Evaluate and Optimise Wireless Communication Performance for Typical Buildings

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Abstract

It is predicted that mobile traffic, mainly taking place indoors, will increase up to 1000 times in the next decade. Future smart buildings/cities will be connected through wireless communication systems. High capacity and reliable wireless communications will play a very important role in future smart building/city. In telecommunications, a femtocell is a small, low-power cellular base station, typically designed for use in a home or small business. It allows service providers to extend service coverage indoors or at the cell edge, especially where access would be limited or unavailable. Since its first commercial deployment by Sprint Nextel Corporation in 2008, femtocell has continued to gain momentum with mobile network operators in America, Asia and Europe. Plenty of phone calls are placed indoor, and the technology is now deployed for residential and commercial use. But, so far, it is not well known how the wireless performance is related to building structures and material properties, and the building design process has not taken into consideration of wireless performance, resulting in poor wireless performance in some passive buildings. In this M.Phil. thesis, first, a set of wireless performance metrics is designed to measure the wireless performance in buildings; second, different building models focus on coverage and capacity are simulated and analysed to compare the influences of typical building structures; third, novel ways to improve building wireless performance will be investigated. The main achievements and contributions of the project are listed as follows:

- 1. In view of the performance evaluation of the indoor wireless communication system, a set of coverage factors and capacity factors are proposed. The coverage factor indicates the signal coverage rate of a signal source in a building, it is affected by the signal power, the location of the signal source, the wall thickness of the house, and the location of the doors and windows. The capacity factor represents transmission capacity of a building within specified channel access, it is not only related to the signal power and its transmission loss but also influenced by the interferences of other sources.
- 2. The coverage factors are calculated through several simulations to prove legitimate for the performance evaluation of the indoor wireless communication. For the typical applications of classroom and dormitory in campus, an analysis method of the influences of building structures on the coverage factor is proposed. The effects of the size of rooms, the position of doors, and the position of windows on the coverage factor are analysed in detail. The correctness of the analysis results is verified by the simulation results of iBuildNet®.
- 3. In order to analyse the capacity factor of the indoor communication system under different structure conditions, the concept of SINR (signal-to-interference-plus-noise ratio) is introduced. The effects of different building structures on SINR were analysed. On this basis, Simulated Annealing Algorithm for SINR calculating is proposed, which can make the SINR tend to be optimal so that the capacity factor is optimised. In the presence of near source interferences, through the analysis and simulation, the architectural design idea that can obtain the optimum capacity factor is given.

4. The signal source deployment density and the building structure of the indoor communication system are very different in different application scenarios. In order to verify the adaptability of the above analysis methods in different occasions, the performances of the indoor communication system in two typical building structures are simulated and analysed. The simulation results verify the validity of the methods and have guiding value for the deployment of indoor communication signal source and the architectural structure of different application scenarios.

Keywords: indoor wireless communications; femtocell; building structure; SINR; signal attenuation; Communication performance evaluation

Chapter 1 Introduction

1.1 Background and Motivation

Typical outdoor environment of communication is influenced by the size and density of buildings, the width and the orientation of streets and also by parks and large squares. In urban area, direct line of sight is often obstructed by tall and intensive buildings, so does the signal propagation. Original communication routines are being affected by signal's scattering from the surface of buildings and diffracting over or around them. On the other hand, a classroom in campus or a same size room like dormitory is a typical example of indoor channel environment. The channel conditions of this kind of indoor channel environment are different from outdoor environment. It varies depending on the radio coverage radius, room size and floors. Communication routines of indoor channel environment are more often obstructed by walls and furniture. What's more, the typical frequency ranges used in outdoor and indoor wireless communication system are different. In the planning of frequency range, certain range will be reserved specially for covering the indoor wireless communication system and this is all determined by the operator. Taking the LTE for example, frequency point E is usually used indoor while frequency ranges like F and D are mainly used in outdoor base station. These characteristics and differences make research of indoor wireless communication environment separated from research of normal outdoor environments.

Those large-scale and heavy concrete buildings usually have strong shielding function to signals sent from mobile communication base stations. In low floors of architectures, underground market and underground parking lots, most cell phones are out of use due to weak signals. These places mainly compose the dead zone of mobile communication. In middle floors, signals from surrounded base station are often overlapped together and the ping pong effect leads to the frequent cut of signal, even the loss of connection. In upper floors, mobile function cannot function well too because of the restricted height of antenna in base station. Besides, even mobile phone can communicate normally in buildings, the large density of users causes the congestion in channel and further leads to the difficulty of keeping online. In brief, indoor dead zone of mobile communication like parking lots, office building and apartments, places with high amount of necessity and density of wireless communication like train station, airports, shopping mall and sports centres, locations that suffers from the overlapped and frequent switch of sources like the top of tall buildings are the dominant areas that in need of indoor wireless communication system covering.

The above challenges also determine that the network coverage and capacity are vital elements which operators need to take into account to gain advantage in competitiveness. It becomes more popular and attracts more attentions these days because of the increasing communication requirements in buildings and small enclosed areas. Using outdoor base station, the coverage and capacity are both hard to be satisfied. Operators count on indoor network to bypass some volume of business. And 80% of the mobile phone using are happened indoor mainly distributing in stations, office and home. In addition, green and energy saving tendency and future wireless communication technology like LTE-Advanced determine the necessity of development of indoor communication. From the above

perspectives, the optimisation of indoor environment communication is a practical and promising research topic.

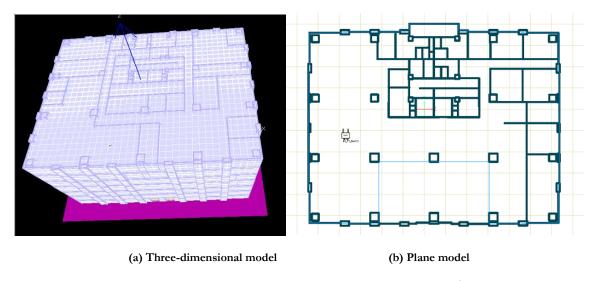


Fig. 1-1 Typical Indoor building model and design in iBuildNet®

Existing researches about indoor environment communication nowadays primarily focus on the network optimisation in buildings that have been constructed. These works would be presented in literature review chapter. However, to optimise the performance of wireless communication of indoor environment, focusing only on the single part of network optimisation is not enough. The influence caused by building structures is the key that determines the metrics of communication like coverage and capacity. For instance, the characteristics of building including materials, shapes and distribution can all affect the wireless communication performance by interfering the propagation way. Though there are already lots of researches conducting on the channel information optimisation, still lots of factors that affect the wireless communication performance significantly are not taken into consideration due to complexities. Taking the building structure into consideration is a necessary tendency and also the emphasis of this essay because of its great influence on signal propagation.

The challenges of indoor wireless communication design include the above aspect but are not restricted to it. Traditional indoor distribution plans are determined mostly by the personal experiences of engineers. They have a large dependence on their own cognition of building constructions, which causes their personal experiences have a strong influence on the final plan. It is hard to validate its rationality and design the assessment before the final construction. The condition of indoor coverage cannot be recognised directly and in later stages, there is a lack of basis in optimisation of the network. Under this situation, methods to improve the performance of indoor wireless communication are strongly limited because the structures are fixed. What's more, outdoor environments have not been placed much value on the influence on indoor communication design because of lack of experience and feasibility. Actually, the signal source in the nearby or base station outside in the street will all have impacts on the performance of indoor wireless communication performance. Influence caused by signal sources in rooms nearby will be mentioned in this essay and

it will be analysed briefly. Intensive research of indoor wireless communication is necessary from this perspective. Problems will also occur as the appearance of changes and improvement. It is a process of circular rise and a long way to go.

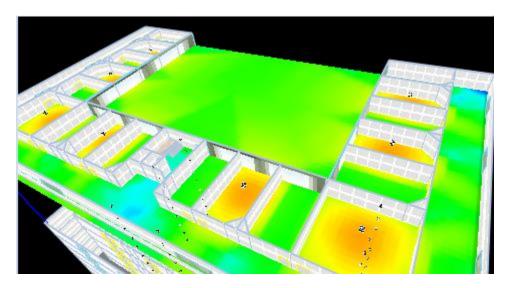


Fig. 1-2 Multi-wall structures that affect the wireless communication performance

My research used femtocell as the source for indoor communication to conduct research on indoor wireless communication system. Femtocell uses the IP protocol and connects by ADSL, LAN and so on that users own. Through IP network, the femtocells are connected to remote mobile network by Special Gateway Interface, As shown in Fig. 1-3. it can fit into the CDMA, GSM, UMTS and other various kinds of standards and support products of 2G and 3G. The operating model and frequency range using of femtocell are same with other mobile base stations so it can be used in multiple mobile terminuses universally. The research of it is valuable from this prospective because of its wide application and the universal characteristic with other kinds of signal source.

