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The Wi-Fi Coverage Analysis Based on Water Consuming Monitoring System

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Abstract

With the rapid increase smart home markets, indoor Wi-Fi coverage should be evaluated to aid the development of smart home devices which are sensitive to network latency. In the current literature, indoor Wi-Fi performance is mainly studied by investigating signal strength either by using signal propagation models or through experiments. However, the signal propagation models have not been calibrated with the actual performance of the smart home system yet. In addition, home Wi-Fi networks are usually established by users who are not electronic engineers; They may not able to use the complex signal propagation models to evaluate the Wi-Fi performance. Therefore, a decision-making framework should be designed to help untrained smart home users without relevant knowledge develop a high-performance Wi-Fi network. In this research, a water-monitoring system was established to obtain real experimental data. A novel data-processing approach was developed to filter the data which can be used to represent Wi-Fi performance. The data were recorded under different router and repeater locations, and data analyses were conducted after processing the recorded data. Then, the performance of Wi-Fi coverage could be assessed. The relationship between the Wi-Fi network latency and the position of the transmitters was determined. Based on the findings, a decision-making framework was established to help untrained smart home users build a reliable Wi-Fi network. At the same time, a signal propagation model was calibrated with the actual performance of the Wi-Fi network. After the calibration, the router and repeater configuration was decided following the proposed decision-making framework for typical Hong Kong apartments. The recommendations were validated using the calibrated signal propagation model.

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a	*constant path loss*
b	*empirical constant*
d	*distance from the transmitter to the receiver*
G_r	*receive antenna gain*
G_T	*transmitter antenna gain*
I	*number of walls the signal penetrated*
L_C	*constant loss*
L_{FS}	*free space loss between transmitter and receiver*
L_f	*penetration loss per floor*
L_w	*penetration loss per wall*
L_{wi}	*penetration loss per wall type i*
L_0	*path loss at* 1 *meter distance from the transmitter*
L_1	*path loss at* 1 *meter distance from the transmitter*
N	*total number of recorded reliable data*
n_i	*frequency of high latency occurence in room i*
n	*path loss exponent*
n_f	*number of floors the signal penetrated*
n_w	*number of walls the signal penetrated*
n_{wi}	*number of type i walls the signal penetrated*
n_1	*refractive index for the medium* 1
n_2	*refractive index for the medium* 2
P_i	*probability of high latency occurrence in room i*
$P_r(d)$	*signal strength at the receiver*
P_t	*power of the transmitter*
α	*coefficient of attenuation*
ε_r	*material's relative permittivity*
θ_i	*incident angle*
θ_t	*the refraction angle*
λ	*the wave length*
μ_r	*material's relative permeability*

CHAPTER 1. Introduction

1.1 Background and Motivations

The Internet of Things (IoT) has become increasingly popular in recent years. As a part of IoT, the users of smart home can connect with in-home devices, such as air conditioners, remotely through the Internet. Moreover, some of these devices can be programmed in the cloud to adjust user experience automatically in accordance with the data captured by sensors. Therefore, smart home is an automation system that includes devices, sensors, software and cloud connected with one another through the Internet in a living space. The devices are the mechanics or electronics that directly serve users, such as air-conditioning, ventilation, lighting, water-monitoring and home security systems. In a smart home, data are captured using the sensor installed inside the devices; afterwards, these data will be translated through the Internet and programmed in the cloud to be in the form of user-friendly interface. Users can then connect with the devices through a smart phone, tablet or computer.

Researchers of conventional smart home have mainly focused on systems which are insensitive to network latency, such as air conditioning. Research related to water-monitoring systems for home use is limited. Such systems are widely used in industries, such as the water treatment industry and hydropower stations. The water-monitoring system based on real-time interaction is highly sensitive to network latency. Water crisis is the number one global risk claimed by the World Economic Forum; hence, a water-monitoring system as a part of smart home should be established to monitor water consumption and provide advices on saving water. A common problem with monitoring systems is that data are not uploaded in a timely manner. An analysis from a hardware perspective indicates several reasons that can cause this problem, such as sensor aging, poor sensor contact and the sensor being considerably far away from Wi-Fi. From a software perspective, other activities may occupy most of the network and cause uploading delays. In the viewpoint of smart home, the Wi-Fi coverage in a home should be evaluated to aid the development of smart home devices which are sensitive to network latency, given that the devices are usually connected with the Internet through Wi-Fi.

1.2 Outline of the Thesis

There are seven chapters in this thesis.

Chapter 1 brief introduces the background of Internet of Things, the smart home, the motivation of this research and the outline of this thesis.

Chapter 2 is the literature review. In this chapter, the relevant knowledges are introduced, which include the Internet of Things, the signal wave propagation mechanism and the indoor signal propagation models. At the end of this chapter, the research gaps are diagnosed, and the corresponding aim and objectives are proposed to fill the research gaps.

Chapter 3 illustrates the methodology used for this research. This chapter can be divided into four parts, which are the water monitoring system implementation method, the data recording procedure, data processing procedure and the implementation of signal propagation model respectively.

Chapter 4 documents and discusses the results given by the processed data. The relationship between the sensors and high latency, time and the network performance, transmitters location and Wi-Fi coverage are investigated.

Chapter 5 compares and discusses the analysis results given by different periods with different router and repeater configuration.

Chapter 6 derives the decision-making framework used to help the un-trained smart home users to establish a reliable Wi-Fi network. The signal propagation model is also calibrated with the actual performance of the water monitoring system. Then, the decision-making framework is validated by the calibrated signal propagation model.

Chapter 7 concludes the major findings of this research.

CHAPTER 2. Literature Review

2.1 IoT

Almost 21 years have passed since the name ‘Internet of Things’ was created by Kevin Ashton in his presentation at Procter & Gamble in 1999. The original concept of IoT can be traced to the 1970s. At that time, the concept was called Embedded Internet. Figure 1 defines that ‘IoT allows people and things to be connected with anything and anyone at any time and in any place, ideally using Any path/network and Any service.’ The IoT insight report of McKinsey & Company produced by Löffler *et al.* (2017) indicated that the networked devices in 2010 were 12.5 billion, and the number will increase to 50 billion on the basis of their prediction. Network accessibility should be ensured to maintain the performance of a large number of devices.

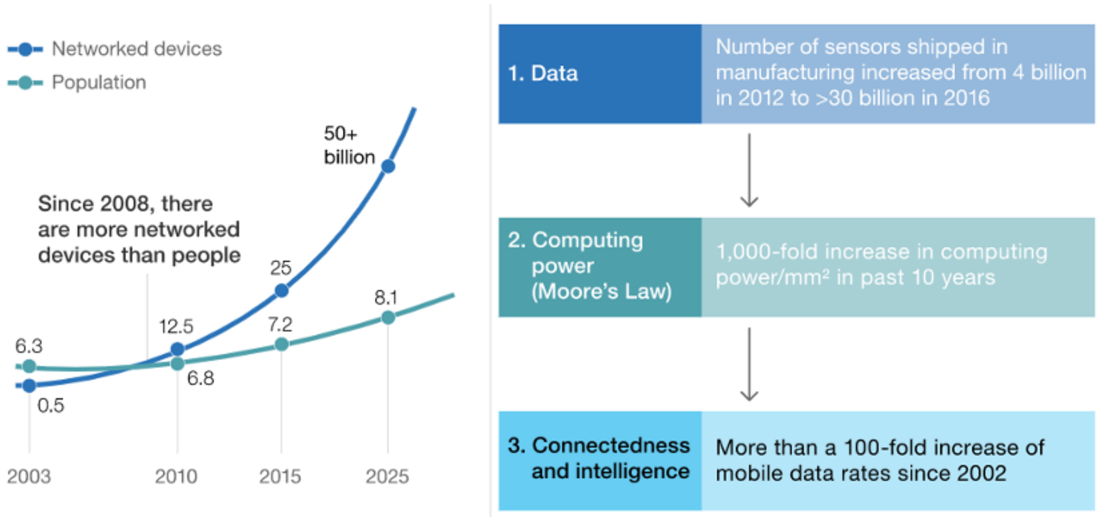


Figure 1. The Historical Number of IoT Devices and the Prediction in the Future (Löffler *et al.*, 2017)

One of the important parts of IoT is the sensor network. It usually comprises one or more sensor nodes, which are wired or connected wirelessly (Akyildiz *et al.*, 2002). Each sensor can capture, process and update data to the server in an IoT system. The sensors are typically seeding around the target objects densely to capture sufficient data for analysis (Akyildiz *et al.*, 2002).

On the basis of the research conducted by Stolikj (2015), the major users of IoT can be divided into three categories: home, industrial and governmental users, as illustrated in Figure 2. The home-use IoT can also be called smart home, which usually allows the home users to connect with the electronic devices installed at home through a smart phone, tablet or computer. Typical smart home devices include home temperature-controlling system (Yang and Newman, 2013), wireless lighting control system (Dandelski *et al.*, 2015), smart television and water-monitoring system. The main feature of the smart home devices can be summarised as the insensitive interoperation with the users. Unlike the IoT applications in a smart home, the IoT applications in industrial and governmental areas usually have an automation feature. For example, in a manufacturing industry, all devices are working automatically towards the same goal, which means the IoT applications require minimal interoperation with humans. The operation of these IoT devices is generally independent and self-controlled.

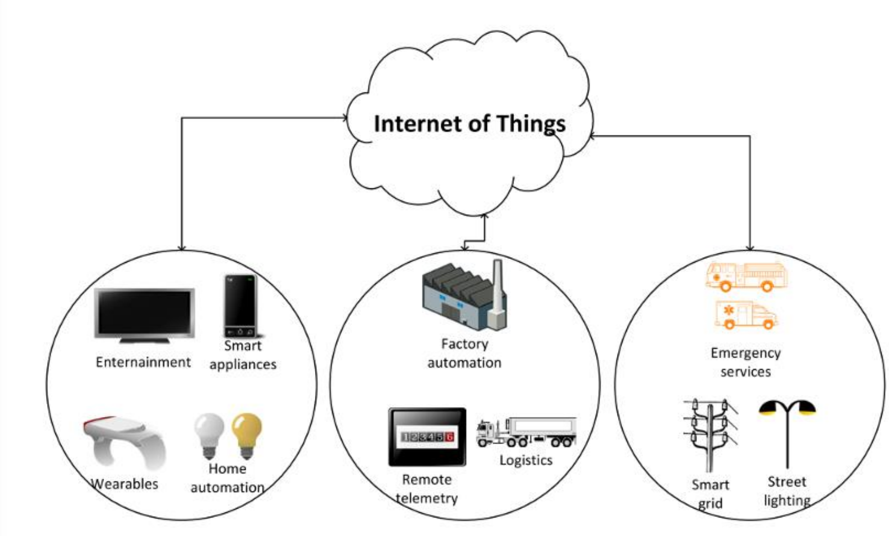


Figure 2. The Major Uses of Internet of Things (Stolikj, 2015)

Network reliability is one of the major issues challenging the performance of IoT (Kelly, 2013). As mentioned in the discussion before, in industrial and governmental areas, IoT devices are usually working automatically without interoperation with humans. Therefore, the networks used in these areas are well designed by the engineer to ensure reliability. Industries and governments need to eliminate the risk of network failure; thus, the cost of establishing the network is not a major concern, which means the devices are under a sufficient and reliable network coverage. However, in a smart home, the network (i.e. Wi-Fi) is mainly established by the homeowner who may not be trained in the field of electronic engineering, and the quality of the Wi-Fi signal coverage can be limited by the budget. Consequently, the Wi-Fi coverage problem can be the greatest issue for a smart home. With the development of smart homes, increasing devices (e.g. the home security system) require a high-quality network coverage with low network latency and high reliability. The study of the Wi-Fi signal coverage is accordingly necessary to support the fast-developing home-use IoT.

2.2 Signal Propagation Mechanism

The Wi-Fi signal is a type of radio wave, and its propagation mechanism is the same as that of the radio wave. Reflection, refraction and diffraction can be considered the three basic propagation mechanisms.

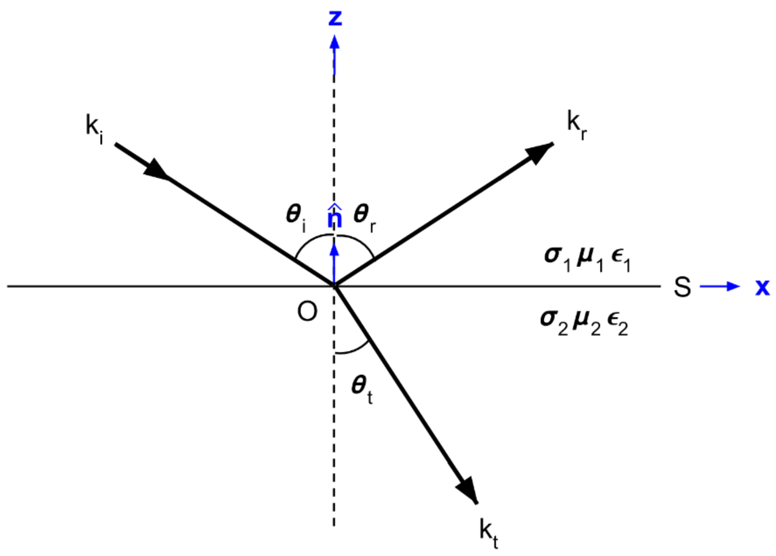


Figure 3. The Relationship Amongst Incident, Refraction and Diffraction Angles

In the radio propagation perspective, the properties used to distinguish different media are conductivity (σ), permittivity (ε) and permeability (μ). The signal will be uniformly propagated through a constant medium (e.g. constants σ, ε and μ). However, when the signal propagates from one medium (σ_1, ε_1 and μ_1) to another medium (σ_2, ε_2 and μ_2), the reflection and refraction will occur on the surface as shown in Figure 3. The incident radio wave will be reflected into the reflection wave and refracted into the refraction wave. During the reflection and refraction, the frequency of the radio wave is not changed. Snell's law of reflection indicates that incident angle (θ_i) is the same as reflection angle (θ_r), as shown in Figure 3. Snell's law of refraction, which is shown in Equation (1), is related to the refractive index of two media.

$$\frac{sin\theta_t}{sin\theta_i} = \frac{n_1}{n_2} \tag{1}$$

Where,

$\theta_i = the\ incident\ angle$

$\theta_t = the\ refraction\ angle$

$n_1 = the\ refractive\ index\ for\ the\ medium\ 1$

$n_2 = the\ refractive\ index\ for\ the\ medium\ 2$

The refractive index is related to the permittivity and permeability of the medium, which can be calculated using Equation (2).

$$n = \sqrt{\varepsilon_r \mu_r} \tag{2}$$

Where,

$\varepsilon_r = material's\ relative\ permittivity$

$\mu_r = material's\ relative\ permeability$

When the surface between two media is perfectly smooth, only one reflection wave will occur. However, in a real scenario, the surface of materials cannot be perfectly smooth. Therefore, multiple reflection directions will exist due to surface irregularity. This type of reflection is called scattering.

When the wave passes through an obstacle or a slit, it will not only be reflected and refracted. The wave can also be bended to pass the obstacle, which means the wave can be propagated to the shadow area behind the obstacle or slit due to diffraction. Nevertheless, the diffraction phenomenon is difficult to be modelled in an accurate approach. The simplest approach to model diffraction is the knife-edge model. However, the obstacle shape cannot be illustrated properly in the knife-edge model. Keller (1961) developed a more accurate model to describe diffraction, which is called geometrical theory of diffraction (GTD). Following the research conducted by Keller (1961), Kouyoumjian and Pathak (1974) updated GTD to uniform GTD, which improve the performance of GTD at the shadow and reflection boundaries.

2.3 Indoor Signal Propagation Models

The conventional approach to analysing Wi-Fi coverage is through signal strength. In theory, the signal strength at any location can be obtained on the basis of appropriate signal propagation models. Signal propagation models can be divided into two types: theoretical and empirical approaches.

