detected	24	29	53
	Observed	10	18	28
19:50	Detected	29	35	64
	Observed	10	16	26
19:55	Detected	13	34	47
	Observed	15	13	28
20:00	Detected	20	23	43
	Observed	11	14	25
			Detected Avg	52.28571429
			Observed Avg	27.71428571

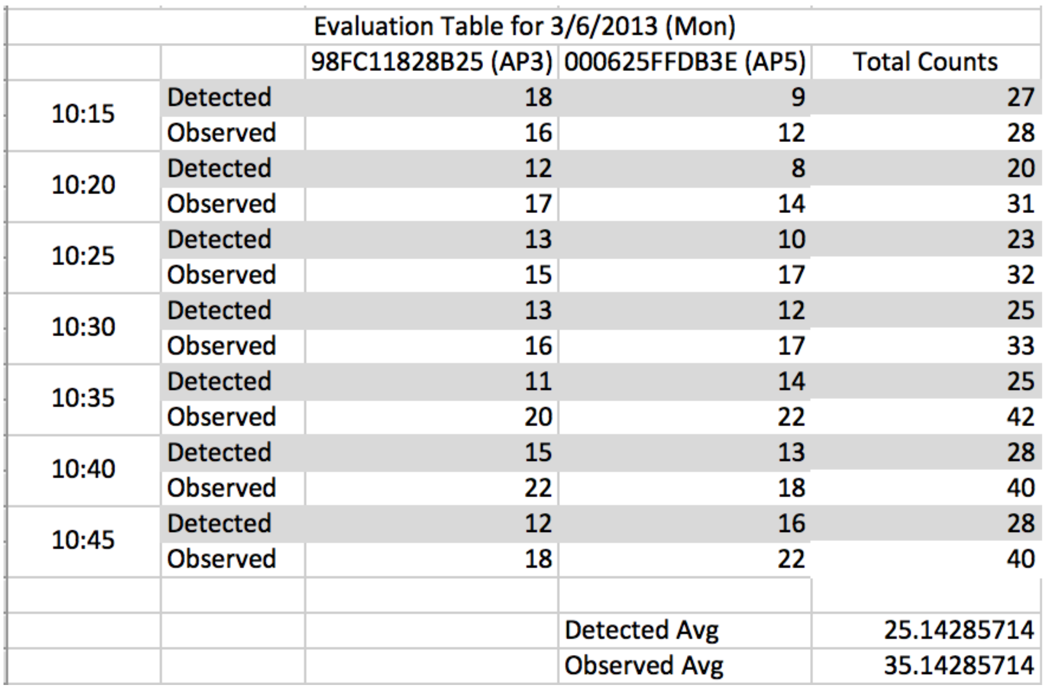
FIGURE A.1: Evaluation tables for experiments on 29/05/2013 (Wed) and 30/05/2013 (Thurs)



Evaluation Table for 31/5/2013 (Fri)				
		98FC11828B25 (AP3)	000625FFDB3E (AP5)	Total Counts
11:30	Detected	15	17	32
	Observed	8	7	15
11:35	Detected	17	16	33
	Observed	12	12	24
11:40	Detected	19	14	33
	Observed	11	10	21
11:45	Detected	15	13	28
	Observed	11	10	21
11:50	Detected	18	17	35
	Observed	12	10	22
11:55	Detected	23	16	39
	Observed	9	16	25
12:00	Detected	22	18	40
	Observed	13	17	30
			Detected Avg	34.28571429
			Observed Avg	22.57142857

Evaluation Table for 1/6/2013 (Sat)				
		98FC11828B25 (AP3)	000625FFDB3E (AP5)	Total Counts
19:15	Detected	8	7	15
	Observed	6	8	14
19:20	Detected	7	7	14
	Observed	6	8	14
19:25	Detected	9	10	19
	Observed	5	9	14
19:30	Detected	12	10	22
	Observed	5	8	13
19:35	Detected	7	11	18
	Observed	5	9	14
19:40	Detected	9	9	18
	Observed	7	7	14
19:45	Detected	11	10	21
	Observed	5	9	14
			Detected Avg	18.14285714
			Observed Avg	13.85714286

Figure A.2: Evaluation tables for experiments on 31/05/2013 (Fri) and 01/06/2013 (Sat)



		Evaluation Table for 3/6/2013 (Mon)		
		98FC11828B25 (AP3)	000625FFDB3E (AP5)	Total Counts
10:15	Detected	18	9	27
	Observed	16	12	28
10:20	Detected	12	8	20
	Observed	17	14	31
10:25	Detected	13	10	23
	Observed	15	17	32
10:30	Detected	13	12	25
	Observed	16	17	33
10:35	Detected	11	14	25
	Observed	20	22	42
10:40	Detected	15	13	28
	Observed	22	18	40
10:45	Detected	12	16	28
	Observed	18	22	40
			Detected Avg	25.14285714
			Observed Avg	35.14285714

Figure A.3: Evaluation tables for experiments on 03/06/2013 (Mon)

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