It may seem confusing when the femtocell appears in people's life because most people have no conception of it. Actually, there are three main technical plans for the realisation of indoor wireless communication system. Femtocell is a pattern of wire access that uses indoor microcell system as the signal source. It has a great advantage of improving the coverage of indoor signal in areas of large telephone traffic. The detailed advantages of it will be discussed in the next two paragraphs. However, in practical use, the coverage of femtocell is also restricted by building structure a lot. How to distribute the signal in largest degree and in most even way in every place in the indoor system is a key point in optimisation. It is also the main consideration in this thesis too. The second technical plan is macro cell. It is a pattern of wireless access that uses outdoor macro cell as the signal source of indoor wireless communication system. It is applied mainly in dead zone in which the telephone traffic is relatively small and area is small too. It appears mainly in suburbs and other remote areas and its dominant advantages are low cost and convenient construction process. The main disadvantage of it is its great effect on microcell wireless specification, especially the call drop rate.

The third technical plan for the realisation of indoor wireless communication system is relay station. It is mainly applied by introducing the outdoor signal to indoor dead zone under the circumstance that there is surplus capacity in outdoor base station. Relay station is more flexible and simply constructed. The disadvantage of it, however, is that it is unable to increase capacity and unable to set up priority. The signal quality of it is much more inferior to that of femtocell and its effect on network is large if it is not controlled well.

	Femtocell	Relay Station
Whether increases capacity	Increase according to the necessity	Cannot increase capacity
Quality of signal	Good	Normal
The effect on network	Small	Large if not controlled well
Whether needs transmission equipment	Need	No need
Whether needs to refresh planning of frequency	Need	No need
Whether supports the dynamic capacity allocation	Do not Support (pre- allocation of capacity)	Support
Whether supports multiple operators	Do not Support (pre- allocation of capacity)	Support
Whether supports multi- frequency and multisystem environment	Do not Support (pre- allocation of capacity)	Support
Time used in installation	Long	Short
Investment	Large	Small

Table. 1-1 Comparison of Femtocell and Relay Station

In current mobile services, the low coverage rate of indoor signal is mainly the result of the loss caused by wall. The coverage radius of base station and the available bandwidth for each user is always a pair of contradiction. On the one hand, the coverage radius of base station is not satisfactory because of the loss caused by wall is noticeable and on the other hand, the available bandwidth because more and more restricted because of the explosive increase of user and use density. The new mobile base stations also face multiple problems like the choice of location, management of power supply and environment protection. Location of base station should consider multiple aspects like the coverage radius, convenience and safety in management of power supply and the influence on environment to local area.

The good news is, because of the characteristic of femtocell itself, operators and customers obtain many benefits as the following: Firstly, for operators, using femtocell can enhance the quality of service. Because of the enhancement of indoor signal coverage quality, the qualities of broadband and voice service are all elevated in great degree. The capacity of network is also enhanced because each femtocell can be considered as a base station. The number of extra base stations is added to the existing system so the whole network capacity is elevated. In addition, because femtocells are bought by users so the corresponding demand of capital expenditures can reduce the investment on the capacity enlargement in network appliance. And because application of femtocell are all placed in users' house so it saves the operating costs like computer room, power supply, air condition and circuit preservation. Secondly, for users, the full-signal experience gives people great convenience. Both high capacity and coverage rate gives the best service quality for users and they get more ample and comprehensive services like voice service and internet service. Compared to Wi-Fi, femtocell does not need the dual mode mobile phones supporting Wi-Fi to support it, which means that users do not need to change the terminal to get standardised access. The network coverage based on the unit of family gives the assurance that the number of users will not increase obviously in this condition, which ensures the quality of network service. Users can buy and allocate base station of femtocell flexibly according to their needs and that arouses the research hotspot of access point deployment. In addition, it even supports the seamless switching between indoor and outdoor in the community. It is also more economical. Because of the placement of femtocell is in home, operator can give users subsidy, coupon and some kind of packages which can help them save a lot of money. What's more, because of the low quantity of users covered by each femtocell and new technology in coding voice, the quality of voice is more attractive. This mechanism saves the battery power too because the covered radius is small and the connected mobile phone will decrease its emission power so it saves the battery and at the same time decreases the exposure of human body to radiation. All of these unique advantages of femtocell determine that it is a new popular indoor wireless communication source and leads to a series of new research topics on the source deployment and building structure design to fit in the characteristic of this new signal source and realise the optimisation of performance of indoor wireless communication system

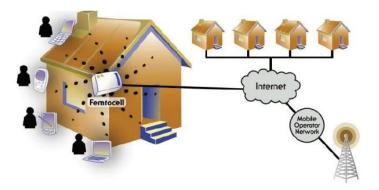


Fig. 1-3 Femtocell Network Architecture

1.2 Objective of the Thesis

The scope of this thesis is to design two metrics, coverage factor and capacity factor to evaluate and optimise the communication performance of buildings. Those factors are affected by parameters of the building structure and should be able to be used by future architects to design the parameters of the building with a better performance. To realise this purpose, the following four steps are designed.

First of all, researches of the field are conducted. The topic varies from the source deployment to influence of building structure on signal propagation and receiving. Basic knowledge of femtocell is introduced and this part of literature review demonstrates the importance and necessity of this thesis, which focuses on the femtocell type of signal source and related optimisation of source deployment and building structure design. There are also some minor aspects of research like the influence of human body density. The comprehensive research on the topic can help the following research in several aspects. The research of building structure has direct value in researching and the minor aspects of research can provide more brilliant thoughts and possible direction of further research. The research of source deployment is especially valuable in the optimisation part because it is used for reference in the optimisation of building structure. Methods are similar and conclusions are also taken into account. Analysis related to building structure is based on the precondition of optimisation of source positions.

Secondly, performance metrics are designed to measure the wireless performances of buildings. Performance metrics for buildings include different perspectives such as coverage factor and capacity factor. These metrics can reflect different properties of the building in various aspects. For instance, the coverage efficiency will display the coverage situation of the building by intuition with direct data distribution, and the capacity efficiency will display how well the network system is running in this building. The relationship between the two metrics is also revealed, which includes the similarity and difference and explains why some of the analysis and simulation are left out. Further possible new metrics are taken into consideration too, like the combination consideration of both the average value and variance of SINR to make the metric design more scientific and optimisation process more convenient.

Thirdly, the evaluation of these metrics of typical buildings will be revealed. By using simulation tools to do data analysis, the evaluation of metrics because of different characteristics can be done and the property of the building can be reflected. By comprehensively summarising the elements that affect the specifications, improvement can be identified and optimisation will be ultimately realised in the research. This step is conducted throughout the thesis and is the most vital part of it. Various aspects are taken into account, including those which are conducted a lot of research in previous researchers' work and some new perspective which is raised innovatively in this work.

The last step is to use the evaluation results to evaluate typical building structures to discuss methods that can improve the communication performance. The data used in the evaluation will be used to do the optimisation. Parameters are adjusted by referencing the previous simulation results towards the target of improving building wireless performance. Certain algorithm will be adopted in this part to

ensure the scientific and professional principle. The conclusion got from this step is practical and can be used in real engineering problem and indoor wireless communication design projects.

From this perspective, various building models should be taken into consideration to cover a large pool of types of buildings. More detailed consideration will enable the application of the method or system more suitable or the evaluation result more accurate. Evaluating the performance at indoor environment requires different conditions to be taken into consideration, not only the channel information, the MIMO influence, but also the placement of sources and the structures of the building. Accordingly, to implement optimisation and evaluation to building models, a series of parameters that can reflect the impact of the building design on wireless performance of wireless network will be taken into consideration. Not only the channel characteristics will be considered, but also building physical characteristics will be added into simulation to provide different solutions for optimisations. Large pool of factors will be taken into account and the relationship of them with the final performance will be evaluated both respectively and synthetically. One reason that there is less emphasis on the influence of building structures is that the architectural design parameters cannot be easily altered in real world. For instance, to test the effects of a variety of room sizes, one cannot just simply change the building walls position after each measuring. Therefore, measurement is not suitable for the research related to building alteration. In this case, iBuildNet® is chosen as a simulation tool for my research, which can easily build different 3D building models and do simulation on each of them as Fig.1-4 and Fig.1-5. Though some of the models cannot be realised in reality, it can interpret a phenomenon using scientific way without wasting real labour for financial resources. Instead of copying the original design, designs in reality always borrow the certain idea and put it into practical use. The meaning of these simulations is that optimisation can be done in initial steps of constructing a building in the future.

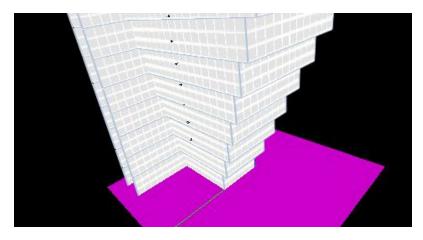


Fig. 1-4 One building model with increasing room size on each floor, which is only possible in simulations.