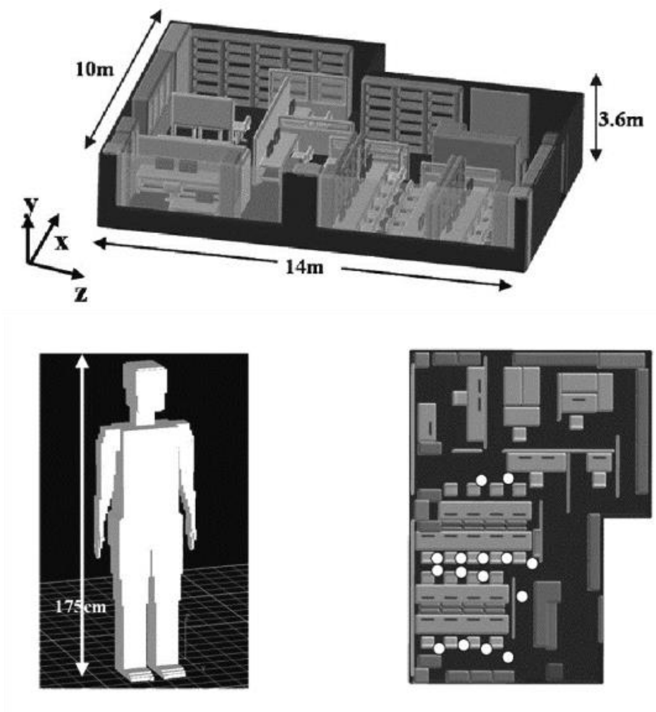


Figure 4. The FDTD Indoor Environment Modelling (Harris, Hikage and Nojima, 2009)

In theory, the most accurate method to model indoor signal propagation is solving the Maxwell equation. For example, finite-difference time-domain (FDTD) models have been used to simulate indoor signal propagation, such as in the studies conducted by Litva, Wu and Ghaforian (1996), Lee and Lai (1998) and Harris, Hikage and Nojima (2009). The FDTD method solves the Maxwell equation and is sensitive to the objects the signal penetrated; therefore, the objects within a room shall be modelled as accurate as possible to simulate a real room configuration. In the research conducted by Harris, Hikage and Nojima (2009), furniture and people were numerically modelled to simulate the complex indoor office environment, as shown in Figure 4. In a time-domain method, analysis accuracy highly depends on the interaction time step. In every time step, the matrix will be inversed and multiplied. The more sophisticated the numerical model is, the larger the required computational power will be. Even the objects in a room have already been considerably simplified in the research conducted by Harris, Hikage and Nojima (2009), as shown in Figure 4, the required computational power remains extensive. This condition may be the reason for the considerable research related to empirical models for signal propagation. Empirical propagation equations are usually logarithmic functions which include such variables as transmitter frequency and the distance from transmitter to receiver. Depending on the complexities of the propagation function, the propagation function may contain other variables which are used to describe the objects between transmitter and receiver. The output of the propagation function is the signal strength with the unit of decibel (dB). Several empirical propagation functions are available. They include the free space propagation, one-slope, wall and floor factor, COST231 multiwall and linear attenuation models.

2.3.1 Free Space Propagation Model

The free space propagation model can be considered as the simplest signal propagation function since it assumes no object between the transmitter and the receiver. The first published free space propagation model was derived by Friis (1946). Jasik (1993) modified the initial propagation equation to the form that usually used in nowadays, which is shown in Equation (3).

$$P_r(d) = P_t \cdot G_T \cdot G_r \cdot (\frac{\lambda}{4\pi d})^2 \quad (3)$$

Where,

$P_r(d) = the\ signal\ strength\ at\ the\ receiver$

$P_t = the\ power\ of\ the\ transmitter$

$G_T = the\ transmitter\ antenna\ gain$

$G_r = the\ receive\ antenna\ gain$

$\lambda = the\ wave\ length$

$d = the\ distance\ from\ the\ transmitter\ to\ the\ receiver$

This Equation (3) can also be expressed in the logarithmic scale, which is shown in Equation (4).

$$P_{r|dBm}(d) = P_{t|dBm} + G_{T|dBi} + G_{r|dBi} + 20log_{10}(\frac{\lambda}{4\pi d}) \quad (4)$$

In the logarithmic scale function, the unit of the signal strength becomes Decibel (dB) since both sides of the equation are ten-based logarithmic.

We can assume there is no antenna gains in both the direction of transmitter and the receiver. Therefore, Equation (4) can be written as the path loss model, which is shown in Equation (5).

$$PL\ (d) = 20log_{10}\left(\frac{4\pi d}{\lambda}\right) = 20log_{10}\left(\frac{4\pi}{\lambda}\right) + 20log_{10}(d) \quad (5)$$

From the equation, there will be a constant loss which is related to the wavelength and the variable loss which is related to the distance between the transmitter and the receiver.

The following empirical signal propagation model researches might be inspired by the free space propagation model derived by Friis (1946) as mentioned above. The empirical functions derived by the following researches usually have the form like

$$PL\ (d) = a + 10 \cdot n \cdot log_{10}(d) \tag{6}$$

Where,

$a = the\ constant\ path\ loss$

$n = the\ path\ loss\ exponent\ (equal\ to\ 2\ for\ free\ space\ propagation)$

The path loss exponent, n is highly related to the environment of the signal propagation (Ren *et al.*, 2011). In general, the lath loss exponents are smaller for the in-home signal transmission scenario (Ren *et al.*, 2011). Table 1 records the path loss exponents derived by Ren *et al.* (2011).

Table 1. Path Loss Exponents after (Ren et al., 2011)

Environment	Path Loss Exponent	Average Path Loss Exponent
Urban macrocells	3.7–6.5	5.1
Urban microcells	2.7–3.5	3.1
Office building (same floor)	1.6–3.5	2.55
Office building (multiple floors)	2–6	4
Store	1.8–2.2	2
Factory	1.6–3.3	2.45
Home	3	3
Free-space	2	2
Two-ray model	4	4
Outdoors (usually)	2.8	2.8

2.3.2 One-Slope Model

The one-slope model derived by Lott and Forkel (2001) can be considered as the updated version of the free-space propagation model. The corresponding propagation equation is shown in Equation (7).

$$PL\ (d) = L_0 + 10 \cdot n \cdot log_{10}(d) \tag{7}$$

Where,

$L_0 = the\ path\ loss\ at\ 1\ meter\ distance\ from\ the\ transmitter$

The one-slope model is simple and easy to be implemented. However, the one-slope model describes all the potential path loss mechanisms into one single parameter (i.e. the path loss exponent). Therefore, the uncertainty of this path loss exponent will be high, which means using the one-slope model may not be accurate to simulate the indoor Wi-Fi signal propagation. The home environment can content many path loss mechanisms (e.g. the walls, the furniture and the material of floor) which are different from the environment where the equation derived.

2.3.3 Wall and Floor Factor Models

The wall and floor factor propagation models were derived by Keenan and Motley (1990). This model can also be considered as the improved version of the free space propagation model. Unlike the single path loss exponent used in one-slope model, the wall and floor models include more parameters to describe the path loss due the penetration of walls and floors. According to Keenan and Motley (1990), the function of wall and floor factor models is shown in Equation (8).

$$PL\ (d) = L_1 + 20 \cdot log_{10}(d) + n_f L_f + n_w L_f \tag{8}$$

Where,

$L_1 = the\ path\ loss\ at\ 1\ meter\ distance\ from\ the\ transmitter$

$n_f = number\ of\ floors\ the\ signal\ penetrated$

$L_f = the\ penetration\ loss\ per\ floor$

$n_w = number\ of\ walls\ the\ signal\ penetrated$

$L_w = the\ penetration\ loss\ per\ wall$

It is clear that the wall and floor factor propagation equation are the free space propagation plus the losses due to the penetration of the walls and floors. Therefore, compared with the free space and one-slope models, using the wall and floor factor models may be more accurate to describe the in-home Wi-Fi propagation scenario.

2.3.4 COST231 Multi-Wall Model

The COST231 multi-wall model (COST Action, 1999) is a free-space-propagation-based model which was derived by COST 231 project operated by European Communities in 1999. According to the report produced by COST Action (1999), the propagation function of COST231 multi-wall model is shown in Equation (9).

$$PL\ (d) = L_{FS} + L_C + \sum_{i=1}^{I} L_{wi} n_{wi} + L_f n_f^{\left(\frac{n_f+2}{n_f+1} - b\right)} \tag{9}$$

Where,

$L_{FS} = free\ space\ loss\ between\ transmitter\ and\ receiver, equal\ to\ 20 \cdot log_{10}(d)$

$L_C = constant\ loss$

$I = number\ of\ walls\ the\ signal\ penetrated$

$L_{wi} = the\ penetration\ loss\ per\ wall\ type\ i$

$n_{wi} = number\ of\ type\ i\ walls\ the\ signal\ penetrated$

$L_f = the\ penetration\ loss\ per\ floor$

$n_f = number\ of\ floors\ the\ signal\ penetrated$

$b = empirical\ constant$

For Equation (9), similar with the previous wall and floor factor models the COST231 multi-wall model can also be described as the free space path loss plus the penetration losses due to the walls and floors. The COST231 multi-wall model can be considered as the updated version of the wall and floor factor models. In the wall and floor factor models, only the single wall type can be assumed, while the COST231 multi-wall model allows the various wall types. However, in the practice the wall types are better to be simplified and reduced to increase the computational time. The other update is the relationship between the floor penetrated losses are no longer linear with the number of penetrated floors, which is more realistic than the previous wall and floor factor models.

2.3.5 Liner Attenuation Model

In the COST231 project, the linear attenuation model was also be developed (COST Action, 1999). According to the report produced by COST Action (1999), the propagation function of linear attenuation model is shown in Equation (10).

$$PL\ (d) = L_{FS} + \alpha d \tag{10}$$

Where,

$L_{FS} = free\ space\ loss\ between\ transmitter\ and\ receiver, equal\ to\ 20 \cdot log_{10}(d)$

$\alpha = the\ coefficient\ of\ attenuation\ with\ unit\ dB/m$

Different with the one-slope model, the linear relationship between the distance and the path loss in the linear attenuation model. In the study like the Karlsson (1995), the additional parameters to describe the penetration loss due to the wall were added to increase the performance of the model.

2.4 Research Gap, Aim and Objectives

From the previous literature review, the number of IoT devices has been doubled in the past decade, and it is still growing at a high speed. Network performance has been determined as the major issue of IoT. Smart home devices may have a high chance to suffer insufficient network coverage because the Wi-Fi network in a smart home is usually not established by a well-trained engineer. The installation of multiple Wi-Fi routers in a home is also inflexible due to the following four reasons:

- The budget is limited.
- The Wi-Fi router is usually plugged with multiple cables.
- In some old buildings in Hong Kong, only one cable is used for the Internet.
- The houses in Hong Kong are usually excessively small to set multiple routers.

Some of the devices which are sensitive to network latency may be failed to serve due to the insufficient Wi-Fi coverage. For example, the home security system may fail to respond to the home user to lock or unlock the door, and the lighting system may not turn on time when the home user is exposed to the dark.

The most efficient approach to establishing the network for a smart home should be investigated to ensure the stable communication of smart home devices. Most of the studies related to indoor Wi-Fi performance are based on indoor signal propagation, such as the research conducted by Baba, Ibrahim and Ahmad (2005), Luo (2013), Midoglu, Svoboda and Rupp (2016) and Hosseinzadeh *et al.* (2017). In their research, Wi-Fi performance was described as the signal strength, which can be calculated using the propagation models described before. The major problem in the current literature is that no one has calibrated the signal propagation models with the actual performance of smart home devices (i.e. relate the signal strength to the performance of the smart home devices). Moreover, the Wi-Fi network in a smart home is usually not established by a well-trained engineer, which means users may not be able to apply the complex propagation models to evaluate their Wi-Fi coverage. Performance-based indoor Wi-Fi coverage has not been studied yet. Accordingly, the investigation of indoor Wi-Fi coverage on the basis of the actual performance of IoT devices is valuable.

To fill the research gaps, the current research aims to study the Wi-Fi coverage on the basis of the data from a water-monitoring system and develop a decision-making framework to help untrained smart home users easily establish a high-performance Wi-Fi network. The following stages are performed to achieve these objectives.

- A water-monitoring system is established, and data are obtained.
- The positions of transmitters are changed, and new data are collected from the water-monitoring system.
- The collected data are analysed.
- The relationship between the location of transmitters and the performance of the Wi-Fi coverage is summarised.
- A decision-making framework based on the result summarised by comparison is developed.
- Signal propagation models are calibrated with the decision-making framework.
- The optimised location and configuration for the transmitters are suggested by using the decision-making framework based on typical Hong Kong

apartments.

- The suggestion is validated through the calibrated indoor signal propagation models.

CHAPTER 3. Methodology

The methodology used for this research can be divided into three parts. The first part is the implementation of the water-monitoring system. The water-monitoring system includes sensors, gateways, Wi-Fi router, Wi-Fi repeater and cloud. It has been updated twice. The data obtained from the system can be divided into three periods accordingly. Initially, the system used only a single Wi-Fi router to upload data to the cloud. Then, one Wi-Fi repeater was added to this system to enhance the signal in a certain location. Lastly, one more Wi-Fi repeater was added. The second part is processing the recorded data during the three periods. The Wi-Fi coverage performance can be obtained by comparing the analysis results in the different periods. Based on the analysis result, a framework can be established to evaluate the Wi-Fi coverage, and this framework can be used to help smart home users establish their Wi-Fi network. The decision-making framework can also be used to evaluate the actual Wi-Fi coverage performance for typical Hong Kong apartments. To relate the actual Wi-Fi performance with the theoretical signal propagation, the decision-making framework will be calibrated with the signal propagation models discussed in the literature review. The signal wave propagation will be simulated for the experimented apartments by using the propagation models implemented in MATLAB, and the performance of the different signal propagation models will be compared and discussed. Finally, the location of the router and repeaters will be determined on the basis of the proposed decision-making framework for typical Hong Kong apartments as examples. The suggested router and repeater locations for two apartments will also be validated using the calibrated signal propagation models implemented in MATLAB.

The procedure used to conduct this research can be summarised as a flow chart, which is shown in Figure 5. The detailed methodology is shown in subsections 3.1, 3.2, 3.3 and 3.4.

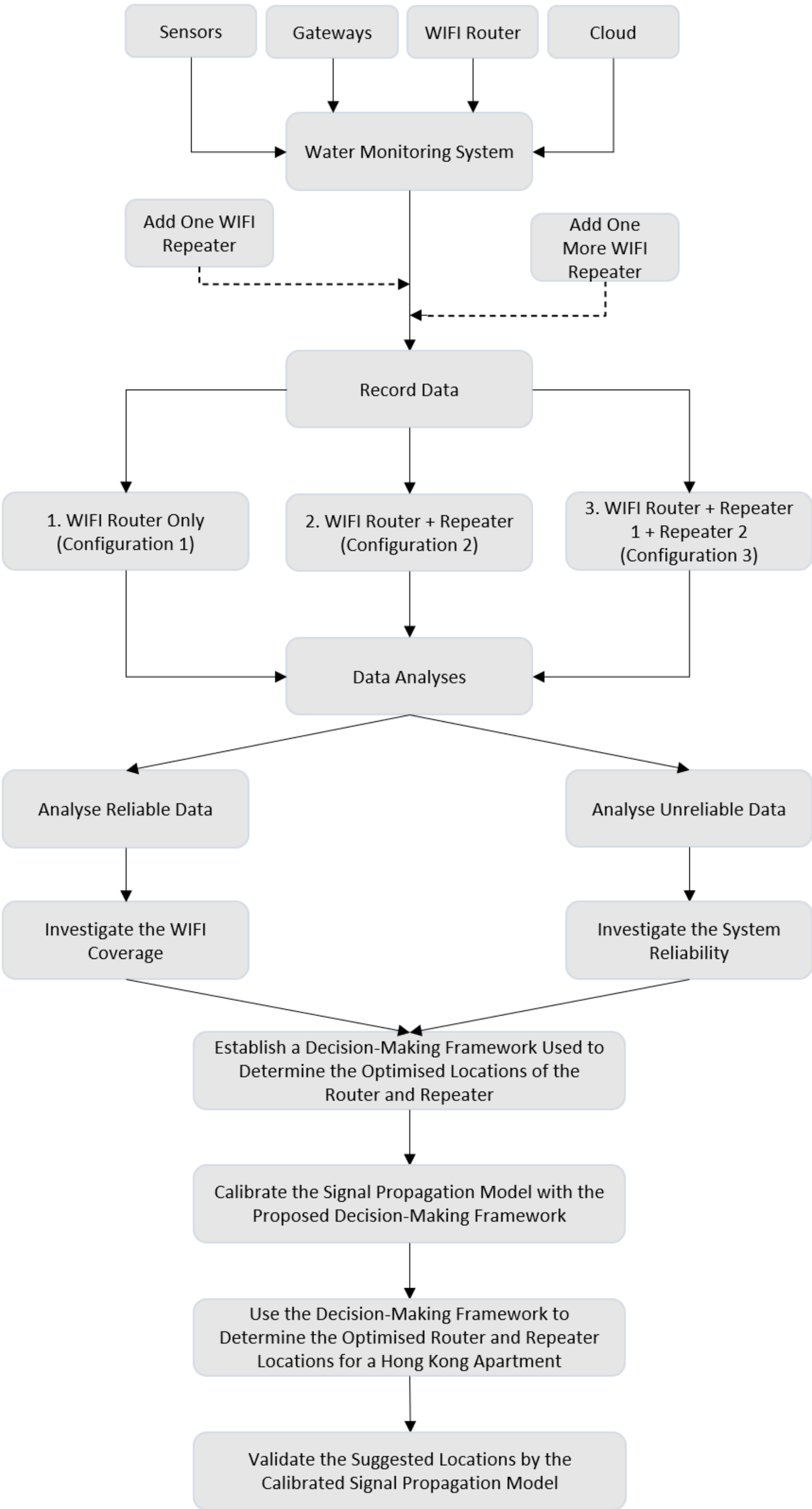


Figure 5. The Flow Chart Summarising the Methodology Used in This Research

3.1 Implementation of a Water Consumption- Monitoring System

The wireless water-monitoring system comprises four components: sensors, gateway, Wi-Fi router and the cloud. The architecture of this water-monitoring system and the data upload path are illustrated in Figure 6. From Figure 6, the local monitoring unit is the combination of sensors, gateway and Wi-Fi router. The sensors implemented in each tap can collect the water usage information in real time and transmit the data to the gateway wirelessly. Then, the gateway passes the data to the Wi-Fi router, and the Wi-Fi router uploads these data to the cloud. The data can be downloaded from the cloud for further analysis at any time.

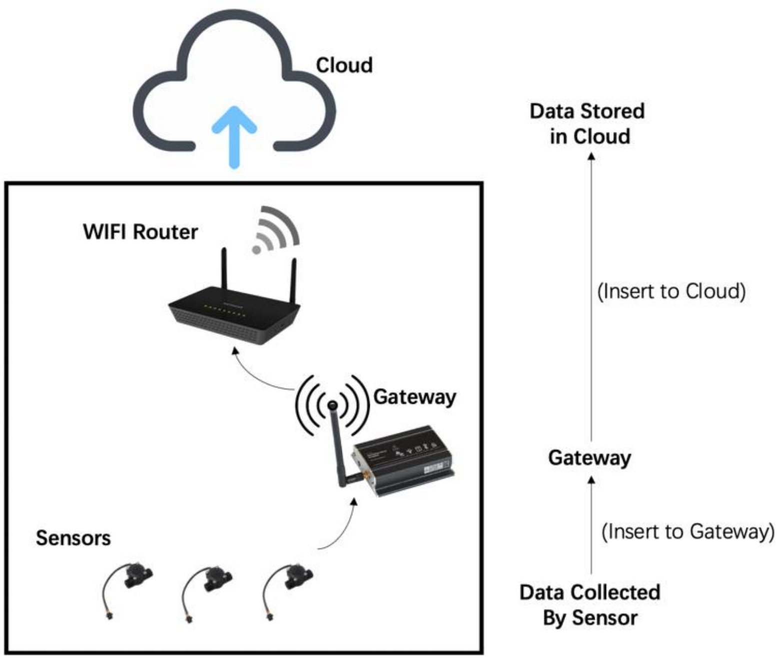


Figure 6. The Architecture of the Water Consumption-Monitoring System

To illustrate the location of devices clearly, the room plan of a typical Hong Kong apartment is provided in Figure 7.

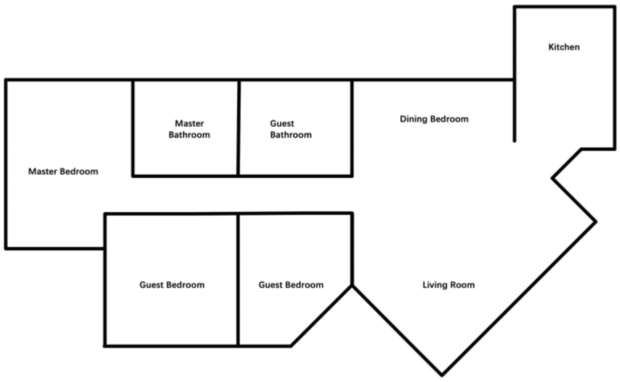


Figure 7. The Floor Plan of a House

In this project, we use two houses with the similar room configuration given in Figure 7 to perform the analysis; they are named No.1-House and No.2-House. The sensors, gateway and router were implemented in different rooms in the houses. To test the Wi-Fi signal intensity in different parts of the houses, sensors were placed in different rooms, as shown in Table 2 and Table 3.

All sensor IDs follow the same naming sequence. The first digit of a sensor ID represents the house number (i.e. No.1-House is 1, and No.2-House is 2), the second digit represents the room (i.e. the guest bathroom is 0, the kitchen is 1, and the master bathroom is 2), and the third digit represents the serial number of the sensors in the same room. The sensor IDs and the corresponding locations for No.1 and No.2 houses are summarised in Table 2 and Table 3, respectively.

Table 2. The Location of Sensors in No.1 House

Located Room	Located Tap	Sensor ID
Guest Bathroom	Guest Bathroom Basin Cold	No.101
	Guest Bathroom Basin Hot	No.102
	Guest Bathroom Bathtub	No.103
	Guest Bathroom Fixed Shower Head	No.104
	Guest Bathroom Movable Shower Head	No.105
Kitchen	Kitchen Basin Cold	No.111
		No.112
	Kitchen Basin Hot	No.113
		No.114
	Washing Machine	No.115
		No.116
Master Bathroom	Master Bathroom Basin Cold	No.121
		No.122
		No.123
	Master Bathroom Basin Hot	No.124
		No.125
	Master Bathroom Bathtub	No.126
	Master Bathroom Movable Shower Head	No.127
		No.128

Table 3. The Location of Sensors in No.2-House

Located Room	Located Tap	Sensor ID
Guest Bathroom	Guest Bathroom Basin Cold	No.201
	Guest Bathroom Basin Hot	No.202
	Guest Bathroom Bathtub	No.203
	Guest Bathroom Fixed Shower Head	No.204
		No.205
Kitchen	Kitchen Basin Cold	No.211
	Kitchen Basin Hot	No.212
	Washing Machine	No.213
Master Bathroom	Master Bathroom Basin Cold	No.221
	Master Bathroom Basin Hot	No.222

Only one Wi-Fi router was initially installed in No.1-House, as shown in Figure 8. The water-monitoring system had been run for 43 days under this layout plan from 10th December 2019 to 22nd January 2020.

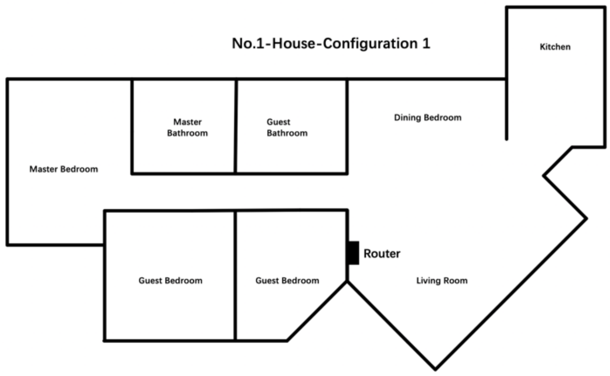


Figure 8. The Location of the Devices under the First Configuration

To investigate the relationship between the performance of data uploading and the Wi-Fi coverage further, one Wi-Fi repeater was added to enhance the Wi-Fi signal. In No.1-House, the repeater was installed in a position near the kitchen, as shown in Figure 9. The system had been run for 13 days from 22nd January 2020 to 7th February 2020 with the repeater installed near the kitchen. In No.2-House, the repeater was installed in a position near the master bathroom, as shown in Figure 10.

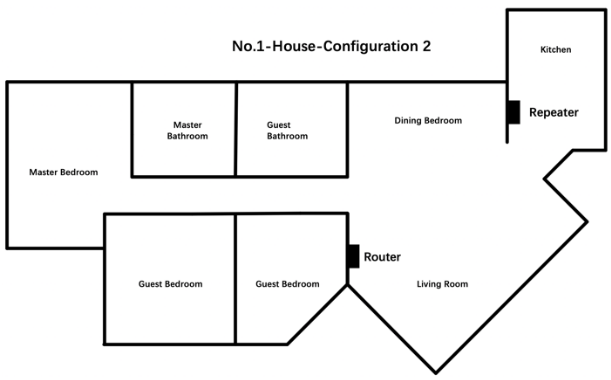


Figure 9. The Location of the Devices under the Second Configuration

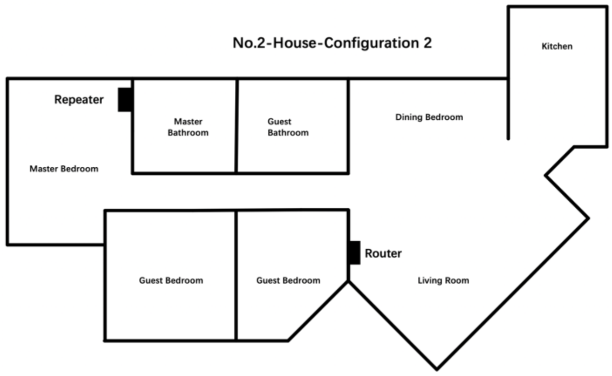


Figure 10. The Location of the Devices under the Second Configuration

Then, the second Wi-Fi repeater was added, as shown in Figure 11, and the system had been run for 114 days under this layout plan from 7th February 2020 to 31st May 2020.

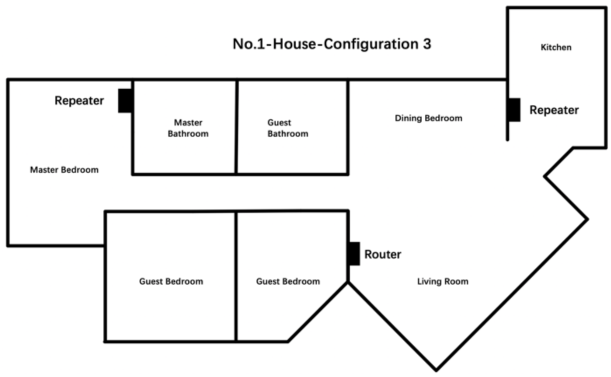


Figure 11. The Location of the Devices under the Third Configuration

3.2 Data-Recording Procedure

After the implementation of the water-monitoring system, the real-time water usage data can be collected using the sensors installed within the taps. The collected data are uploaded to the cloud via the gateway and Wi-Fi router once the taps are opened. The uploading time can be calculated by subtracting the timestamps of data collection at the sensors and cloud. The uploading time can also be called latency. The latency represents the speed of data uploading, which can be an indicator of the Wi-Fi performance.

Trivial data, such as water usage information, can be ignored, considering that this research focuses on the analysis of Wi-Fi coverage. The data are recorded in a fixed form, as shown in Figure 12, through a programming embedded in the cloud. As presented in Figure 12, the actual recorded data are the data that can be used for Wi-Fi coverage analysis. They include the sensor ID, gateway ID, timestamp, latency from the sensors to the gateway and latency from the gateway to the cloud. The sensor and gateway ID can be used to locate the sensors. The summation of the latency from the sensors to the gateway and the latency from the gateway to the cloud represents the total uploading time. We need the timestamp representing the time in a day once taps are opened to determine the uploading performance at different times in a given day.

GuestBathroomBasinCold

sensor_id	gateway_id	latency_from_sensor_to_gateway	timestamp	latency_from_gateway_to_cloud
6958D70F8F662B00	hhgw-b827ebc401c2	6082	2020-02-07 17:06:23.000	287
6958D70F8F662B00	hhgw-b827ebc401c2	9979	2020-02-07 17:07:56.000	293
6958D70F8F662B00	hhgw-b827ebc401c2	4853	2020-02-07 17:10:39.000	294
6958D70F8F662B00	hhgw-b827ebc401c2	5730	2020-02-07 17:25:21.000	290
6958D70F8F662B00	hhgw-b827ebc401c2	4176	2020-02-07 17:28:19.000	299
6958D70F8F662B00	hhgw-b827ebc401c2	4280	2020-02-07 17:39:20.000	1825
6958D70F8F662B00	hhgw-b827ebc401c2	5035	2020-02-07 17:40:22.000	289
6958D70F8F662B00	hhgw-b827ebc401c2	5833	2020-02-07 18:05:28.000	293
6958D70F8F662B00	hhgw-b827ebc401c2	5253	2020-02-07 18:16:11.000	287
6958D70F8F662B00	hhgw-b827ebc401c2	5393	2020-02-07 18:35:14.000	293
6958D70F8F662B00	hhgw-b827ebc401c2	4666	2020-02-07 18:36:03.000	284
6958D70F8F662B00	hhgw-b827ebc401c2	5981	2020-02-07 18:41:56.000	283

Figure 12. The Data Recorded in the Cloud (Incomplete)

3.3 Data-Processing Procedure

As mentioned before, the collected data need to be translated wirelessly from the sensors to the cloud. This transmission procedure takes time, and the time consumed by data transmission can be called latency. The data in the IoT field are usually translated wirelessly through Wi-Fi, which may not be as stable as those when using a cable. In some cases, the transmission latency may be high due to the poor Wi-Fi coverage. Data with high latency should be analysed to investigate the reason why high latency occurs and improve the Wi-Fi coverage. However, no fixed definition related to high latency exists. The magnitude of latency is mainly related to the performance of devices (i.e. sensors, gateways, routers and repeaters) and the Internet condition. Therefore, the magnitude of latency may vary in different water-monitoring systems or IoTs, i.e. the magnitude of high latency in each system needs to be defined. High latency is generally introduced by network failure or insufficient Wi-Fi coverage. Hence, high latency can be defined as the latency higher than the normal operation latency in an IoT system. We can use a statistical approach to determine the threshold of high latency in an IoT system. The recorded data are processed using Python v3.6.9 to determine the threshold. The original first step to determine the threshold is that empty cells are deleted, and the total latency is calculated by summing up the latency from the sensors to the gateway and the latency from the gateway to the cloud.

3.3.1 Filtering of Unreliable Data

After the total latency is defined and calculated, we can investigate why some total latencies are extremely large. Under a normal situation, the total latency for data uploading is approximately a few seconds or minutes. However, when packet loss and system shut down occur, the data updating will be paused. After the system realises that packet loss and shut down occur, it will ask to resend the data. Consequently, the total latency under these situations will be extremely large.

Hence, we can define that the unreliable data are caused by the packet loss and system shut down. These data can be used to illustrate the instability and unreliability of the system, which means including these data into the Wi-Fi coverage analysis can introduce inaccurate results. On the basis of the data analysis, the threshold used to define the packet lost and system shut down is 20 min (120,000 ms). The data with total latency higher than 20 min are filtered for the system reliability analysis, and these unreliable data are excluded from the Wi-Fi coverage analysis.

The analysis related to unreliable data (i.e. the packet loss and system shut down) will be elucidated in Chapter 5.

3.3.2 Processing of Reliable Data

After the unreliable data are filtered, the data without packet loss and system failure can be used for the Wi-Fi coverage analysis. We can quantify the performance of Wi-Fi coverage at certain locations as the probability of the occurrence of high latency. In general, the location which is sufficiently covered by Wi-Fi signal has a low probability of high latency occurrence. When high latency does not occur, the data uploading time should be normally distributed around a mean value (i.e. following the normal distribution).

However, in a real scenario, the distribution is positively skewed due to the presence of high latency. Therefore, we can draw the pseudo random distribution on the basis of the values located before the peak value (i.e. the mode). This assumed pseudo normal distribution represents the scenario in which the data set is collected using the monitoring system under extremely sufficient Wi-Fi coverage. That is, no high latency occurs in this assumed extreme scenario.

We can define the empirical end of the pseudo normal distribution (three-sigma:

99.7% confidence interval) as the threshold of the occurrence of high latency.

From Figure 13 and Figure 14, the threshold of high latency occurrence for both homes is approximately 8600 ms. Uploading time larger than this threshold (i.e. 8600 ms) indicates the occurrence of high latency. We can calculate the probability of the occurrence of high latency (i.e. insufficient Wi-Fi coverage) at different rooms under diverse configurations. This probability represents the Wi-Fi coverage situation.