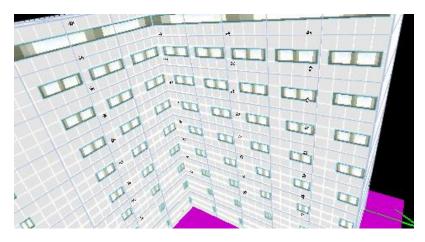


Fig. 1-5 One dormitory model with increasing window size on each floor

With enough building models, it would be possible to compare and judge the efficiency or the quality of the wireless communication performance among all models. Capacity and coverage factor are two key specifications in building evaluation. It is a common sense that those buildings that have a better capacity and coverage factor are those with better performance. And the optimisation is the process that researching on "why" this building model has higher coverage rate and capacity and "how" to obtain a model with better results. With more in-depth research, these questions can be answered and the optimisation can be realised through a more rigorous inference.

1.3 Structure of the Thesis

This thesis is mainly about designing and evaluating two metrics that used on building wireless communication performance. In this part, the paragraph organisation will be introduced to help readers understand the structure of the thesis and provide convenience for reading.

There will be 6 chapters in this essay. The literature review will be presented first in Chapter 2, and then the two-stage researches of mine are distributed in Chapter 3 and Chapter 4. Chapter 5 is composed of two practical analysis of real indoor communication systems using the model introduced in previous chapters. In Chapter 6, challenges and further considerations will be presented to arouse more focus and solutions on related topics.

Literature Review Part

In Chapter 2 a summary of my research will be presented in the fields about building wireless communication performance, from three different directions: network evaluation and optimisation, building structure evaluation and optimisation, and other elements' effect such as human density. The literature review will mainly display what researches in this field focus on, why I chose this direction to conduct researches, and how the current research results can help me. Research of the same topic and related topics will all be involved because of their reference meaning in this thesis.

Evaluation and Optimisation of Coverage Factor

In Chapter 3, simulations on different building models will be presented to analyse and used to evaluate the performance of coverage factor. Firstly, the definition of coverage factor is introduced. It is one of the most important specifications throughout the thesis. As the main part of my simulating experiment, the evaluation of coverage rate with gradient changing building models are presented and analysed. Specific steps for what to choose as parameters and how to evaluate them will be displayed step by step in detail. Various elements that will possibly affect the coverage factor in building models will be analysed too including the door position, room size, window size, the thickness and material of walls. Assumptions will be given and simulations will be done to give evidence to the assumptions. The initial conclusion will be made based on simulations of the metrics.

Evaluation and Optimisation of Capacity factor

In Chapter 4, the evaluation and optimisation of capacity factor will be finished. Different kinds of optimisation algorithms will be presented and simply compared. Annealing algorithm will be selected and elaborated in the principle level and then used here to do the optimisations of metric. A distinctive perspective will be presented and the initial simulation will keep accordance to it. Optimisation process and results will be elaborated. Reasons for phenomenon will be explained and further consideration to make the optimisation more scientific and corresponding solutions will be presented. It is worth mentioning that the simulated annealing algorithm is used to do the source deployment first though building structure is the emphasis on this research. The reason for this will be introduced in the distinctive perspective.

Practical application of the model

In this section, two typical wireless communication systems are presented. One is cinema which serves as the delegate for those which have an unsatisfactory performance and the other is office building which serves to be the delegate for those with a good performance. Reasons for them to be good or not are all presented too. Simulation of certain aspects that may cause difference in wireless communication performance will be conducted here again because in real cases the influence will be more convincing. These examples enrich the simple models simulated before and prove that the research in this paper is close to the real life.

Challenges and Further Considerations

After the reflection, deficiency in definition and demonstration will be summed up and presented here. The possibility of the second possible definition or a more suitable algorithm will be analysed. The reliability of data will be criticised.

Chapter 2 Literature Review

To penetratingly comprehend the current research status on evaluation and optimisation of indoor communication environment, it is necessary to review various aspects of research related. The literature review will be separated into three parts. The first one will focus on the field of building structure that mainly related to my thesis. The second part introduces the simulation tool iBuildNet® and literature that published related with iBuildNet® to verify its reliability. The third part displayed some other fields of research focus in indoor communication, for instance source deployment and channel modelling to reinforce the algorithm used in chapter 4.

2.1 Structure Evaluation and Optimisation

Indoor wireless coverage performance is influenced not only by signal properties, but also the properties of the building its own. Though the effect by network is hard to analysis but more easily to go deep into, the effect by building structure is intuitive but much more difficult to analyse and conclude. The shape of building itself, the inner structure and the inner condition like how the items like the table, chair and human being place all have the direct link with the performance of indoor wireless communication system. On the other hand, these considerations are varied in large degree so it is hard to generalize a theory or rule. The research on building structure is much more decentralized.

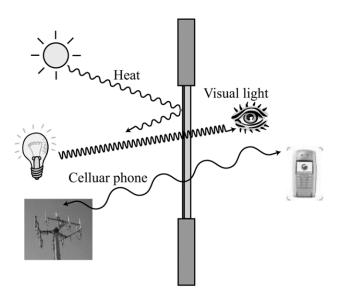


Fig. 2-1-1 Frequency selective window in [18]

Signal propagation is significantly affected by physical features within the indoor environment [17], and those walls and partitions do more influence on radio interference. Furthermore, physically the transmitter and receivers are close with each other because they are located in the same room in most cases. This is also different with outdoor scenarios. Some other building structures are considered in different researches, such as windows in [18] and Fig.2-1-1, Frequency Selective Surface (FFS) in [19] and [20], partitions with absorbing board in [21], and intelligent walls in [22]. However, those

researches did not focus on the position and complication of building structures and shapes. Most models simplify the building models to focus on the influence that the materials make. Frequency Selective Surface is used to improve the performance of capacity rate, which is known as SINR by more people. The surface selected the wanted frequency to pass through and it is also the frequency of targeted signal source. Signal source from interference with other range of frequency will be filtered out directly by the wall and the ratio of Signal to interference and noise is increased in this way then. But in real situations, even with FFS covered, there still should be enough space spared for windows, doors and furniture that are necessary in users' living. There extra elements will behave jointly to cause complicated influence on wireless communication performance.

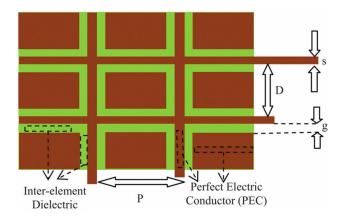


Fig. 2-1-2 Frequency selective wall array in [19]

The reflection, refraction and Bragg's law in Indoor wave propagation

When the model that calculating the path of signal is programmed, some basic optical theorem will be taken into consideration. The wireless performance differences between indoor and open space are mainly related to walls, and the signals also have reflection and refraction phenomenon when they reach walls and other different mediums, which have different loss factors. Reflection happens when the wavefront meets the interface of two different medias and the change of direction occurs so the wavefront returns into the medium that it comes from, which is defined in [26]. Refraction is a phenomenon that often occurs when waves travel from a medium with a given refractive index to a medium with another at an oblique angle. At the boundary between the two mediums, the wave's phase velocity is altered, and this change usually causes a change in direction. Its wavelength increases or decreases during this process while its frequency remains constant during this process. This characteristic ensures that entities like the wall or desk will not disturb the normal function of Frequency Selective Surface because it does not change the frequency of signal by the way. Snell's law is about the relationship between the angles of incidence and refraction which is elaborated in detail in [27]. The ratio of trigonometric function of the angles measured from the normal of the boundary on the two sides is equal to the ratio of wavelength of the light in the respective medium, which is also equal to the ratio of two velocities and refractive indexes. The relationship is derived from Hamilton evolution equations and finite refraction conservation laws and these two are both derived from the common incremental equations. In [28], the negative index of refraction is

introduced to provide a variety. The reason for the phenomenon in quantitative level is given and corresponding calculation is deduced.

When a model is created in the simulation tool, not only the path of reflection and refraction need to be considered, but also the effect of Bragg's Law need to be taken into consideration when programming. Bragg's law gives the angles for coherent and incoherent scattering from a crystal lattice. When X-rays are incident on an atom, they make the electronic cloud move like electromagnetic wave does. The waves that own the same frequency are re-radiated by the movement of charges and the movement is blurred a little because of the variety of effects caused by reradiation. This phenomenon is called Rayleigh scattering (or elastic scattering). The scattered waves can be scattered by themselves but this secondary scattering is assumed to be negligible. A similar process occurs upon scattering neutron waves from the nuclei or by a coherent spin interaction with an unpaired electron. These re-emitted wave fields interfere with each other sometimes to make the overlapping waves added up together and in this way produce a strong peak of wave and sometimes to destructively make them subtracted from each other and weaken the signal. All of the above phenomenon produces a diffraction pattern on a detector or film. Diffraction analysis, which is based on the resulting wave interference pattern, is called Bragg diffraction. This will further make the analysis of propagation of wave more complicated. However, few researches take this effect into account in evaluating the propagation of signal because of its uncertainty in causing effect and large degree of dependence on the material of wall. It is more like a pure physical problem rather than an engineering problem.

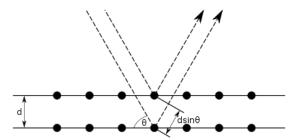


Fig. 2-1-3 Example of Bragg's Law

Simple Wall Penetration

Conducting researching further on building wall effect, there are some focus on the penetration loss through walls and building structures. In [29], a model is presented that can estimate the penetration for indoor building environment with high elevation angles involved. It assumed that the building is built with concrete walls and normal window size, and mainly focus on the impact made by elevation angles. In [30], The effect caused by penetration loss through walls was considered, which pointed out that larger proportions of incident power were reflected with walls in wet condition. Authors measured different concrete walls with dry and wet conditions. And it was suggested that moisture effect should be incorporated in the penetration loss parameters for additional confidence level of systems. These two are some minor aspects in consideration of wall effect. In this thesis, these aspects are left out for simplicity. The high elevation angle increases another dimension of source

deployment and will cause a big complexity. The moisture effect is of low necessity because in most cases moisture in walls indoor is not that easily to be affected by the weather.

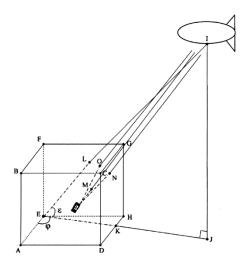


Fig. 2-1-4 the building penetration model with high elevation angles in [29]

Complex Wall Penetration

Besides the research on wall materials and wall surfaces, complex wall research is also an important direction in current field. In realistic indoor environments, walls will not be as simple as those models in most indoor simulation models that with only square shapes and empty inside. The shape of wall itself is complicated and the shape of room which is surrounded by walls is also greatly affected by the deployment of wall. What's more, the propagation characteristic of a realistic wall is not as simple as directly through and considering the corresponding attenuation value. The multiple functions of reflection, refraction and other effects are the real case. Mostly, walls are scheduled beelines with complicated distributions. In [30], some effects of complex wall structures are studied to focus on the characteristics and capacities of indoor propagation environments. The opinion in [30] that wall structures can be considered as two different kinds of structures, which one is homogenous solid slabs while the other is complex structures, is useful in my consideration about how walls' effect in my simulations. Not only path loss prediction, but also small-scale fading and the MIMO capacity are examined by authors. Results on the effect of complex walls for different simulations turned out that the patterns of the local mean power distribution for the complex wall cases are quite different from that of the slab and effective wall cases. Complex wall structures give larger capacities for some regions except line of sight region, where the capacity is similar to slab wall cases.

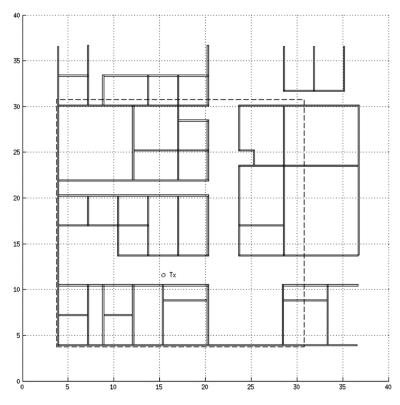


Fig. 2-1-5 Complex wall model for a floor plan in [30]

Other Indoor Structures (window, door and floors)

With some more researches and investigations on characterizing the effects of wall thickness, dielectric parameters, and complex geometries of walls on the accuracy of propagation prediction models, the importance of the influence made to communication performance by building structures is clearer. In short-path propagation modeling, the effects of composite walls are analyzed by [32], which displayed a model for analyzing the reflections and transmissions for those electromagnetic waves from complicated building structures. Properly representing the wall reflections for short propagation paths is the main target. However, still, it still only presented a type of structure with a regular pattern and also it pointed out that once the period of the structure becomes large, simple expressions for the reflection coefficient are not available. In [33], authors focus on different types of propagation models to improve the accuracy of available models and the computation efficiency. It used finite difference time domain (FDTD) method to characterize unique indoor environments for doors, windows and brick corners. In an effort to improve the accuracy of the indoor propagation prediction model, the multi-grid FDTD code was used to calculate reflection and transmission coefficients for inhomogeneous walls (multi-layer, metal bars, etc.), as well as to analyze unique outdoor-to-indoor structures such as the windows, doors, brick corners, etc. This can be applied to the situation that room without source because it helps analyzing how signal source from room next door or nearby penetrating into the indoor wireless system and influencing the system. In [34], it classified building structures into exterior walls, interior walls, floors, windows and wood doors, which is very similar to my current research and building model properties, which displayed an example in Fig. 2-1-6. The permittivity, conductivity and thickness of each structure were also input

to the model for the calculation of corresponding reflection, transmission and diffraction coefficients. With various building dielectric parameters, authors did the simulation that is classified into narrowband and wideband indoor channel characterizations. The simulation results displayed that, compared with path loss effect, root mean square (RMS) delay spread is more sensitive to the building dielectric parameters, which also proves the importance for researching the building structure influence. The blueprint of the one floor in [34] shows its consideration in placing the elements wall, door, and window. It has high reference meaning in my thesis because the first job needed to be done before optimisation is the deployment of sources and building elements. The former has been conducted thorough researches while research on the latter is scarce and precious. An indoor Line of Sight (LOS) and an office-like obstructed non-LOS scenario are measured in the research. They are the most typical structures in the building. Many other researches of indoor wireless communication mentioned these scenarios in their works too. There are also some other researches related to complex walls, for instance, [35] provided a direction on the ultra-wide pulse propagation through complex walls in indoor wireless communications environments, and [36] focused on the effects on fading and MIMO capacities by complex walls in wireless communication environments.

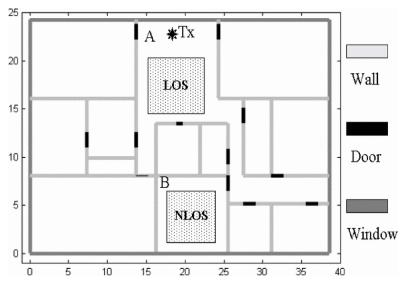


Fig. 2-1-6 Blueprint of one floor in an office building in [34]

Due to the complicated indoor environment, it is considered to have a probabilistic metaheuristic for not only the source placement but also other parameters of both buildings and sources to go further in coverage optimisation. Simulated annealing algorithm [37] is suggested as a generic probabilistic metaheuristic for optimisation problems in my research, especially for the parameters optimisation. Some research [38-41] using simulated annealing algorithm on relays placement and layout designs are able to help during my second-stage research using simulated annealing algorithm to optimise the building structure. In the literature review of sources deployment, plenty of optimisation algorithms are presented and I also evaluate the realisation of them in different research. During this process, a deeper understanding of all of these algorithms applying on indoor wireless communication problem is set up and this solid cognition supports me to face choice when selecting algorithm in my thesis. The detailed process of choosing an optimisation algorithm will be introduced in Chapter 4.

Femtocell Related

Existing research related to indoor wireless communication are mostly focused on Wi-Fi. In this thesis, the adopted signal source is femtocell, which was mentioned in the introduction. It can fit into the CDMA, GSM, UMTS and other various kinds of standards and support products of 2G and 3G. The operating model and frequency range using of femtocell are same with other mobile base station so it can be used in multiple mobile terminuses universally. Comprehensive analysis of characteristic of Femtocell has been introduced in Chapter 1 and some comparison with another type of signal source has also been presented. Though the research method focused on Femtocell and Wi-Fi is similar, there are also researches focused on Femtocell that worth extra mentioning. Femtocells, lowpower cellular (indoor) base stations, not only improve connectivity but are also assumed to reduce human exposure to electromagnetic waves. In [42], however, another view of point is presented: Although Femtocell's function in reducing human exposure to electromagnetic waves is true for exposure caused by uplink traffic, the exposure due to downlink traffic may increase when using femtocells. Therefore, it is important to investigate and characterise both the power received and transmitted by the receiver device. In this research, a prediction tool for the transmitted and received power of a cellular device is designed and a case study is conducted in an office building to do actual measurements and proves the accuracy of the prediction tool. It is a research focused on a very important sub-topic on engineering problem, that is, the influence of technology to the environment and human body. Though it deviates a little bit from the focus of this thesis, it actually provides a more comprehensive understanding to Femtocell.

In [43], an indoor propagation model analysis and path loss measurements for a wireless third generation (3G) femtocell in indoor environments are presented. An indoor LOS and an office-like obstructed non-LOS scenario are measured by using the femtocell which is connected to 3G network to enable live signal measurements. The measurement results are compared with conventional indoor wireless models. Two typical indoor channel models are optimised to increase the accuracy of the path loss estimation. The proposed model can be applied in real life to do prediction on the indoor radio propagation.