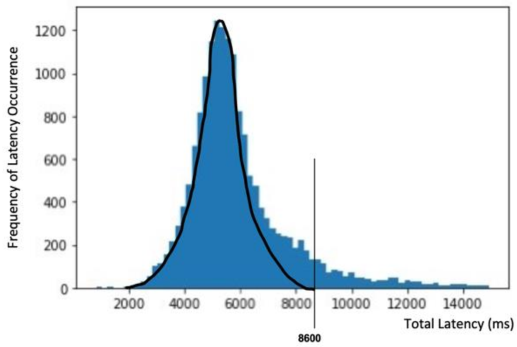


Figure 13. Data Distribution at No.1-House

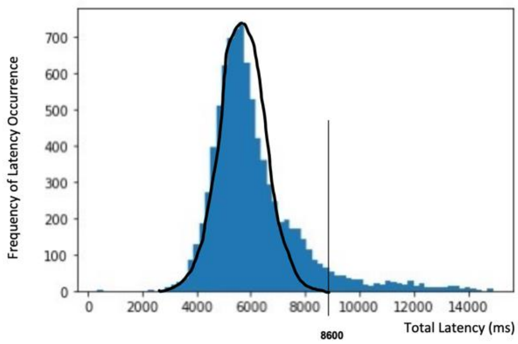


Figure 14. Data Distribution at No.2-House

The detailed Wi-Fi coverage analysis will be discussed in Chapter 4 and Chapter 5, and the relationship between the locations of transmitters and the performance of the water-monitoring system will also be investigated in these chapters.

3.4 Indoor Signal Propagation Model

After fully studying the relationship between the locations of transmitters and the performance of the water-monitoring system, we can calibrate the theoretical signal propagation with the experimental performance of the water-monitoring system.

Several signal propagation models have been discussed in the literature review. FDTD models require extensive computational time and accurate indoor environment modelling. In this research, the calibration is conducted by implementing the empirical signal propagation equation in MATLAB due to the limitation in time.

The main features of Hong Kong apartments can be summarised as single floor, small (approximately 50 m^2) and fully functional. Unlike typical European houses with dual floors, Hong Kong apartments usually have a single floor. We can assume that all the devices connected to the Wi-Fi network are in the same level, and the signal propagation amongst floors can be ignored. As mentioned, typical Hong Kong apartments are generally small but fully functional, which indicates that the ratio of the house area to the number of walls is usually small. Therefore, the penetration loss due to walls can be the major loss compared with the path loss in the area with a low ratio of area to number of walls. The empirical propagation function should include the effect of penetration loss. However, the penetration loss due to walls is not described properly in free space, one-slope and linear attenuation models. Consequently, these models are not selected as validation models. Considering that the COST231 multiwall model is the updated version of the wall and floor factor model, we select it to describe the indoor signal propagation.

The MATLAB code developed by Hosseinzadeh *et al.* (2017) is used to generate the simulation results given by the free space propagation and COST231 multiwall models. The code is modified to satisfy the apartment configuration of this research. Signal propagation is simulated for the first configuration of No.1 house by using the free space and COST231 multiwall propagation models. The corresponding contour maps for signal propagation are shown in Figure 15 and Figure 16.

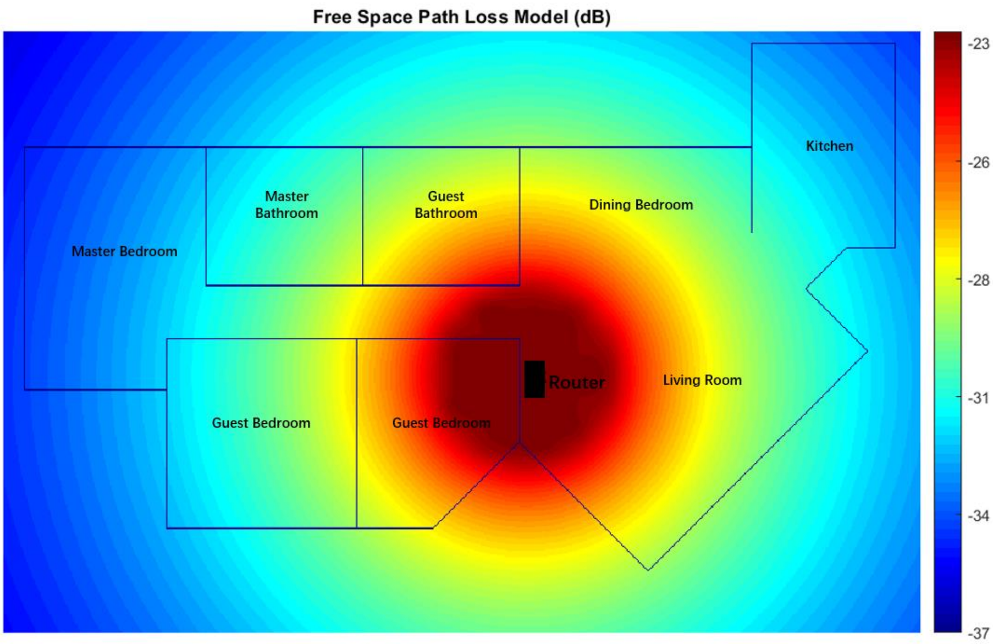


Figure 15. The Signal Propagation Contour Map Generated using the Free Space Model

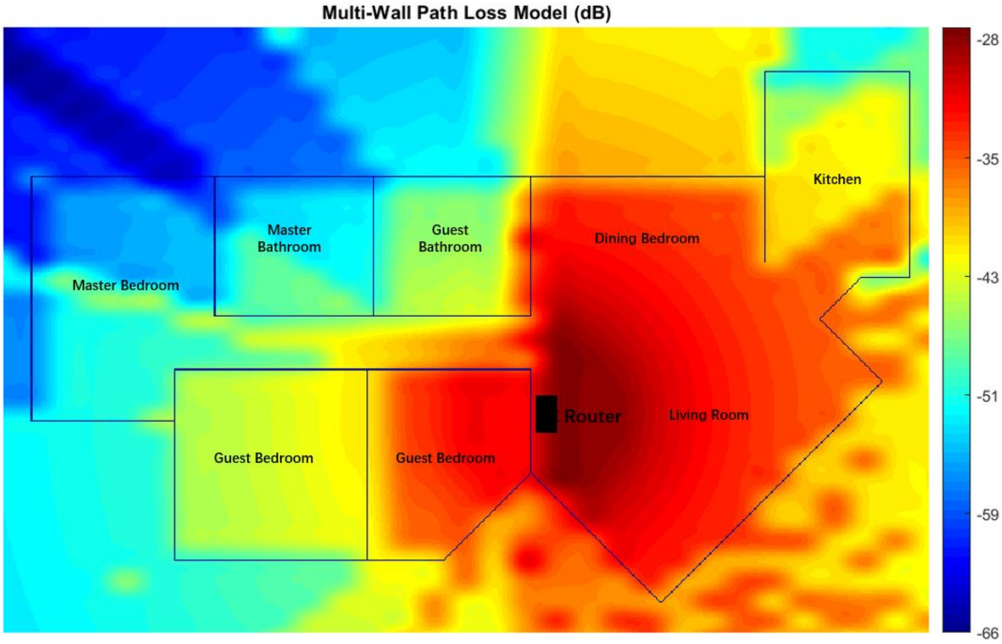


Figure 16. The Signal Propagation Contour Map Generated using the COST231 Multiwall Model

From Figure 15 and Figure 16, we can determine clearly different signal propagations between the free space and COST231 multiwall propagation models. In the free space propagation model shown in Figure 15, the signal strength uniformly decreases with distance. In the COST231 multiwall model shown in the Figure 15, the contour map is not a symmetric shape due to signal penetration loss. Comparison of the contour maps shown in Figure 15 and Figure 16 demonstrates that the penetration loss due to walls is significant for typical Hong Kong apartments. Therefore, the COST231 multiwall model can be considered to have improved performance for indoor signal propagation. The free space propagation model may have considerable performance for an indoor environment with a large open area, such as an office, but the performance may be unreasonable for typical Hong Kong apartments.

The detailed calibration between the theoretical signal propagation model and the actual performance of Wi-Fi coverage will be illustrated in Chapter 6.

CHAPTER 4. Analysis of Reliable Data in Three Configurations

From the discussion in the methodology chapter, the unreliable data due to packet loss and system failure should be excluded from the Wi-Fi coverage analysis. Therefore, this chapter documents the Wi-Fi coverage analyses during three periods on the basis of data without packet loss and system failure. The filtered unreliable data will be analysed and discussed later.

The entire data packet was recorded from December 2019 to May 2020. Two device updates were conducted amongst the three periods, as discussed in the Methodology Chapter (i.e. adding repeaters at different locations). This process can be regarded as three transmitter configurations because the number of transmitters was changed twice. The data recorded in the three configurations were analysed to determine the Wi-Fi coverage of rooms under these configurations.

The first transmitter configuration was set from 10th December 2019 to 22nd January 2020. Under the first configuration, only one Wi-Fi router was used to cover an entire house. The second transmitter configuration was set from 22nd January 2020 to 07th February 2020. Under the second configuration, one repeater was added close to the kitchen, and the position of the existing Wi-Fi router was retained. The third transmitter configuration was set from 07th February 2020 to 31st May 2020. Under the third configuration, one Wi-Fi router and two repeaters were used to cover the entire house. The positions of existing Wi-Fi router and repeater were not changed, and one more repeater was added near the master bathroom.

The entire data packet was divided into three parts depending on the three transmitter configurations based on the updates. The detailed information of the three data sets, including the start and end dates, the number of records and the transmitter configuration, is shown in Table 4.

Table 4.Three Configurations and the Corresponding Start and End Dates, the Number of Records, and the Transmitter Configuration

Configuration Name	Start and End Times	The Number of Total Latency	Situation of Device
First Configuration	2019-12-10, 2020-01-22	3232	One router
Second Configuration	2020-01-22, 2020-02-07	3403 / 9033	One router and one repeater (repeater in two different places)
Third Configuration	2020-02-07, 2020-05-31	10059	One router and two repeaters

4.1 Data Analysis under the First Configuration

The first period was from 10th December 2019 to 22nd January 2020. In this period, the device location was under the first configuration (i.e. only one router was placed in No.1-House), as shown in Figure 17.

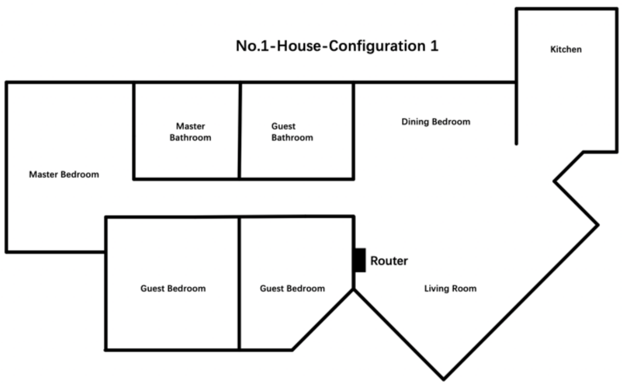


Figure 17. The Location of Devices under First Configuration

4.1.1 Relationship Between Sensor and High Latency

Suspicious data (i.e. total latency larger than the threshold) were determined using the methodology stated before. We can draw a bar chart showing how frequent high latency occurs for each sensor (Figure 18). The x-axis shows the frequency of high latency occurrence; the y-axis shows the ID of the sensors.

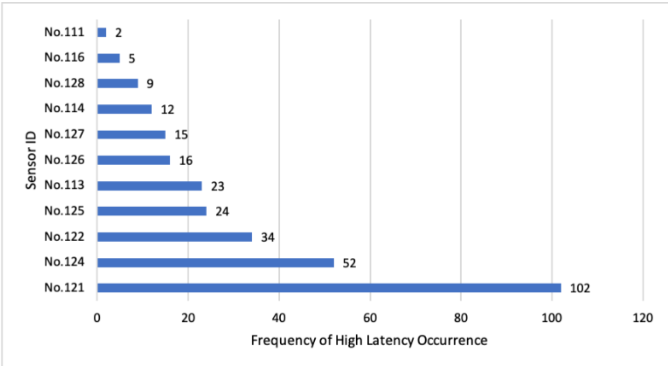


Figure 18. The Situation of Each Sensor under the First Configuration

Form Figure 18, we can determine that the sensor with ID No.121 has a high frequency of high latency occurrence for uploading data. This phenomenon means that this sensor may fail. For example, a battery contact problem, drained battery or sensor aging may occur. Checking and making a record of these devices regularly are necessary. These checks ensure that no problems occur with the hardware devices and allow for an accurate analysis of subsequent Wi-Fi coverage.

4.1.2 Relationship Between Time and Wi-Fi Coverage

In this part, the relationship between Wi-Fi coverage and the time of one day is illustrated. The time in a day when high latency will most likely occur should be determined. This work can identify the Wi-Fi coverage situation in a day in accordance with the probability of high latency occurrence. We divided a day into

24 h and then counted the number of high latency occurrence per hour, as shown in Figure 19. The x-axis shows the hour scale of the day; the y-axis shows the frequency of high latency occurrence.

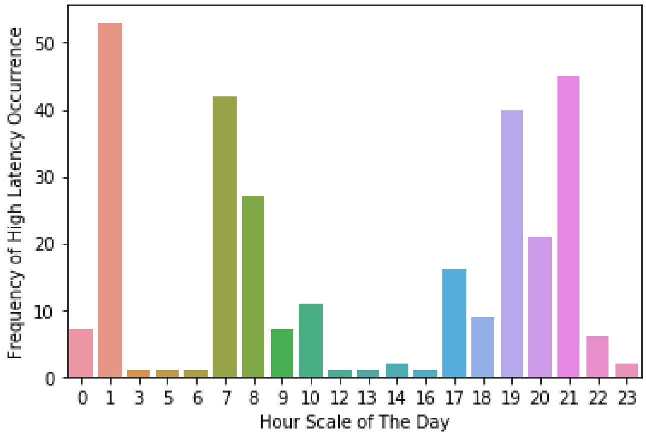


Figure 19. The Frequency of High Latency Occurrence Per Hour under the First Configuration

From Figure 19, high latency most likely happens from 7:00 to 8:00 in the morning and from 19:00 to 21:00 in the evening, whereas the chance of high latency occurrence is low from 22:00 to 00:00 and from 9:00 to 18:00. This phenomenon indicates that the probability of high latency occurrence is related to human activities. Two activities may cause this phenomenon. One is the intensive use of Wi-Fi during these periods. For example, in the evening, the Wi-Fi resources may be occupied by other activities, such as watching YouTube, refreshing social media and having a video call. Therefore, the Wi-Fi coverage will be influenced by this intensive use.

The other one is that the taps are frequently opened during these periods. Investigating how many times water is used during these periods is necessary. We can draw a bar chart that shows the frequency of water consumption per hour, as indicated in Figure 20.

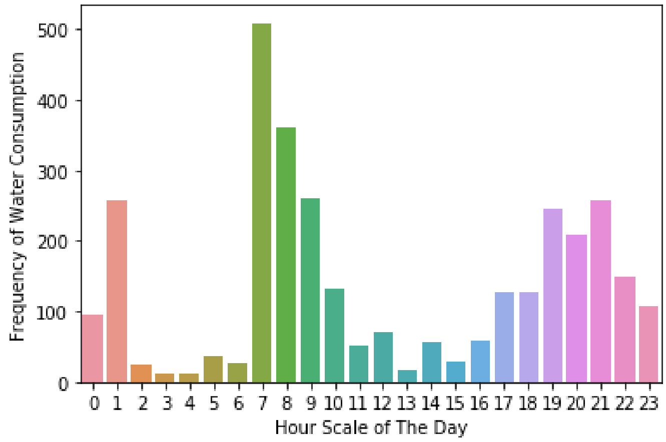


Figure 20. The Frequency of Water Consumption Per Hour under the First Configuration

From Figure 20, the busy periods for using water are the morning from 7:00 to 9:00 and the evening from 19:00 to 01:00. Comparison of Figure 19 and Figure 20 implies that from 7:00 to 9:00, water is used frequently. High latency also likely occurs during this period. This phenomenon indicates that the frequent use of water may significantly increase the probability of high latency occurrence.

Therefore, for the different times in a day, the probability of high latency occurrence is related to the frequency of using water and the intensive use of Wi-Fi. When intensive use of Wi-Fi occurs and the taps are opened frequently, high latency occurs recurrently and the Wi-Fi coverage is poor.

4.1.3 Relationship Between Device Location and Wi-Fi Coverage

After the influences of sensors and time on Wi-Fi coverage have been learnt, the relationship between device location and Wi-Fi coverage is analysed in this part.

The recorded data can be located at the corresponding rooms on the basis of the location of sensors shown in Table 2. Figure 21 shows the location of high latency occurrence in terms of corresponding room. The x-axis shows the frequency of high latency occurrence; the y-axis shows the name of rooms.