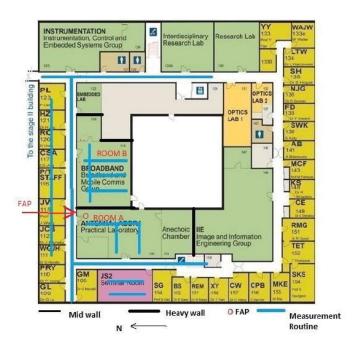


Fig. 2-1-7 Floor Plan and Femto Access Point Position in [50]

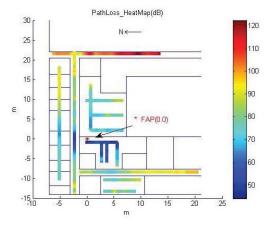


Fig. 2-1-8 Path loss on the whole floor in [50]

2.2 Simple Models implemented by iBuildNet®

In order to meet the requirements of simulation, iBuildNet® is chosen in building modelling and signal performance predictions [41]. Fig. 2-2-1 and Fig.2-2-2 show the iBuildNet UI interface and some simulation results.

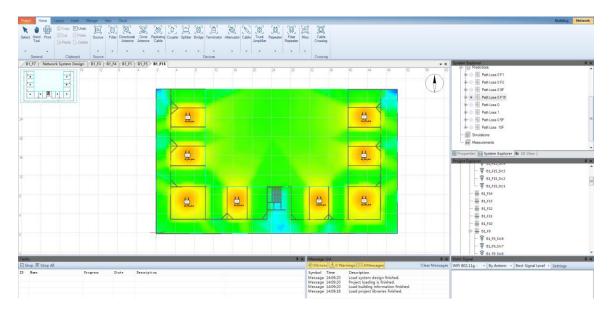


Fig. 2-2-1 iBuildNet UI interface

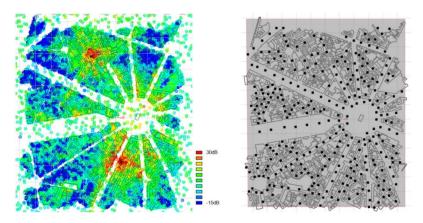


Fig. 2-2-2 Simulation results in iBuildNet® and lampposts location in real city

iBuildNet® is used for solutions of designing and optimising outdoor/indoor wireless networks and supports multi-system technologies to deliver a seamless network environment. Using advanced 3D modelling, fast and accurate 3D ray-tracing and powerful data analysis, iBuildNet® automatically optimises AP locations, antenna type, power and channel assignment. It can be used to observe the coverage condition stretching over different floors because of its support of taking an overview of the whole building or layer by layer. Provided the data like strength of signal, a precise anticipation of best-served area will be provided. It also supports the calibration function of propagation model so the simulation results of it are in most cases extremely close to real condition. The strong 3D characteristics of iBuildNet® determines that its outstanding ability of identification of objects, walls, doors and windows, ceiling and ground, even the material of architecture. This can be summarised as its complete system of information input system. It also promises its various functions like wireless signal assessment, 3D distributed antenna system design, associated simulation of indoor and outdoor and Wi-Fi multi-system design and optimisation.

Current research that used iBuildNet® [42-44] are mostly based on the deployment and localisation at indoor environment, which will not only use the building modelling function but also the signal modelling. In [45], an indoor IRLA (Intelligent Ray Launching Algorithm) is used in iBuildNet® with prediction results and comparisons with the measurement results shown in Fig. 2-2-3:

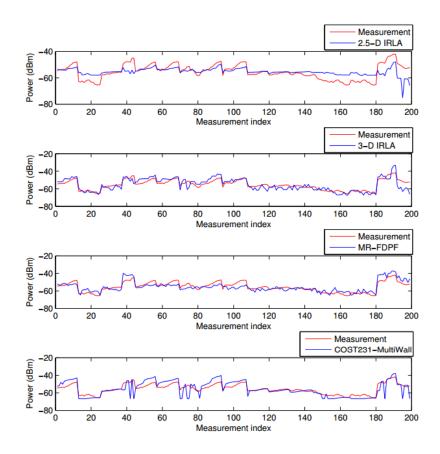


Fig. 2-2-3 Accuracy comparison between iBuildNet® prediction results and measurement results

It can be observed that these models in [45] give a high agreement between prediction and measurement. Furthermore, in [46], a hybrid model for indoor-to-outdoor radio coverage prediction is also verified with results of measurement. Due to different heights of the transmitters and receivers, there is a relatively large discrepancy between the simulation results and the measurements in Fig. 2-2-4. In the literature review, it was also mentioned that the research of height of signal source is a new and valuable topic because no previous research takes it into account. In [46], it further proved there is a large discrepancy that can be caused by the different horizontal position of transmitter and receiver. To avoid that and simplify the model, all transmitters and receivers will be placed at the same height in all my models and simulations.

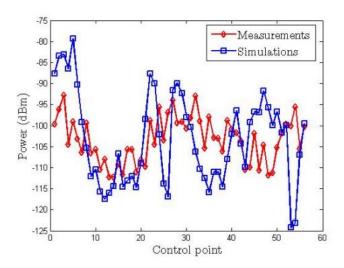


Fig. 2-2-4 Comparison between measurements and simulation results in [46]

From existing researches, it is easy to find that iBuildNet® has been used extensively in different models. However, it is still necessary to verify the simulation results by comparing the results between iBuildNet® and MATLAB® since MATLAB® is one of the most official simulation tool for engineering problems and the accordance of results of the two tools can be more convincing. To achieve that, programming in MATLAB® with an ITU indoor radio propagation model and comparison of the result with the same model simulating in iBuildNet® is conducted.

In [54], The ITU indoor path loss model is formally expressed as:

$$IPL = 20\log f + N\log d + P_f(n) - 28 \tag{2-2-1}$$

Where d is the distance between transmitter and receiver in metres, and f is the signal frequency in MHz. N is the quantity that expresses the loss of signal power with distance, which is provided as 28 in residential area with a 2GHz frequency band. $P_f(n)$ is the floor penetration loss factor, which is provided as 15 + 4(n-1) when the frequency is 2.6 GHz. n is the number of floors between the transmitter and receiver.

The multi-wall model in MATLAB® is configured as a normal 4-squares room, so does iBuildNet®. The comparison is displayed as below:

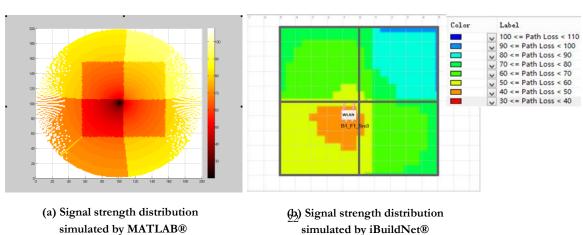


Fig. 2-2-5 Comparison between the results of simulation in MATLAB® and iBuildNet®

The comparison shows a match between two results of different simulation tools. Some more tests are shown as below.

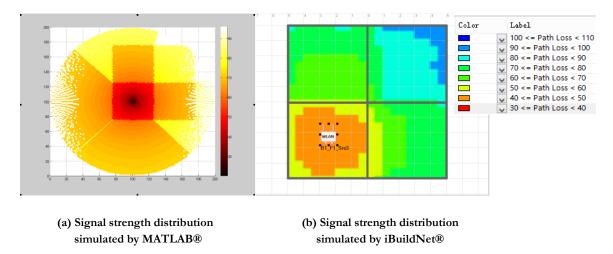


Fig. 2-2-6 Another comparison between the results of simulation in MATLAB® and iBuildNet®

The details of result of the two simulation tools have noticeable differences. In MATLAB®, dominant differences are shown in the unit of big squares and slight division takes use of circular ring and uses the depth of colour to differ the strength of signal. In iBuildNet®, all divisions are presented by the unit of small squares. However, the overall distributions of strength of signal because of different allocation of sources in two simulation tools are similar. Because of the enhanced feature of iBuildNet® and the authoritative status of MATLAB®, iBuildNet® can be used more than a substitution in the research of in-building wireless communication but an improved version. iBuildNet® is a convenient tool that easily can be got used to. It has its own component library including devices like separator, coupler and so on. The 3D model of it uses different colour to represent different materials so it is easy to monitor. The 3D wireless performance simulation function can cover the consideration of several floors. The influence of each floor on its upstairs or downstairs can all be included and calculated. It can even identify the type of service and do some prediction of them. It is the only tool in the world can realise a joint simulating, planning and optimising in both indoor and outdoor of the whole community or other types of large and complete models. In the next step, iBuildNet® will start to be used in models in my thesis to do the relative simulations and optimisations.

2.3 Indoor Network Evaluation and Optimisation

Channel Characteristics Modelling

It is necessary to take an overview of the characteristics of channel modelling before jumping into network optimisation for the necessity of understanding how the channel characteristics work in wireless network planning. Traditionally, the most popular channel characteristics in wireless network planning that being put emphasis on are power, delay and angular information. Power characteristics are widely characterised by the path loss models and statistical fading models [1]. The channel delay characteristic is captured in a small scale region and is characterised by the power delay profile (PDP) function [2]. The angular characteristic is modelled as the power angle profile [3], and also is modelled in a statistical way as the power angle spectrum (PAS) [4]. Both concepts describe the directional characteristics of the channel.