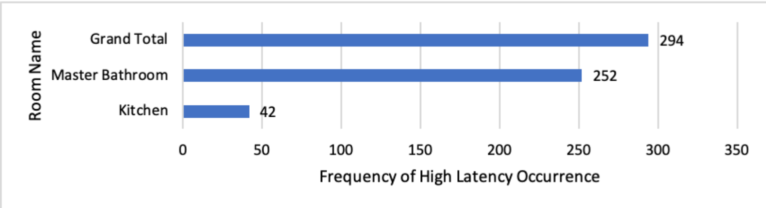


Figure 21. The Situation of Each Room under the First Configuration

From the discussion in the Literature Review and Methodology chapters, the conventional approach to representing the Wi-Fi coverage is using signal strength. In this research, a performance-based Wi-Fi coverage analysis was conducted. However, from the previous study, the frequency of high latency occurrence is related to the frequency of water usage. Therefore, the frequency of high latency occurrence cannot be used to describe the Wi-Fi coverage situation. We can normalise the frequency of high latency occurrence by the number of recorded data, which means the probability of high latency occurrence was used to represent the performance of indoor Wi-Fi coverage. The probability of high latency occurrence within each home can be determined using the frequency of high latency occurrence divided by the total frequency of water consumption. The probability of high latency occurrence can be calculated using Equation (11).

$$P_i = \frac{n_i}{N} \tag{11}$$

Where,

$P_i = the\ probability\ of\ high\ latency\ occurrence\ in\ \ room\ i$

$n_i = the\ frequency\ of\ high\ latency\ occurence\ in\ room\ i$

$N = total\ number\ of\ recorded\ reliable\ data$

The percentage of sufficient Wi-Fi coverage can be calculated using Equation (12).

$$P(sufficient\ coverage) = 1 - \sum_{1}^{i} P_i \tag{12}$$

The calculated results can be shown as a pie chat in Figure 22.

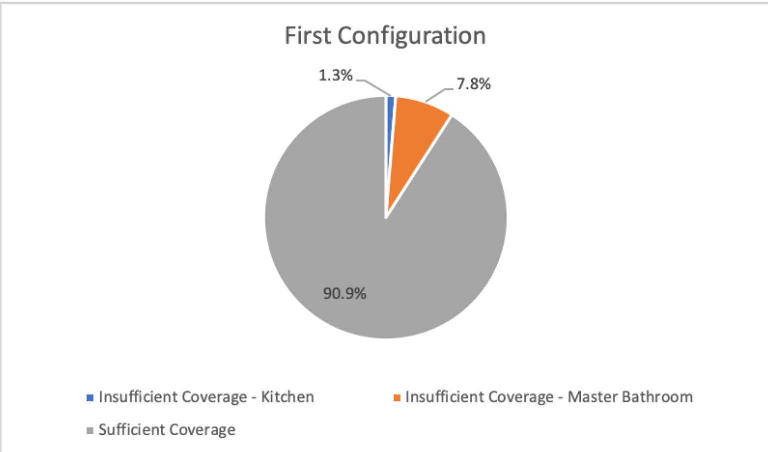


Figure 22. The Situation of Wi-Fi Coverage under the First Configuration

From Figure 22, two phenomena can be found. Firstly, approximately 9.1% of the insufficient coverage happened in the entire house. Secondly, approximately 7.8% of high latency appeared in the master bathroom, and approximately 1.3% occurred in the kitchen, which means the Wi-Fi coverage in the kitchen may be better than that in the master bathroom. From the floor plan of the house and the location of router shown in Figure 17, the master bathroom and kitchen are far away from the router, and numerous walls are blocking the signal from the router to the master bathroom. Therefore, the distance between sensors and router and the number of walls that signal penetrated have a large influence on Wi-Fi coverage. The Wi-Fi coverage performance is related to the distance and the number of penetrated walls, which is consistent with the signal propagation models described in the literature review.

4.2 Data Analysis under the Second Configuration

The second period was from 22nd January 2020 to 07th February 2020. In this period, the device location was under the second configuration: based on the investigation in the previous section, one repeater was added. In No.1-House, repeater was added near the kitchen shown in Figure 23. In No.2-House, the repeater was placed near the master bathroom for the comparison, which is shown in Figure 24. This change aims to illustrate the impact of the repeater (i.e. the addition of repeater and the different location of repeater in the house) on Wi-Fi coverage, which allows us to better understand and adjust the in-door Wi-Fi coverage.

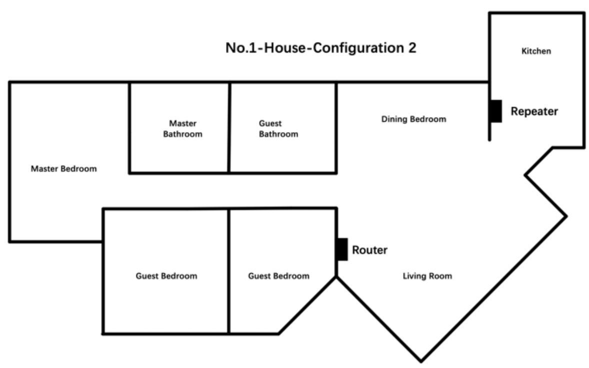


Figure 23. The Location of Devices under Second Configuration in No.1-House

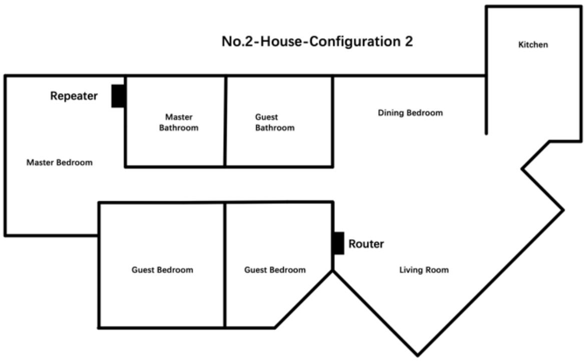


Figure 24. The Location of Devices under Second Configuration in No.2-House

4.2.1 Relationship Between Sensor and High latency

Same as the first period, suspicious data (i.e. total latency larger than the threshold) were determined using the methodology stated before. The frequency of high latency occurrence for each sensor at No.1-House and No.2-House can be shown in Figure 25 and Figure 26. The x-axis shows frequency of high latency occurrence; the y-axis shows the ID of the sensors.

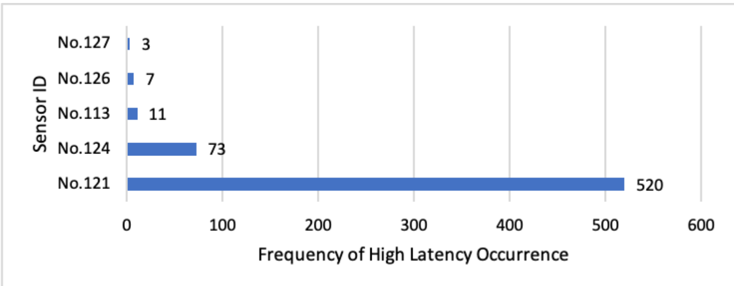


Figure 25. The Situation of Each Sensor under the Second Configuration in No.1-House

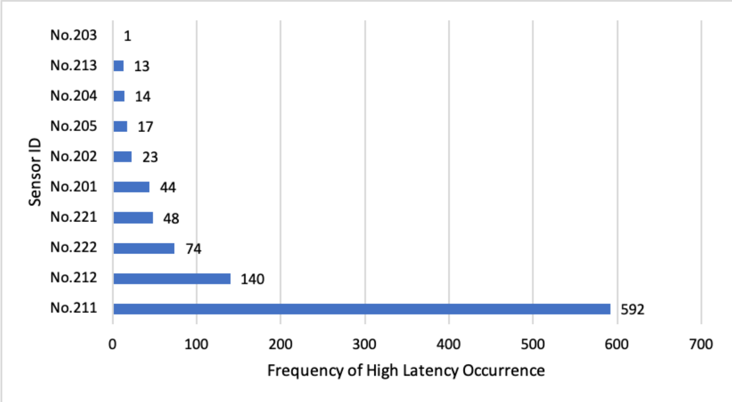


Figure 26. The Situation of Each Sensor under the Second Configuration in No.2-House

Figure 25 and Figure 26 shows the sensor with ID No.121 and No.211 have a high frequency of high latency occurrence for uploading data. These sensors were checked before the following analyses.

4.2.2 Relationship Between Time and Wi-Fi Coverage

As shown in the analysis under the front configuration, the relationship between Wi-Fi coverage and the time of one day under the second configuration will be illustrated. A day was divided into 24 hours, and then counted the number of high latency occurrence per hour, as shown in Figure 27 and Figure 28. The x-axis shows the hour scale of the day; the y-axis shows the frequency of high latency occurrence.

In this configuration period, high latency most likely happens from 13:00 to 22:00, whereas the probability of high latency occurrence is low from 23:00 to 12:00. This phenomenon is slightly different from the first configuration. However, it also indicates that the probability of high latency occurrence is related to human activities.

Then, Figure 29 and Figure 30 show the frequency of water consumption per hour. By comparing with Figure 27 and Figure 28, it is obviously that the frequency of high latency occurrence is related to the intensity of the water usage.

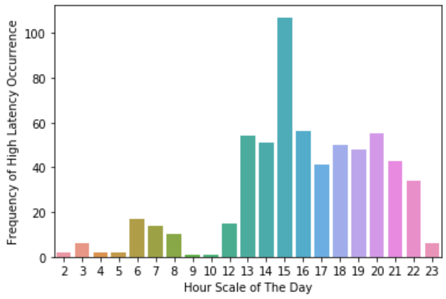


Figure 27. The Frequency of High latency Occurrence Per Hour under the Second Configuration in No.1-House

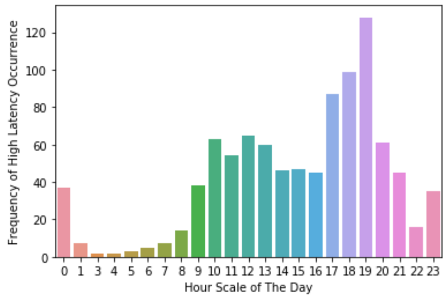


Figure 28. The Frequency of High latency Occurrence Per Hour under the Second Configuration in No.2-House

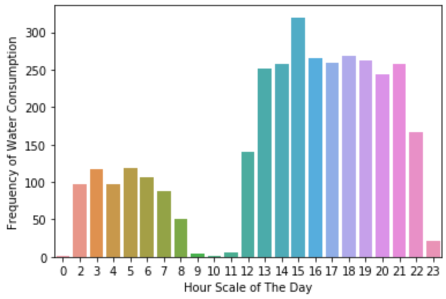


Figure 29. The Frequency of Water Consumption Per Hour under the Second Configuration in No.1-House

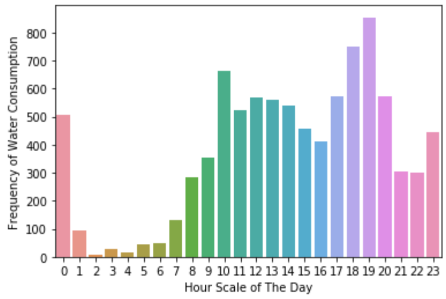


Figure 30. The Frequency of Water Consumption Per Hour under the Second Configuration in No.2-House

4.2.3 Relationship Between Device Location and Wi-Fi Coverage

After checked the reliability of the sensors, the frequency of high latency occurrence for each room can be determined by the location of sensors shown in Table 2 and Table 3.

Figure 31 and Figure 32 shows the frequency of high latency occurrence at each room for the No.1 and No.2 houses. The x-axis shows the frequency of the high latency occurrence; the y-axis shows the name of rooms.

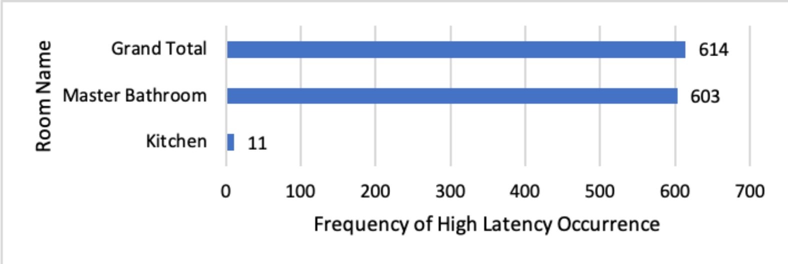


Figure 31. The Situation of Each Room under the Second Configuration in NO.1-House

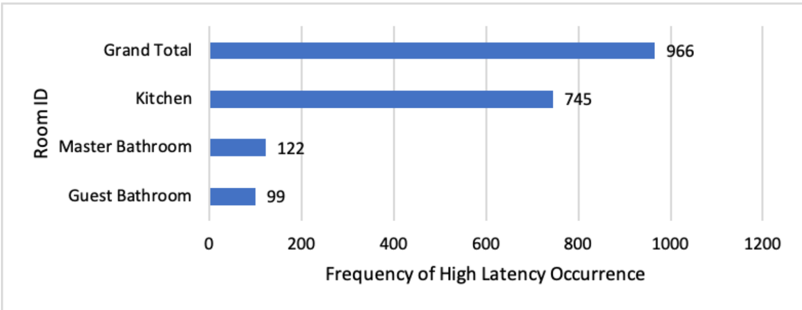


Figure 32. The Situation of Each Room under the Second Configuration in NO.2-House

Using the same approach in the previous analysis, the probability of high latency occurrence in each room and the probability of sufficient Wi-Fi coverage in the whole house can be worked out. The results can be shown as the pie charts in Figure 33 and Figure 34.

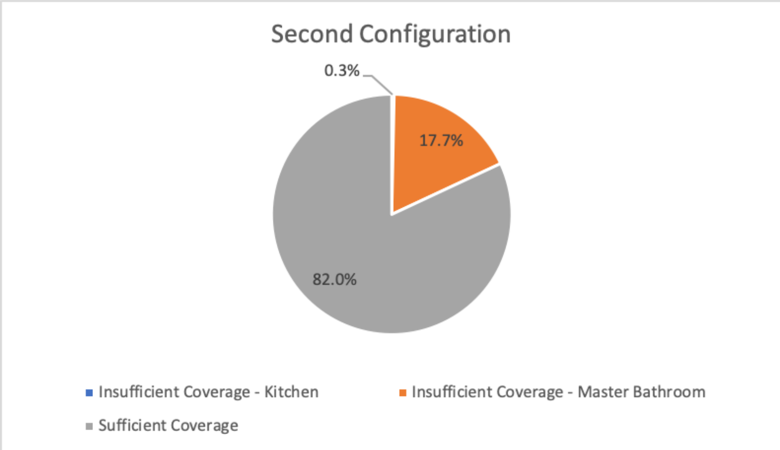


Figure 33. The Situation of Wi-Fi Coverage under the Second Configuration in No.1-House

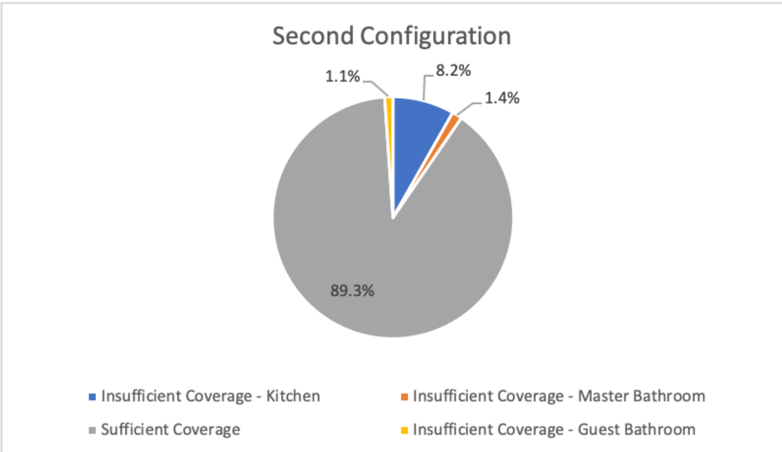


Figure 34. The Situation of Wi-Fi Coverage under the Second Configuration in No.2-House

From the beginning of this part, we know that in No.1-House, the repeater was added near the kitchen. Figure 31 and Figure 33 show the sensors in the kitchen no longer produced high latency under the second configuration. It means adding a repeater near the kitchen can enhance the signal and make a significant effect on Wi-Fi coverage. However, compared with the configuration 1, the performance of Wi-Fi coverage in master bathroom has a significant degradation due to the added repeater. For the entire house, 18% of the house was under the insufficient

Wi-Fi coverage.

At the same time, the repeater was added near the master bathroom in the No.2-House. From Figure 32 and Figure 34, we can know the repeater near the master bathroom enhanced the signal in master bathroom significantly. However, the Wi-Fi coverage in kitchen even has a worse performance. For the whole house, 10.7% of the house was under the insufficient Wi-Fi coverage.

Summarizing Wi-Fi performance in the above two houses under the similar configuration with one router and one repeater, the Wi-Fi coverage of the place near the repeater can be improved. However, Wi-Fi coverage of the place far away from the repeater and the whole Wi-Fi coverage was getting worse.

4.3 Data Analysis under the Third Configuration

The third period was from 07th February 2020 to 31st May 2020. In this period, the device location was under the third configuration (i.e. one router and two repeaters were placed in the No.1-house), as shown in Figure 35.

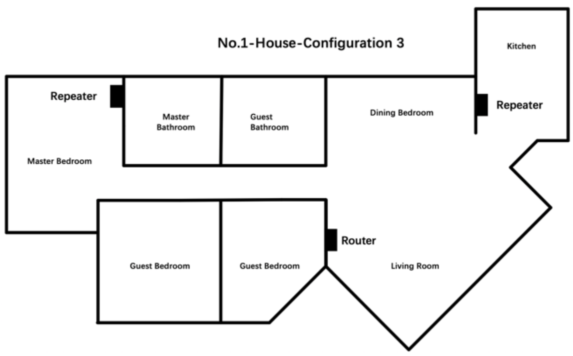


Figure 35. The Location of Devices under Third Configuration

4.3.1 Relationship Between Sensors and High latency

Applying the same methodology used for the first and second configurations, suspicious data (i.e. total latency larger than the threshold) were determined. We can draw a bar chart showing the frequency of high latency occurrence of each sensor (Figure 36). The x-axis shows the frequency of high latency occurrence; the y-axis shows the ID of the sensors.

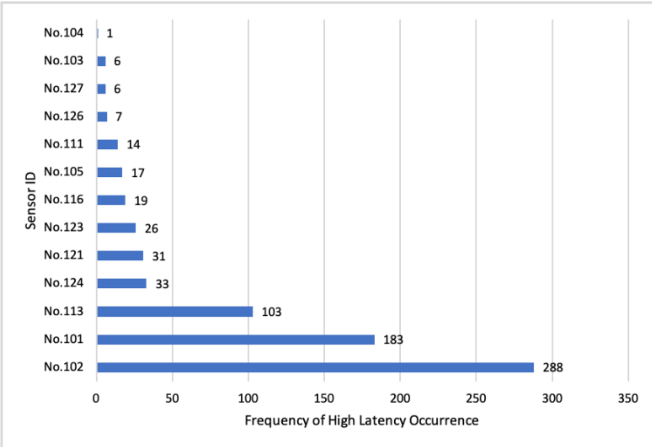


Figure 36. The Situation of Each Sensor of under the Third Configuration

From Figure 36, the sensor with ID No.102 has a high frequency of high latency occurrence for uploading data. Therefore, this sensor was checked without any problem for the following analysis.

4.3.2 Relationship Between Time and Wi-Fi Coverage

As with the analysis of data under the previous two configurations, the relationship between time and Wi-Fi coverage under the third configuration will be figure out in this part, as shown in Figure 37. We divided a day into 24 hours, and then counted the number of high latency occurrence per hour. The x-axis shows the hour scale of the day; the y-axis shows the frequency of high latency occurrence. From this figure, high latency most likely happens in the morning and evening of the day, whereas the frequency of high latency occurrence is low at the midnight. Same as previous analysis, this phenomenon indicates the intensive use of Wi-Fi during these periods.

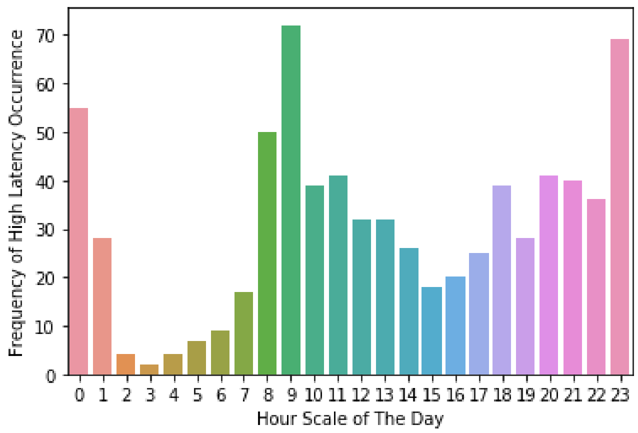


Figure 37. The Frequency of High Latency Occurrence Per Hour under the Third Period

Then, to find out the relationship between water consumption frequency and the frequency of high latency occurrence, the frequency of water consumption per hour was shown in Figure 38.

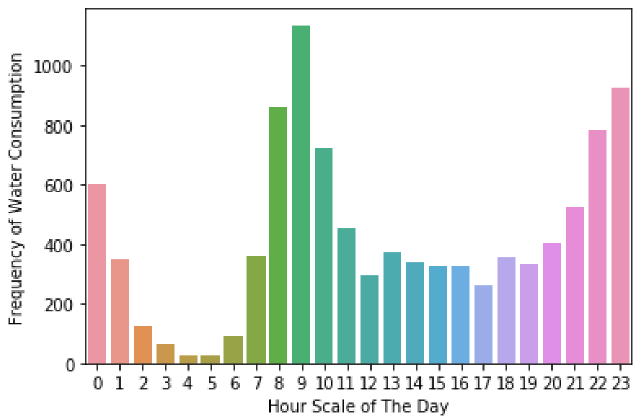


Figure 38. The Frequency of Water Consumption Per Hour under the Third Period

By comparing Figure 37 and Figure 38, it is obviously that the frequency of high latency occurrence increased with the increasing frequency of water consumption.

4.3.3 Relationship Between Device Location and Wi-Fi Coverage

As with the analysis under the previous two configurations, the relationship between devices location and Wi-Fi coverage under the third configuration will be analysed in this part. Figure 39 shows the location of high latency occurrence in terms of corresponding room. The x-axis shows the frequency of the high latency occurrence; the y-axis shows the name of rooms.

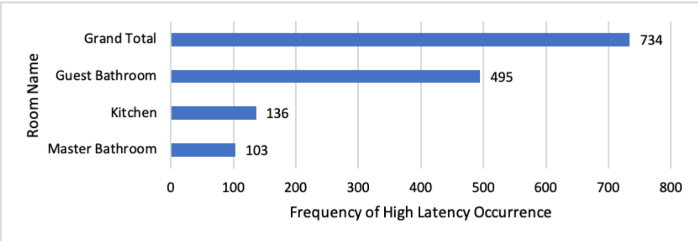


Figure 39. The Situation of Each Room under the Third Configuration

Figure 40 shows the probability of high latency occurrence in each room and the probability of sufficient Wi-Fi coverage in the entire house.

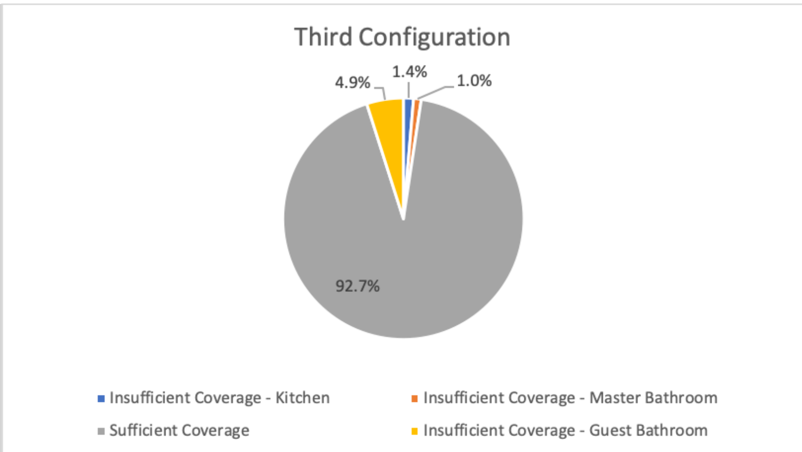


Figure 40. The Situation of Wi-Fi Coverage under the Third Configuration

From Figure 39 and Figure 40, two phenomena can be found. Firstly, as one router put in the kitchen and another one put near the master bathroom, the probability of high latency occurrence in these two rooms decrease. However, as the repeaters and router relatively far from the guest bathroom and there are more walls between the router and repeater, the probability of high latency occurrence in guest bathroom was higher than the kitchen.

Then, it is obviously the probability of sufficient Wi-Fi coverage for the entire house under third configuration increase to 92.7%. It is better than 90.9% under first configuration and 82.0% (for No.1 house) and 89.3% (for No.2 house) under the second configuration.

CHAPTER 5. Comparison

5.1 Effect of Repeater on Wi-Fi Coverage

A device update occurred amongst the three configurations, as discussed in the Methodology Chapter (i.e. the implementation of repeater at different locations). In Chapter 4, the collected data have been analysed in detail for each of the three configurations.

The high latency (i.e. total latency larger than the threshold) was identified via Python by using the methodology stated before. Then, the probability of high latency occurrence under each configuration can be calculated, as shown in Table 3. From the Methodology Chapter, we can determine that the performance of Wi-Fi coverage at certain locations can be quantified as the probability of high latency occurrence, which means the probability of high latency occurrence represents insufficient Wi-Fi coverage.

Under the first configuration, the probability of insufficient Wi-Fi coverage is 9.1%; under the second configuration, for No.1 and No.2 houses, the probabilities of insufficient Wi-Fi coverage are 18.0% and 10.7%, respectively; under the third configuration, the probability of insufficient Wi-Fi coverage is 7.3%. From the analyses before, we can determine that adding a repeater may not improve the Wi-Fi coverage for the entire house. The unsuitable repeater location may increase the probability of high latency occurrence. On the contrary, the appropriate location of repeaters can improve the Wi-Fi coverage significantly.

Table 5. The Probability of Insufficient Wi-Fi Coverage for Each Configuration

Configuration	The Situation of Devices	The Number of All Collected Data	The Frequency of High Latency	The Probability of Insufficient Wi-Fi Coverage

1	1 router	3232	294	9.1%
2	1 router, 1 repeater (repeater in 2 different places)	3403 / 9033	614 / 966	18.0% / 10.7%
3	1 router, 1 repeater	10059	734	7.3%

The high latency can be located at each room by tracking the ID of the sensors. Pie charts that represent the insufficient Wi-Fi coverage (i.e. the probability of high latency occurrence) in each room and the sufficient Wi-Fi coverage for the entire house under the three configurations can be drawn, as indicated in Table 6.

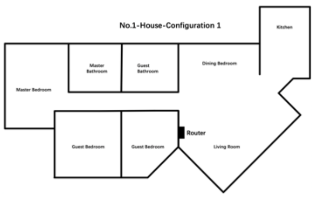
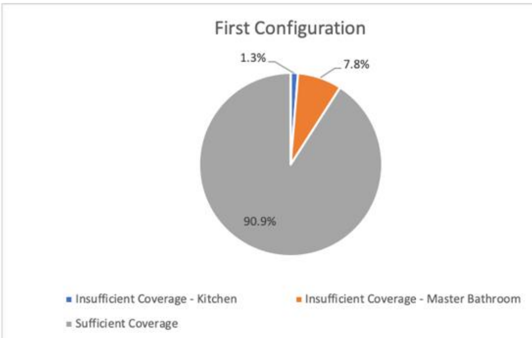
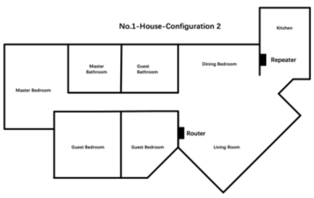
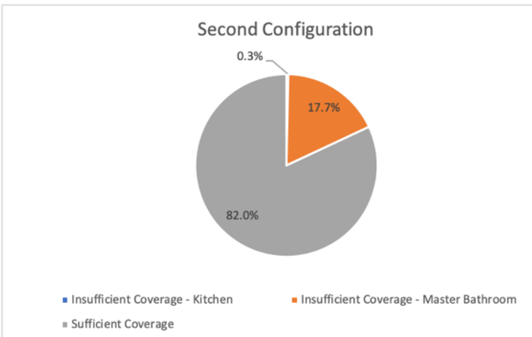
Table 6 presents that in configuration 1, the distance between the router and sensors exerted a significant influence on uploading speed. As the distance increased, the probability of high latency occurrence increased due to insufficient Wi-Fi coverage. To solve this problem, one repeater was added.

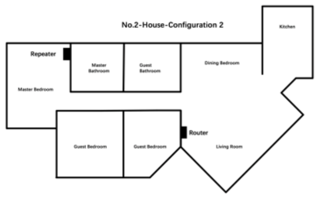
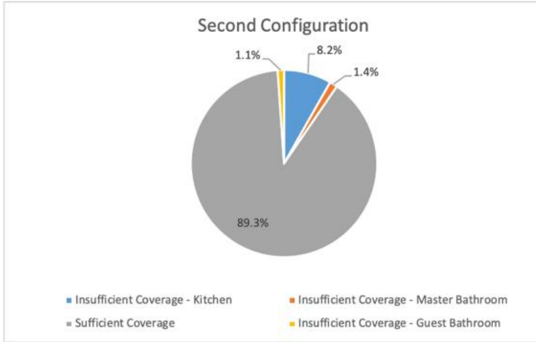
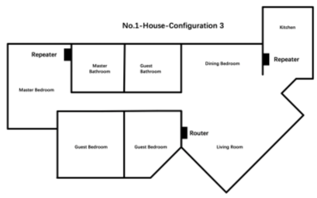
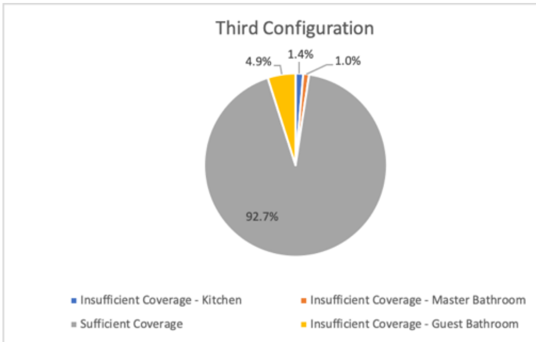
The result of adding one repeater was shown in configuration 2. In No.1 house, the possibility of high latency occurrence in the kitchen decreased sharply, but the entire possibility of high latency occurrence and the possibility in the master bathroom were increased. In No.2 House, the possibility of high latency occurrence in the master bathroom decreased sharply, whereas the possibility in the kitchen increased.

Repeater could enhance the signal strength around it. Therefore, if we want to improve the signal somewhere, we can place a repeater nearby. However, this behaviour will attenuate the network in the other direction which is also at a location far from the router. This unsuitable location of repeater also increases the probability of high latency occurrence for the entire house. Hence, if we have only one repeater and want to improve the Wi-Fi coverage, the repeater should be moved to the middle of the two positions which are far away from the router.

Configuration 3 illustrated the situation with two repeaters in the house. These repeaters were placed in the two rooms which are most far away from the router. This configuration could improve the Wi-Fi coverage significantly. However, the Wi-Fi coverage in the guest bathroom was most insufficient under this configuration, which meant the repeaters should be move near the guest bathroom. This change would improve the Wi-Fi coverage in the guest bathroom and the entire house.