On the other hand, in practice network planners usually use channel prediction tools to acquire the channel information of the planning sites. These computer simulation tools are categorised as site-specific channel modelling tools [1]. These simulation-based site-specific channel modelling tools offer complete channel information of the planning site. For example, the frequency domain Par-Flow method in [5] offered an efficient numerical solution to the propagation wave equation in an indoor environment. Many site-specific modelling tools employ the ray tracing principle to model the channel for its efficiency and versatility [6], [7]. The model is designed to determine the channel information at each location on the planning site. Therefore such solutions give a complete channel information map of the planning site.

Even simulation based site-specific channel prediction tools provide a set of detailed channel information, the large set of detailed channel information is too complex to give a direct evaluation of the overall channel characteristic in the environment. Dimensioning is a process to evaluate the overall network performance and determine the key performance requirements in the early stage of the network planning. It requires simple and direct channel characteristics to be used to determine the overall network performance requirements. A complete and detailed channel characteristics set characterising the channel information is time-consuming and unnecessary for this early stage dimensioning task.

To consider the in-building wireless coverage performance, there are also researches focusing on influence of different frequencies. in [8], it is compared at different frequencies for both macro cellular and in-building wireless coverage performance. The 700MHz band is also researched in building penetration performance compared to higher-frequency bands in [9]. However, in the in-building propagation scenarios, lower frequency coverage is similar to higher frequency coverage at higher floors due to the decreased building shadowing, while at floors below tenth, the high-frequency coverage is smaller than the lower one. What's more, it is mentioned before in the introduction of femtocell that it needs to refresh planning of frequency when the frequency changes while the Repeater has no need to worry about change in frequency. From this perspective, influence of different frequencies is not worth too much discussion in a thesis which uses femtocell to be the signal source because the preferred frequency seldom changes and has been researched solely.

Source Deployment

By further conducting extended research, the phenomenon that the source deployment will also change wireless coverage performance greatly has been noticed. Large amount of research has been conducted in this realm because of great necessity. My research mainly focused on the influence of

the position of single source, and the influence of the positions of fixed multiple sources. However, the source deployment will greatly simplify the environment parameters and make the analysis easier. In the qualitative analysis of simple models, single source and fixed multiple sources are still used to focus on the effect caused by building structure. In the optimisation chapter, however, the source deployment will be put on great emphasis because all of the analysis and optimisation in this phase will be based on the optimised source place environment and it will be elaborated in chapter 4. In here, the various research conducted on source deployment will be listed to provide theoretical basis for further consideration.

In [10], three algorithms are used to reach the coverage requirement with selected relays in indoor environments. Under the circumstance of a given environment, [11, 12, 13] give different methods and algorithms to meet highest coverage and connectivity. What's more, there are other researches on access points (AP) location optimisation. In [14], the author provided Differential Evolution algorithm to optimise AP locations. It can be seen that most research that focus on algorithms use very simple and intuitional indoor environment models because their focus are mainly the feasibility of using optimisation algorithm to solve source deployment problem. The emphasis on building structure is rare by comparison. In [15], an innovative view is given by not only focusing on the network deployment for positioning but also evaluating the original purpose of connectivity requirement. In this research, the authors proposed an innovative approach to model WLAN planning and positioning error reduction, and optimise it using a mono-objective algorithm called Variable Neighbourhood Search. From Fig. 2-1-1 we can also see that the indoor environment that they used is complex and typical with complex walls and enough users. With enough simulations, this research provided a solution to deal with error reduction for WLAN planning and positioning, and those accuracy goals can be evaluated. Still, the algorithm they use is a mono-objective algorithm. By improving it further in the future, multi-objective algorithm can be realised and fix the problem. Compared to the researches that uses simple and intuitional indoor environment models, it is a noticeable improvement. The optimisation done in this kind of environment is more practical in real life because complex walls and human beings in the room are all ordinary state and there is high necessity to take these factors into considerations. In real engineering project, engineers also face problems and plane graph like Fig. 2-3-1 instead of simple models like single square room with single source.

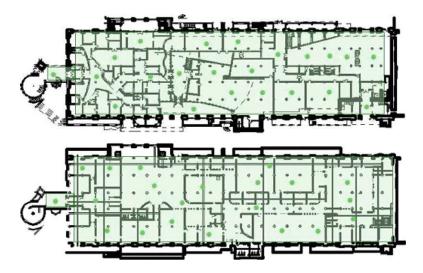


Fig. 2-3-1 the topology of the test building in [15]

A different algorithm was used in [16] and this one is related to my research more closely because of its focusing on target on coverage requirement in indoor environment. Research on the layout of APs (access points) and corresponding topological structures were included, and K-nearest neighbor algorithm was used in optimisation for the AP deployment. As displayed in Fig. 2-3-2, this simulation also used an indoor environment with complex building structures. As shown in the building structure in the figure, one of the main light spot of this research compared to others it that it differentiates the building into different degree of necessity in coverage requirement. None, medium, high, ultrahigh four levels of coverage requirement are defined to be referenced in AP deployment. In this way, the goal is not to achieve the average high coverage rate any more. Instead, meeting the respective goals according to their needs is the most important thing in optimisation process.

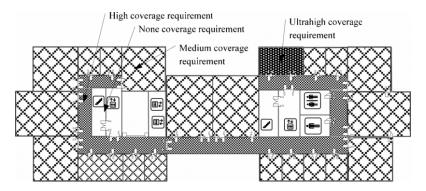


Fig. 2-3-2 Floor plan of the experimental environment in [16]

In [48], to overcome the lack of consideration of the way to use pre-existing APs in target environment for achieving high localization performance in existing mechanisms in the realm of wireless indoor localization systems, a measurement-based AP deployment mechanism (MAPD) is proposed. It takes the advantage of pre-existing APs to identify candidate positions with poor localization accuracy for deploying new APs. It is a new train of thought. In the previous literature, all the AP deployments are finished in one step. In this research, however, improvements are made based on the first round of AP deployment. It is applicable in cases like the existing building in which

AP has deployed while the performance of wireless communication is not satisfactory. Further AP deployment can be finished by identifying candidate positions using method in [48]. Greedy search algorithm is used in identifying m positions out of the n candidate positions (m<=n) while minimizing the location error. Experiments results in this research demonstrate that the localization errors can be largely reduced, from 11% to 27% respectively.



Fig. 2-3-3 Experiment environment, distribution of the access points and new AP layout in [48]

Genetic algorithm (GA) is one of the widely used optimisation algorithm that owns a high publicity. The first step of using GA is generating an initial population and then finding optimal solution by iterations. [47] is an example of using genetic algorithm to plan a WLAN deployment for indoor system. In this research, number of sources and the position of them are all set to be variables. GA is used to find the optimal combination of number and position. In its planning approach, Geometric Dilution of Precision (GDOP) is used to evaluate the positioning accuracy of a deployment scheme. This planning approach can also provide AP deployment scheme for different positioning algorithms like Time of Arrival (ToA) and Angle of Arrival (AoA). In [51] genetic algorithm is used to do the optimisation of deployment of Wi-Fi wireless access points. It provides various deployment methods according to the weight of every decision making condition. It gives empirical results and practical suggestions to show that the proposed model serves as a resolution based on users' capacity requirement. Both of the experiment in [47] and [51] use the genetic algorithm and iteration is used to approach the convergence. What's more, both of the experiments select discrete points of candidate access points and do the optimisation by choosing an optimal one among them. It is also one of the main characteristic of genetic algorithm. The density of candidate points will in large degree affect the precision of simulation result. This will be mentioned in Chapter 4 when choosing optimisation algorithm for this thesis.

2.4 Summary

As my literature review indicated, researches that related to evaluation and optimisation of wireless communication performance are separated into two main fields, one for structure planning and the other for building network planning. Some minority aspects are considered too. The researches that focused on network planning used single and changeless building models, while those researches considering mainly about building structures focus on complex walls and materials. In overall,

researches about source deployment accounts for dominant part of the existed literature because researches in this aspect are more organised in a complete system. On the other hand, in my thesis, building structure is placed on more emphasis because of the lack of previous research and great potential in further research. Methods and algorithms used in researching source deployment would also be referenced in the research in building structure and contribute to both the analysis and optimisation of wireless communication performance influenced by building structure. Researches related to network planning is still included not only because of the integrity of research of indoor wireless communication system, but also because in research of building structure planning, some of the method used in source deployment will be taken for reference as well, especially in chapter 4 in which the optimisation of building structure will be realised.

As a summary, these researches provide wise solutions and potential perspectives in solving indoor wireless communication performance problems. There are always some unexpected perspectives proposed by new researcher like the complex effect of wall or influence caused by the height of signal source. There are also plenty of algorithms proposed which indicates the variety of ways to solve and also gives the chance to evaluate the performance of each algorithm. These literature are strong impetus in the process of finishing my thesis.