Table 6. The Comparison of Wi-Fi Coverage under Each Configuration

Configuration	House	The Situation of Devices	The Situation of Wi-Fi Coverage
1	No.1		
2	No.1		

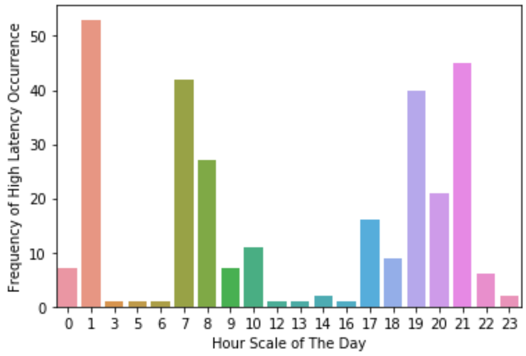
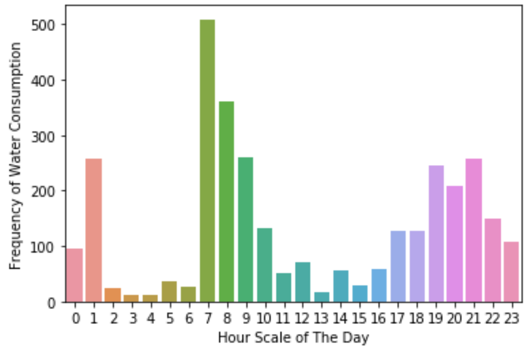
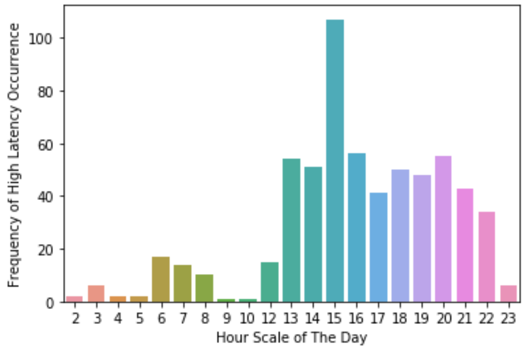
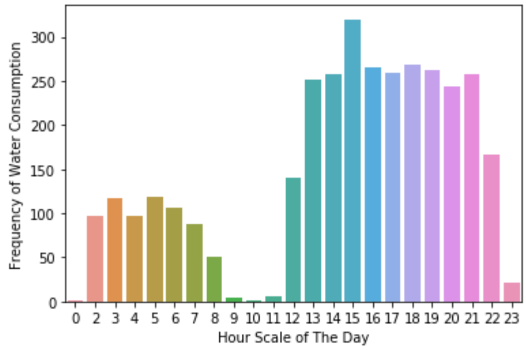
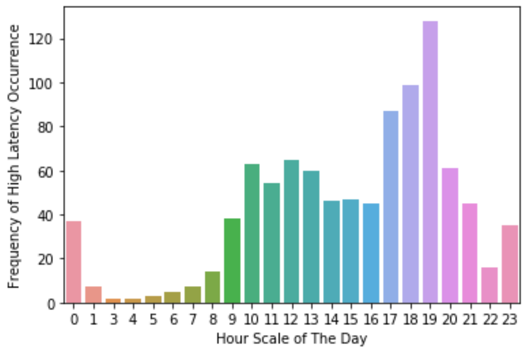
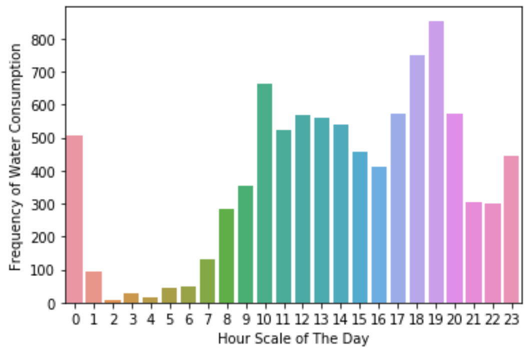
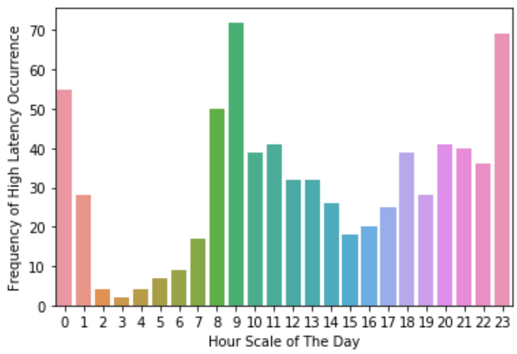
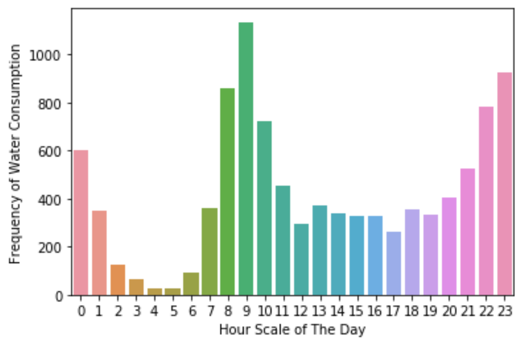
	No.2		
3	No.1		

In the final step, the relationships between time and the frequency of high latency occurrence under the three configurations were compared (Table 7). From Table 7, two phenomena can be found.

Firstly, adding the repeaters had not improved the data updating speed at any specific time, and the frequency of high latency occurrence was high in the morning and evening.

Then, for different times in a day, the frequency of high latency occurrence was related to the intensity of water and Wi-Fi usage. When intensive use of Wi-Fi occurred and the taps were opened repeatedly, high latency occurred frequently, and the Wi-Fi coverage was poor.

Table 7. The Frequency of High Latency Occurrence

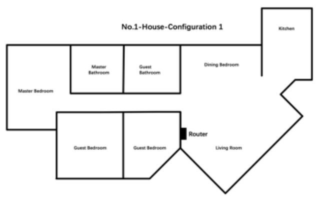
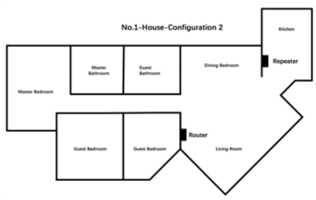
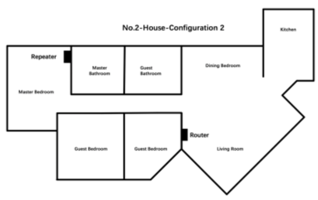
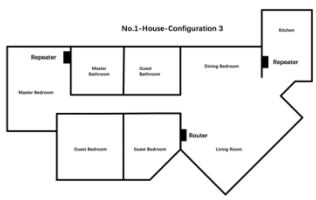
<table>
<tr><th colspan="2">Configuration</th><th>The Frequency of High Latency Occurrence Per Hour</th><th>The Frequency of Water Consumption Per Hour</th></tr>
<tr><td colspan="2">1</td><td>
</td><td>
</td></tr>
<tr><td rowspan="2">2</td><td>No.1 House</td><td>
</td><td>
</td></tr>
<tr><td>No.2 House</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">3</td><td>
</td><td>
</td></tr>
</table>

5.2 Analysis of System Reliability

This chapter aims to analyse the unreliable data collected using the sensors located at different taps in detail. From the Methodology Chapter, we can determine that packet loss and system shut down can introduce extremely high uploading latencies. The appearance of these situations will have an extremely negative impact on the system stability. Therefore, an evaluation can be conducted to clarify the reliability of the water-monitoring system.

The probability of unreliable data occurrence can be calculated and summarised in Table 8. We can quantify the reliability of the monitoring system at different periods as the probability of packet loss and system failure occurrence.

Table 8. The System Reliability under Each Configuration

<table>
<tr><th>Configuration</th><th>House</th><th>The Situation of Devices</th><th>The Probability of Reliable System</th><th>The Probability of Sufficient Wi-Fi Coverage</th></tr>
<tr><td>1</td><td>No.1 House</td><td>
</td><td>99.3%</td><td>90.9%</td></tr>
<tr><td rowspan="2">2</td><td>No.1 House</td><td>
</td><td>97.7%</td><td>82.0%</td></tr>
<tr><td>No.2 House</td><td>
</td><td>96.5%</td><td>89.3%</td></tr>
<tr><td>3</td><td>No.1 House</td><td>
</td><td>99.3%</td><td>92.7%</td></tr>
</table>

From Table 8, we can determine that the probability of the system to work reliably was up to 99% under configurations 1 and 2. The probability of sufficient Wi-Fi coverage was also up to 90%. These results showed that the network system exhibited poorest reliability and Wi-Fi coverage under configuration 2.

Therefore, the reliability of the network system is also related to the situation of Wi-Fi coverage. If the Wi-Fi coverage in the house is improved, the reliability of the network system will be increased at the same time.

CHAPTER 6. Calibration, Suggestion and Validation

6.1 Wi-Fi Location Decision-Making System

Based on the analysis, the decision-making framework can be designed, as shown in Figure 41.

Figure 41. The Wi-Fi Location Decision-Making System Framework

The decision-making system is designed on the basis of the configuration of typical Hong Kong apartments. The main features of Hong Kong apartments can be summarised as single floor, small (approximately 50 m^2) and fully functional.

Unlike typical European houses with dual floors, Hong Kong apartments usually have a single floor. Therefore, we can assume that all the devices connected to the Wi-Fi network are in the same level, and the signal propagation amongst floors can be ignored. The ratio of the house area to the number of walls is usually small, considering that typical Hong Kong apartments are usually small but fully functional. The penetration loss due to walls can be the major loss compared with the path loss in the area with a low ratio of area to number of walls. The living room, dining room and kitchen are usually connected to be a large open area in Hong Kong apartments. Consequently, the loss of signal strength in this area is mainly the path loss.

From the signal propagation models, the optimised router position is in the middle of the apartment. Therefore, the router should be placed close to the middle of the apartment to ensure the coverage for the entire apartment. Considering that the living room is usually designed at the house centre, we can set the router against the internal wall of the living room. The major Wi-Fi usages are usually related to activities in the living room, such as watching through the Internet. Setting the router in the living room is reasonable to ensure sufficient Wi-Fi coverage.

From the performance studies in No.1 and No.2 houses, the guest bathrooms which are directly connected to Wi-Fi routers have a relatively low possibility of insufficient coverage for the two experimented apartments. In the first period of No.1 house, the sensors in the master bathroom are directly connected to the router. Four walls exist between the master bathroom and the router, and the probability of insufficient coverage in the master bathroom is approximately 7.8%. By contrast, the probability of insufficient coverage in the kitchen is approximately

1.3%. The distances from the router to the sensors are similar for the master bathroom and kitchen, but the number of walls between the router and the sensors is different. Merely one wall exists between the router and kitchen. Therefore, the number of walls between the transmitter and receivers is the major criterion to design the decision-making framework for typical Hong Kong apartments. From Table 6 shown in the previous chapter, the probabilities of insufficient coverage for the guest bathrooms in No.1 and No.2 apartments are 1.1% and 4.9%, respectively. From the room configuration shown in Figure 11, we can see three walls between the router and guest bathroom. Considering that the probabilities of insufficient coverage in the guest bathroom are relatively low, we can assume that the entire room will be sufficiently covered by a single router if less than two walls exist between the router and any room in the apartment. In this case, the users may not need to install any repeater to enhance the Wi-Fi coverage.

For users who have a large apartment (i.e. with a room having three or more walls between the room and router), a repeater may be required to enhance the Wi-Fi coverage. They need to decide if they want to enhance the Wi-Fi coverage for the entire apartment. For example, four walls exist between the master bathroom and router. No smart home device is installed in the bathroom, but smart home devices are intensively installed in the living room and kitchen. Installing a repeater near the bathroom will be unbeneficial; a repeater should be installed near the kitchen if the Wi-Fi coverage is insufficient in the kitchen. Therefore, in the framework, we suggest that for users who do not need to improve the Wi-Fi coverage for the entire apartment, a repeater should be installed only near specific rooms.

For users who want to improve the Wi-Fi coverage for the entire apartment, more than one repeater is recommended to install. From the previous analysis, the repeater can enhance the Wi-Fi coverage nearby, but it can also increase the probability of insufficient coverage in the opposite direction which is also far away from the router. If only one repeater can be added, the recommended repeater position will be the midpoint between two rooms with the worst Wi-Fi coverage. Using more than one repeater (for a typical Hong Kong apartment, two repeaters are usually adequate) can significantly improve the Wi-Fi coverage for the entire apartment. The Wi-Fi coverage needs to be improved for the rooms (e.g. the master bathroom) four walls away from the router. The experiment demonstrates that the repeater can efficiently improve the Wi-Fi coverage nearby. The working principle of the repeater is to extend the signal it received. Hence, the signal at the repeater position should not be excessively weak. The previous analysis indicates that four walls exist between the master bedroom and router. The Wi-Fi coverage in the master bathroom has been significantly improved since the repeater was added in the master bedroom. The repeater cannot improve the Wi-Fi coverage where the coverage is already sufficient. Therefore, the Wi-Fi coverage in the room which is four walls away from the router needs to be improved using the repeater. We suggest that for a room four walls away from the router, the repeater can be installed nearby to improve the Wi-Fi coverage. However, the position of the repeater should not be considerably far away from the router. We propose that the repeater be placed two walls from the router because the Wi-Fi coverage is sufficient for the position two walls away from the router.

6.2 Calibration of Signal Propagation Models

In the Methodology Chapter, the contour maps for signal propagation were drawn in accordance with the free space and COST231 multiwall signal propagation models. For convenient reading, the generated contour maps together with the probability of insufficient Wi-Fi coverage measured via the experiment are redrawn in Figure 42.

From Figure 42, the free space propagation model cannot match the experimental results due to the inappropriate modelling of penetration loss. From the experiment results, the probabilities of insufficient coverage in the master bathroom, guest bathroom and kitchen are 7.8%, 3% (average of 1.1% and 4.9%) and 1.3%, respectively. The free space contour map shows that the signal loss in the master bathroom is smaller than that in the kitchen, which is against the experimental results. The contour map generated using the COST231 multiwall propagation model is consistent with the experimental results. Figure 42 depicts that the signal strength loss in the kitchen is approximately −38 dB, whereas the loss in the master bathroom is approximately −47 dB. From Figure 22 shown before, the probabilities of insufficient Wi-Fi coverage for the kitchen and master bathroom are 1.3% and 7.8%, respectively, which are consistent with the simulation results given by the COST231 multiwall propagation model. As mentioned in the discussion before, the guest bathroom (three walls away from the router, and the path loss is approximately −47 dB) has an acceptable Wi-Fi coverage, and the kitchen (one wall away from the router, and the path loss is approximately −39 dB) has a high-performance Wi-Fi coverage. Therefore, we assume that the entire room will be sufficiently covered by a single router if less than two walls exist between the router and any room in the apartment. On the basis of the simulation given by the COST231 multiwall propagation model, we can calibrate this criterion as the path loss within −43 dB (average values of −47 and −39 dB). From the contour map shown in Figure 42, the guest bedroom is two walls away from the router, and the path loss in the guest bedroom is approximately −43 dB. Thus, the two-wall criterion used in the framework can be considered reliable.

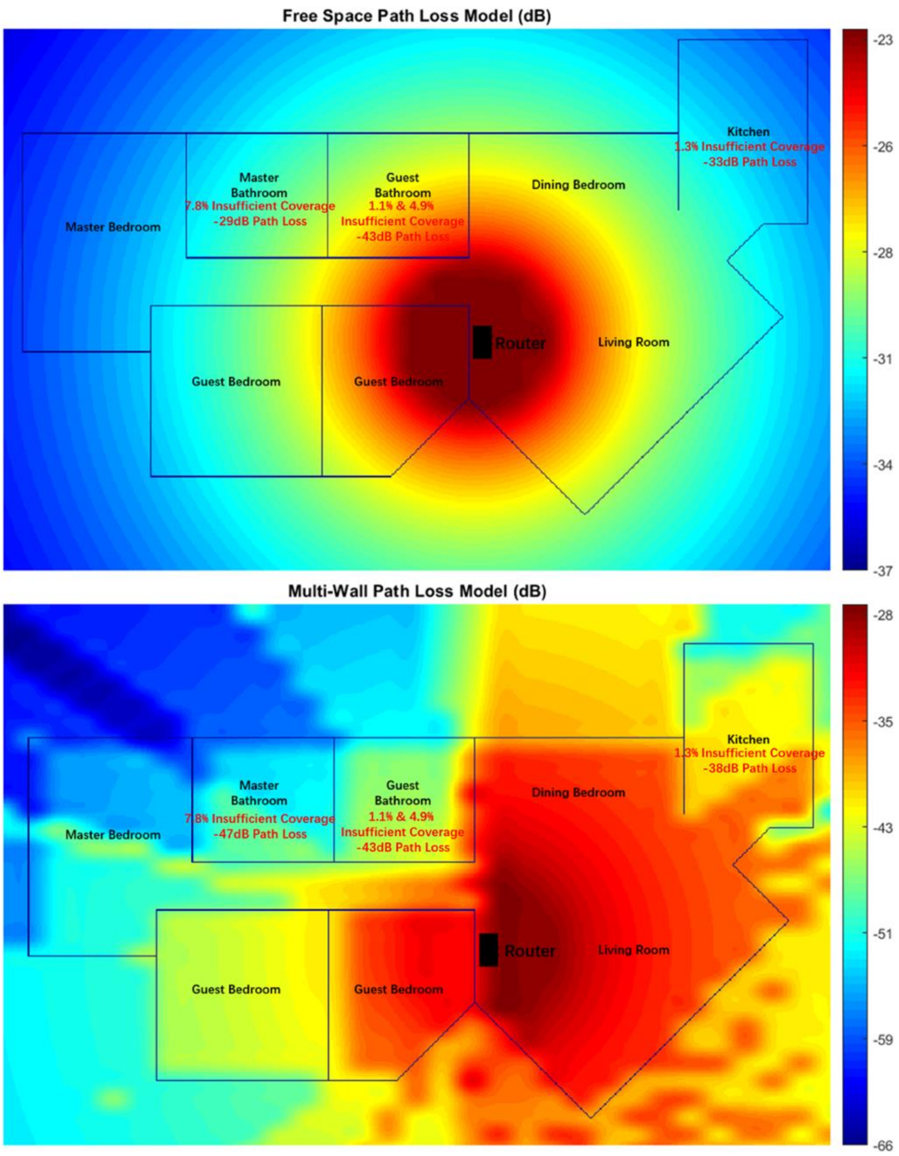


Figure 42. Signal Propagation Contour Maps Generated using the Free Space and COST231 Multiwall Models with the Corresponding Probability of Insufficient Wi-Fi Coverage

In the third configuration, one repeater is placed in the master bedroom against the wall near the master bathroom. The working principles of the repeater are receiving the signal propagated from the router and retransmitting the received signal in the adjacent area. Therefore, the initial signal loss for the repeater is the same as the signal it received; the repeater cannot be placed in a location with significantly poor Wi-Fi coverage. With the installation of the repeater, the Wi-Fi coverage in the master bathroom is improved significantly in the third configuration. Usually, the repeater cannot improve the Wi-Fi coverage where the Wi-Fi coverage is already sufficient. The significant improvement in the Wi-Fi coverage indicates that insufficient Wi-Fi coverage occurs in the master bathroom. Therefore, we propose the other criterion in the framework as that for a room four walls away from the router, the repeater should be installed nearby to enhance the Wi-Fi coverage. We can also calibrate this four-wall criterion by using the contour map derived using the COST231 multiwall propagation model. From Figure 43, the path loss at the location where we installed the repeater is approximately −54 dB. The two other positions located four walls away from the router have similar path losses. Therefore, the four-wall criterion (the Wi-Fi coverage should be improved for the room four walls away from the router) used in the framework can also be calibrated.

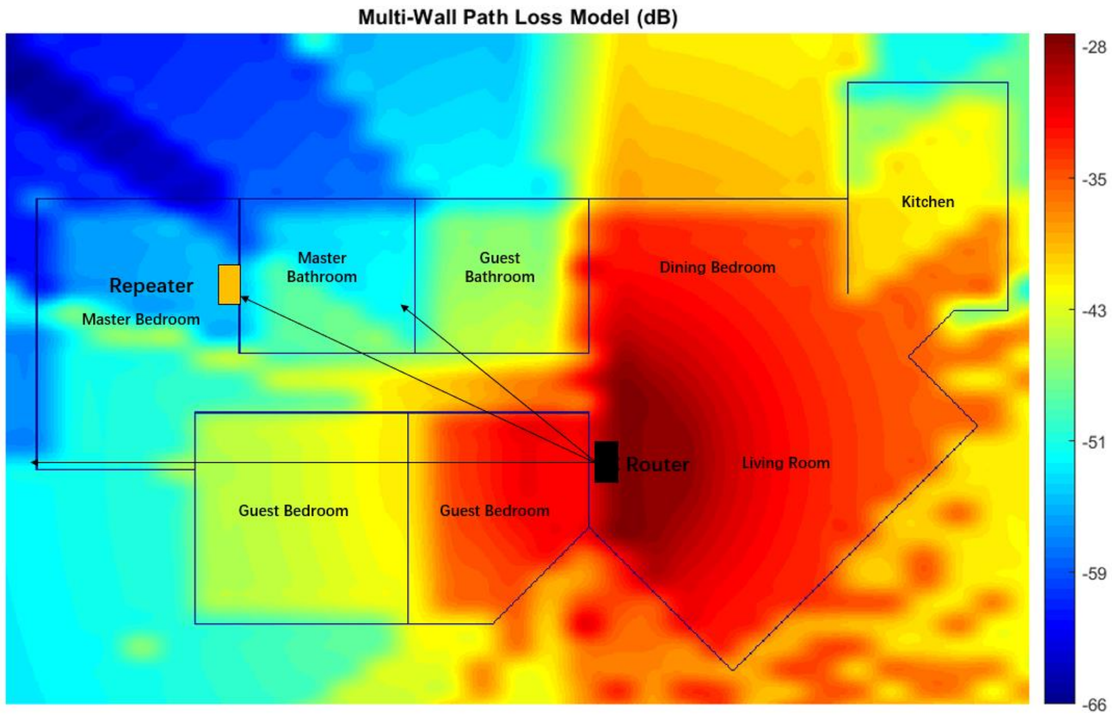


Figure 43.The Locations Four Walls Away from the Router

6.3 Example of the Framework

The example shows a typical Hong Kong apartment with two bedrooms, one living room combined with dining room, one bathroom and one kitchen. The total area of this apartment is approximately 35 m^2. The apartment layout configuration is shown in Figure 44. Following the framework shown in Figure 41, we firstly place the router in the middle of the apartment (the position is usually in the living room), as shown in Figure 44. Then, we can draw the straight lines connecting the router and each room to see how many walls exist between the router and each room.

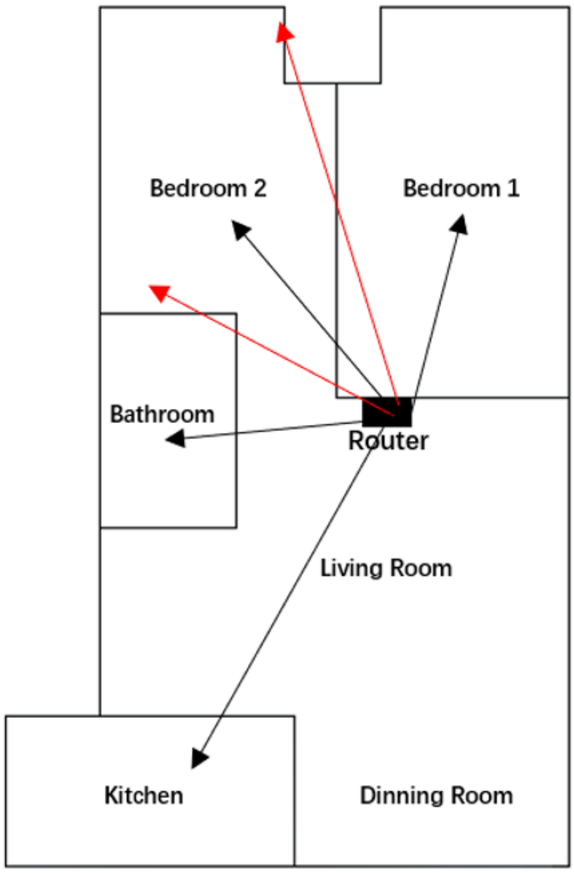


Figure 44. The Apartment Configuration of Example 1 with Corresponding Suggested Router Location

From Figure 44, the most critical room is bedroom 2, and four walls exist between the router and the room. However, only small portions of bedroom 2 (i.e. bottom left and top right corners of bedroom 2) are four walls from the router. In accordance with the framework proposed in Figure 41, the user needs to determine if some devices exist in the corners of bedroom 2. If no devices exist in the corners, a repeater needs not be installed.

In the case in which the user wants to improve the Wi-Fi coverage in the corners, Figure 41 indicates two options to improve the Wi-Fi coverage depending on the budget of the user. The optimised performance can be achieved by installing one repeater in bedroom 2. Nevertheless, the finding from the experiment shows that adding a single repeater will reduce the Wi-Fi coverage in the opposite direction (i.e. the kitchen). Therefore, we have to install another repeater near the kitchen, which means we need two repeaters to ensure optimised Wi-Fi coverage, as shown in Figure 46. An alternative approach is to install one repeater only in the middle of the apartment, as illustrated in Figure 46. In this case, the single repeater can enhance the Wi-Fi signal in two directions (i.e. bedroom 2 and kitchen). The performance of this single-router solution may not have the same performance as that of the two-repeater solution, but it is flexible for users with insufficient budget.

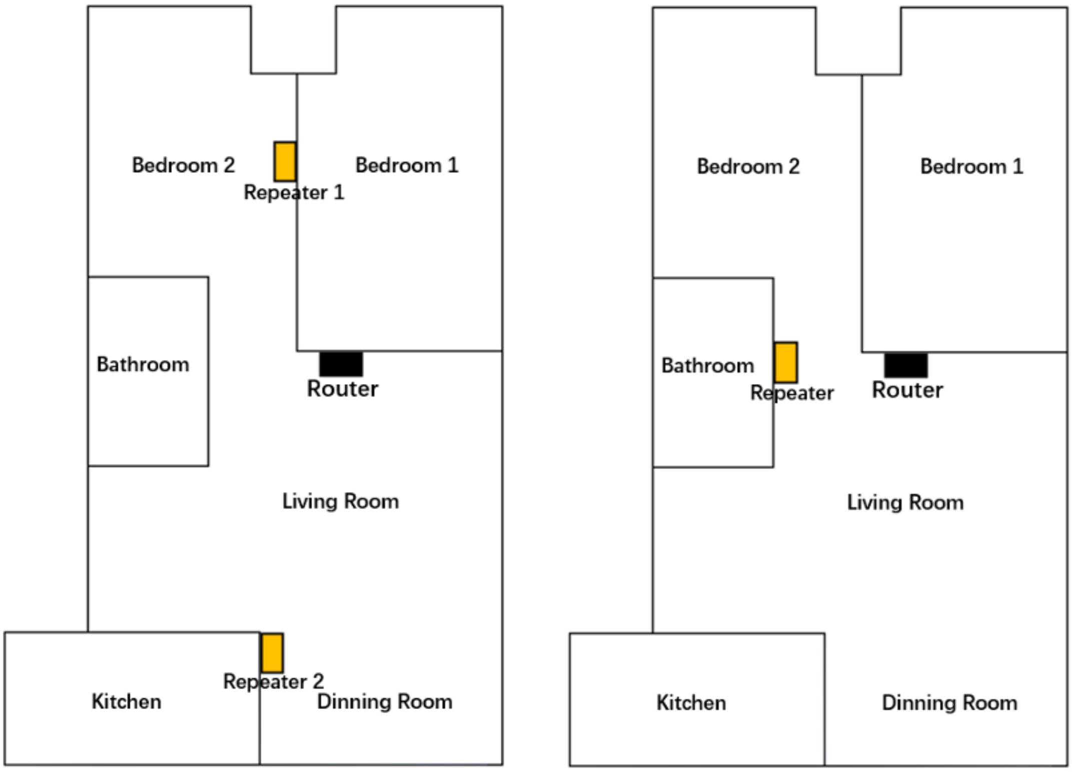


Figure 45. The Router and Repeater Location Solutions of the Example Apartment

We can use the calibrated COST231 multiwall model to validate these suggestions. The corresponding signal propagation contour map for this apartment is shown in Figure 46. In most area of this apartment, except in the corners of bedroom 2, the signal path loss is lower than −43 dB. This situation is consistent with the suggestion made by the framework (i.e. the Wi-Fi coverage is sufficient for most part of the apartment). Figure 46 indicates that the path loss in the corners of bedroom 2 reaches −47 and −50 dB. From the previous calibration, the Wi-Fi coverage in the two corners needs to be improved.

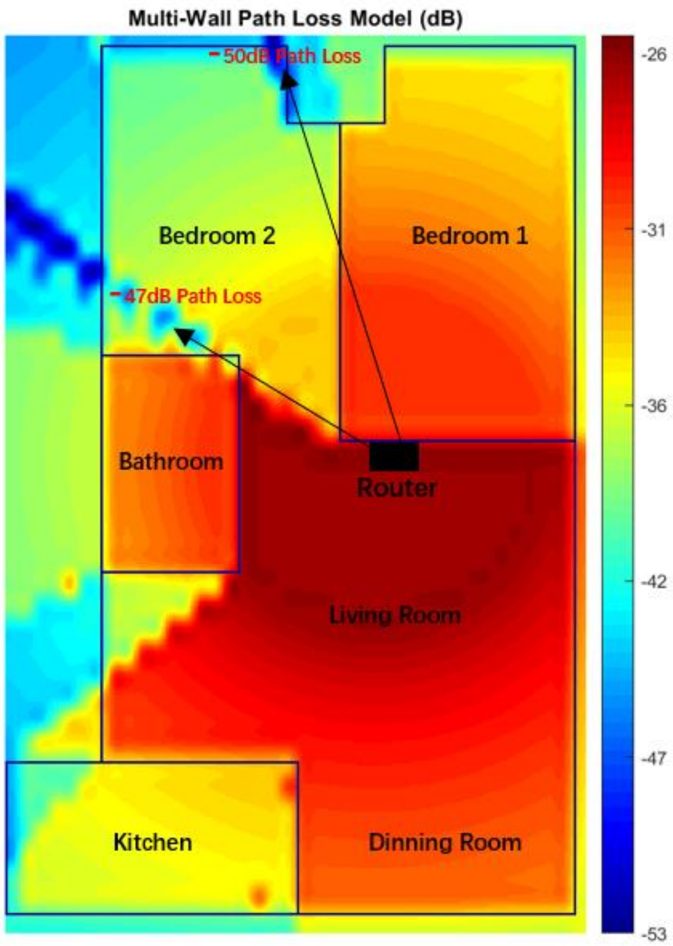


Figure 46. The Contour Map of the Example Apartment

CHAPTER 7. Conclusion

Indoor Wi-Fi coverage has been studied mainly using signal propagation models. However, the actual performance of IoT devices is not calibrated with signal propagation models. Simply applying signal propagation models without calibrated criteria may not be able to establish a high-performance Wi-Fi network. Moreover, the home-use Wi-Fi network is usually established by the homeowner who is not equipped with the knowledge of electronic engineering. Therefore, this research aims to establish a decision-making framework for untrained smart home users to establish a high-performance Wi-Fi network easily.

In this research, indoor Wi-Fi coverage was studied on the basis of the actual performance of a water-monitoring system. A real-time water-monitoring system was designed, in which flow rate sensors were placed in different taps to collect data, and the collected data were uploaded to the cloud via the home Wi-Fi and the Internet. Latency information could be computed by recording the timestamps of data collection at the sensors and cloud. A novel data-processing procedure was developed to obtain data which represent insufficient Wi-Fi coverage. Thus, the Wi-Fi coverage performance could be described using the probability of insufficient Wi-Fi coverage.

Wi-Fi signal transmitters (i.e. router and repeaters) were placed and moved to different locations to determine their effect on the network latency. The probability of latency occurrence of the water-monitoring system could indicate the performance of Wi-Fi coverage. The data collected using sensors were divided into three periods because the configuration of transmitters (i.e. Wi-Fi router and repeater) differed in these periods. Their effect on the network latency could be obtained via comparison. The transmitters were under the first configuration from 10th December 2019 to 22nd January 2020. One router was used for the entire house. The devices were under the second configuration from 22nd January 2020 to 07th February 2020. One router and one repeater were used. The devices were under the third configuration from 07th February 2020 to 31st May 2020. One router and two repeaters were used.

From the data analysis under the three different configurations, the distance and the number of walls between router and sensors affect the performance of Wi-Fi coverage. If the distance and the number of walls between the router and sensors are large, a high probability of high latency occurrence and poor Wi-Fi coverage will occur. That is, the Wi-Fi coverage given by a single router is limited. Adding a repeater is necessary to enhance the signal strength for the place far away from the router.

One efficient approach is to add two repeaters, and these two repeaters should not be considerably far away from the router to ensure high performance. An alternative approach is placing the repeater at the optimised location, and the Wi-Fi coverage is usually satisfied for a small apartment. If the user uses the Internet at the bedroom intensively, the repeater can be placed at the location closed to the bedroom. Otherwise, the repeater should be placed at the middle point of two rooms with poor Wi-Fi signal. The repeater location is important. It is expected to be placed at the optimised position (i.e. at the middle of two places where the signal needs to be enhanced); it can simultaneously enhance the network signal in both areas.

On the basis of the comparison of results under the three periods, adding repeaters exerts limited improvement in the uploading speed in certain times of a day, such as the morning and evening of a day. The high latency in these periods is related to the intensive usage of Internet; the occupied network resources can increase the chance of high latency occurrence. This network problem can be solved by upgrading the Internet.

The relationship between the probability of high latency occurrence and the frequent use of water was also illustrated (i.e. the probability of high latency occurrence increased with increasing number water usage times). This high latency problem cannot be solved by changing the position of the router and repeater. Further solutions could be adding a repeater and replacing the router with a more powerful one.

The probability of packet loss and system failure was determined to be related to Wi-Fi coverage. Packet loss and system failure would likely occur in an apartment with poor Wi-Fi coverage. This finding illustrated the importance of Wi-Fi coverage.

At the end of this research, a decision-making framework was established and used to determine the optimised router and repeater configuration. This framework can help people who have limited knowledge about signal propagation theory establish a high-performance Wi-Fi network. Moreover, the COST231 multiwall signal propagation model was calibrated with the actual performance of the water-monitoring system. The result showed that the Wi-Fi coverage is sufficient for signal loss less than −43 dB. Lastly, the router and repeater configuration of a Hong Kong apartment was determined on the basis of the proposed decision-making framework, and the generated recommendations were validated using the COST231 multiwall model which was calibrated before. The validation results showed that the recommendations given by the framework are reliable.

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