Chapter 3 Evaluation and Optimisation of Coverage Factor

To achieve the target of evaluating the building in different wireless systems, the research is separated into three steps:

- 1. Define what parameters are appropriate to be used to evaluate building wireless performance;
- 2. Analyse how to evaluate them and what elements that will impact these metrics;
- 3. Build models to simulate specific circumstances to evaluate the building wireless performance in a rigorous way.

To reach the requirements of specific coverage and capacity needs, coverage efficiency and capacity efficiency are key specifications for evaluation and optimisation of wireless performance of buildings. To meet the targets of certain coverage rate and capacity factor, how those building environment parameters impact the result will be conducted research in depth. To evaluate the communication performance of the building, two metrics will be designed and be used for future evaluation. In this chapter, coverage factor will be introduced to be comprehensively analysed and in chapter 4, the evaluation and optimisation of capacity factor will be presented.

3.1 Metric Design: Coverage Factor

To provide metrics that can reflect the status of the coverage efficiency of indoor wireless communication performance, the concept of coverage factor is defined as follows:

$$G_{cov} = \frac{1 - F_b}{1 - F_0} \tag{3-1-1}$$

Where F_b is the coverage rate of a network in the given building, and F_0 is the coverage rate of the same network in an open space. The coverage rate is related to the sensitivity of the receiver. If the signal power reaches the required sensitivity of the receiver, the block area is considered as "covered". It is used to calculate the path loss in open space. The formula is provided as below:

$$FSPL(dB) = 10 \log_{10} \left(\left(\frac{4\pi}{c} df \right)^2 \right)$$

$$= 20 \log_{10} \left(\frac{4\pi}{c} df \right)$$

$$= 20 \log_{10} (d) + 20 \log_{10} (f) + 20 \log_{10} \left(\frac{4\pi}{c} \right)$$

$$= 20 \log_{10} (d) + 20 \log_{10} (f) - 147.55$$
(3-1-2)

Where d is the distance between transmitter and receiver in metres, and f is the signal frequency in Hertz. The coverage rate for the given building will be inferred at simulation part.

Coverage factor is a metric that can reflect the wireless communication performance of building structures, which is one of the main goals of the research to be optimised and has great importance and meaning. However, considering only the performance of this metric is not enough because it has several restrictions when used in practical engineering problems. From the expression of path loss, we can see that the only variables that have influence on the value is the distance between transmitter and receiver and the signal frequency. The latter is the characteristic of signal source and the former is the characteristic of the propagation route. However, the performance of a single point of receiver is affected not only by these two elements. The interference from unwanted source can also affect the performance but coverage factor cannot reflect it. That's why we need to introduce the second metric.

3.2 Modelling in iBuildNet®

Two main functions of iBuildNet® are used in my research. One is 3D building modelling and the other one is path loss prediction and coverage efficiency calculation. 3D building modelling can help readers know detailed things about the building which is analysed in a more direct way and path loss prediction and coverage efficiency calculation can make the research more convincing using scientific tools and formula. In the part of capacity factor calculation.

Walls, windows, doors and source positions are key parameters in affecting the coverage rate in different ways. Due to the complication of effects that made by multiple elements, it is necessary to assess their influence one by one with other parameters fixed first so the change of factor value will only be affected by the changing parameter.

Two typical campus buildings are simulated in my research at the first stage. In most school buildings sources are arranged at corridors, while in most dormitory environments, students have their wireless routers inside their rooms, which is the condition with source inside the target area. Both of the two kinds of arrangement are common in real life so both of them are worth discussing and they will be analysed one by one.

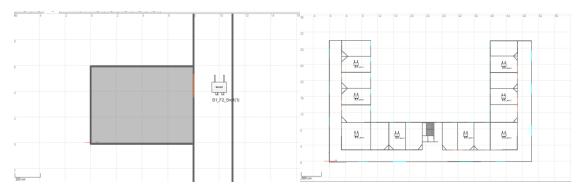


Fig. 3-2-1a Indoor environment with source outside

Fig. 3-2-1b Dormitory environment with sources inside

Corridor network layout is one typical spot for indoor wireless communication environment. Sources are placed at corridors to meet coverage rate requirement with fewer antennas and transmitters. The number of sources is determined by the principle that using as few as possible at the same time ensuring the quality and coverage rate of communication performance.

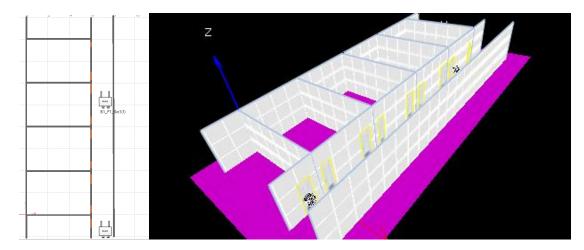


Fig. 3-2-2 Classrooms with sources outside at the corridor

Due to the same size and structure of each classroom, the model can be simplified to a signal room with a corridor in Fig. 3-2-3.

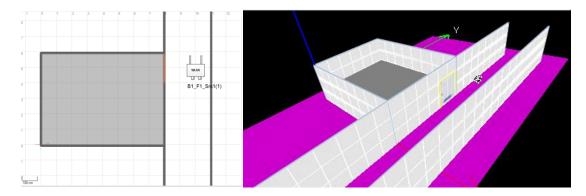


Fig. 3-2-3 Single room model with source outside at corridor

In this case, all parameters that can be changed in this 3D building models are: room door position, source position, door width, room length and width. To focus on the differences made by building structures, network parameters will not be changed and the network configurations in iBuildNet® are set as follows and fixed during simulation:

- 1) FDD-LTE 2.6GHz with 20MHz bandwidth
- 2) Channel 2 used in cells with centre frequency of 2670MHz
- 3) Source position height: 1.5m. Transmitter power: 33dBm, gain: 0dBi
- 4) User equipment (receiver) height: 1.5m, sensitivity: -106dBm

5) Path loss model: RRPS (Ranplan Radio Propagation Simulator)

6) Scheduler: Proportional Fair

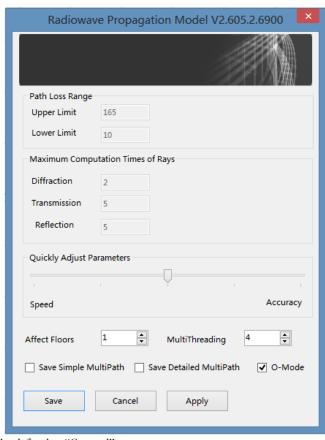
7) Scheduling granularity: Physical Resource Block

8) Shadowing Margin: 3dB

9) Simulation: Monte Carlo, 20 snapshots, TTI: 100

The fixed parameters of the simplified indoor environment are displayed as follows:

Fixed Parameters	Value
Tixed Tarameters	varue
Door width	2m
Door height	2m
Source Distance to the room	2m
Corridor width	3m
Room aspect ratio	3:4
Smallest room size	6m X 8m
Largest room size	13m x 17.33m
Room height	3m
Wall thickness	0.15m
Source type	FDD-LTE
Source frequency	2.6GHz
Coverage Rate Requirement	RSRP greater
	than -106dBm*



*RSRP of a block area reached the sensitivity of the receiver will be defined as "Covered"

Table. 3-2-4 Fixed parameters in the simulation for indoor environment with source outside

In some indoor environments like dormitories and apartments, users have their wireless access inside rooms. With source inside target area, the wireless communication performance that doors and windows effect will not be significant to the room itself, but the impact to the room nearby which has no source inside will be different. In this simulation, the influences caused by adjacent rooms are neglected for simplicity. After all, this pattern of influence is more similar to the environment with source outside and will be analysed too. On the other hand, structures in the room will still affect the performance of the wireless communication. These elements will be simplified or neglected but in real cases, which will be presented in Chapter 5, these elements will be considered and set to be close

to real situations. To evaluate the coverage rate change made by those building structures, complete building models will be needed.

The U-type dormitory building in Fig. 3-2-5 and Fig. 3-2-6 have sources in every two rooms. They have corridors and stairs on each floor. This is close to the arrangement of a real dormitory building.

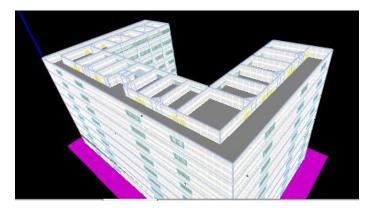


Fig. 3-2-5 3D view of one dormitory building

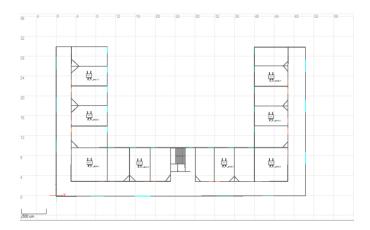
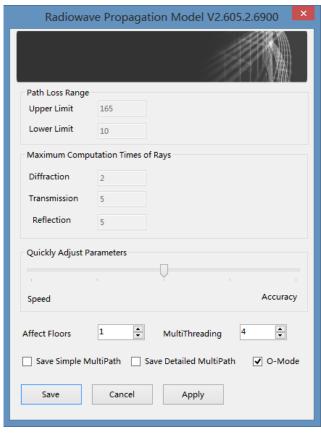


Fig. 3-2-6 2D view of one dormitory building

With the similar method used in the evaluation for coverage factor and capacity factor with source outside, there are also parameters that set to be constant to simplify the evaluation. They are displayed as follows:

Fixed Parameters	Value
Number of rooms	18
Number of floors	10
Sources in each floor	8
Corridor width	3m
Room width	4m
Room length	7m
Corner room size	7m x 7m
Room height	3m
Wall thickness	0.15m
Source type	FDD-LTE
Source frequency	2.6GHz
Coverage Rate Requirement	RSRP greater than -106dBm *



*RSRP of a block area reached the sensitivity of the receiver will be defined as "Covered"

Table. 3-2-7 Fixed parameters in the simulation for indoor environment with source inside

3.3 Modelling, Simulation and Analysis

3.3.1 Door Position Influence

Door is a structure that made of different materials compared with normal walls. In most buildings, doors are made of materials that easy to be penetrated by signals and they are usually much thinner than normal walls. In [55], some researchers have already noticed the influence of doors to the indoor communication performance, and focused mainly on the effect of the door state on the propagated WLAN signal in indoor environments. From the above perspective, the penetrating characteristic of door is much more different from normal walls and intuitively, they are easier for signals to penetrate and improve the performance of wireless communication system. It is considered that the position of door of a room will affect the coverage factor.

Modelling

With models in Fig. 3-2-3, it is predictable that the coverage rate will meet the maximum and the coverage factor will meet the minimum when the door is set to be right in front of the source. When the door is set to be right in front of the source, the source can more easily get into the room from intuitional perspective. To do further research about the influence of door position, two series of

experiments are designed. In the first series of experiment, door and source are combined with each other and moved together and in the second series of experiment the source is set to be stationary and the door is mod. Using both of the experiments makes it efficient and complete to quantitatively test the influence of door position on coverage factor.

The model of the first set of experiment is shown as the following.

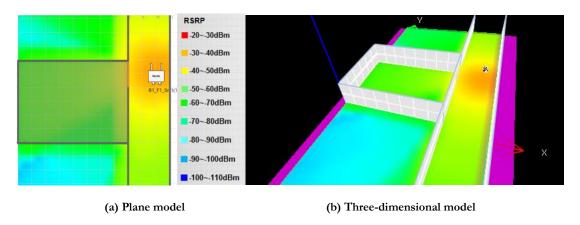


Fig. 3-3-1 Building model evaluating door and source position at one extreme position

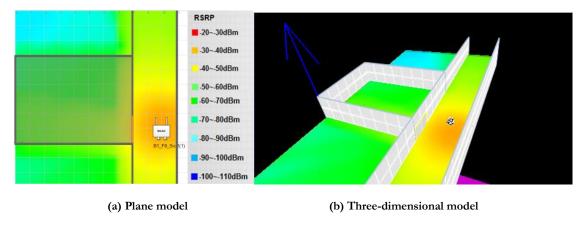


Fig. 3-3-2 Building model of door and source position at opposite extreme position

Parameters of the model are the same as the smallest room in Table. 3-2-4.

Simulation Results

The coverage factor varies as shown in Fig. 3-3-3. It is obvious that with the source staying in front of the door, the coverage rate in room maintained at a high value while the coverage factor kept in a low value. The variance of coverage factor keeps small. The next step is to analyse the influence of relative position of door and source in modelling to provide a more precise result.

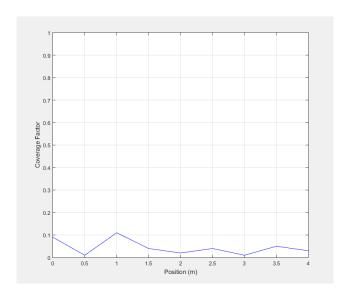


Fig. 3-3-3 Coverage factor with door and source moved together

In this step, sources are deployed to be right in front of the room and door is moved to different locations, while all other parameters remain the same:

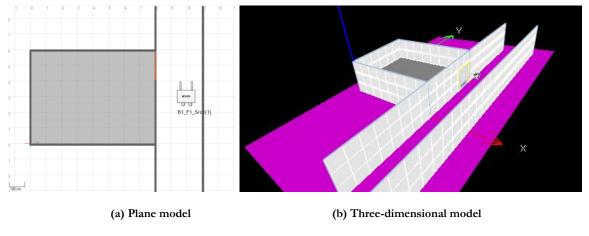


Fig. 3-3-4 Building model of door position at one extreme position

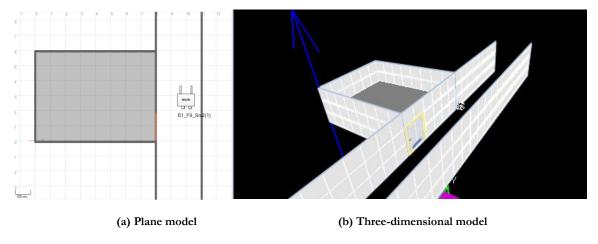


Fig. 3-3-5 Building model of door position at opposite extreme position

From Fig. 3-3-4 to Fig. 3-3-5, one extreme position to another, 10 simulation points in linear step are chosen to calculate the coverage factor. From the line showed in Figure 3-4-6, the overall tendency of the change of coverage factor can be seen clearly.

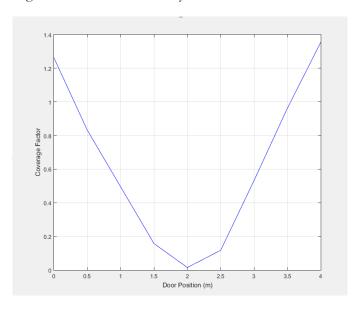


Fig. 3-3-6 Coverage factor with different door positions

From Fig. 3-3-6 we can see that the coverage factor reached the minimum when the door is in the middle position of the wall, which is right in front of the source. Due to the fact that the coverage rate of open area will not change if the network stays the same, it is predicted that at the middle position, the coverage rate will meet the maximum while coverage factor meets the minimum because when the source is right in front of the door, the indoor space right close to the door can be taken as in the same space with source. The small area can be taken as open area. As we can see, the simulation results match the prediction. In other positions, because of the obstruction function of door to the signal source, coverage factor rises as the deviation of the relative position enlarges. The relationship is more like a linear one.

Summary

The summary on the door position influence can be concluded as that opposite position of door and the signal source is the most important factor. The performance of coverage comes to the optimal situation when the door and the signal source are front to front. The absolute position of them when they are deployed together does not have much effect on the value of coverage factor.

3.3.2 Room Size Influence

With a bigger room, the same source will be harder to cover the entire space. In several simulations of different papers, the size of room is always the key parameter for the indoor environment, for instance in [56], they changed the room size for simulations of indoor visible-light communication systems. It is predicted that with a larger room, the coverage rate will decrease while the coverage

factor is increased, and with a room that large enough, the coverage rate of given building will approach the coverage rate of open space, while the coverage factor will approach to 1.

Modelling

The respective influence of length and width of the room can be complicated. To simplify the condition, the ratio of length and width of the room remains 4:3 in this model, and with the increased width, the length will be lengthened at the same rate.

Parameters of the model are the same as those in Table. 3-2-4.

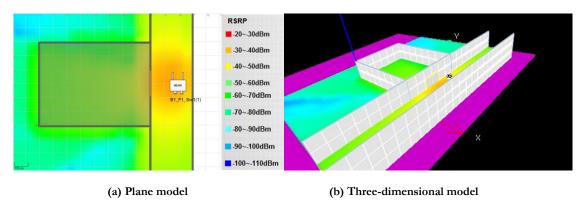


Fig. 3-3-7 Building model with room size 6m*8m

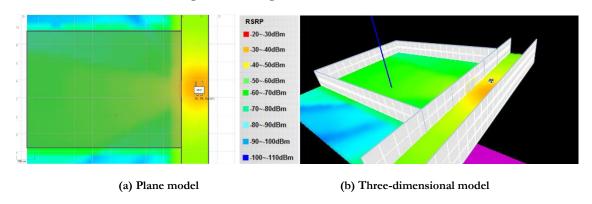


Fig. 3-3-8 Building model with room size 13m*17.33m

From Fig. 3-3-7 to Fig. 3-3-8, the room size continues to increase, with all other parameters remain the same, the door and the source stay in the middle to provide maximum signal power. Similar to the door-position simulation, the process of increasing room size can be divided into a sufficient number of short segments. Build a model for each segment like in Fig. 3-3-9. The model is only built here for convenience in simulation and a building structure in the figure cannot be realised in real life.

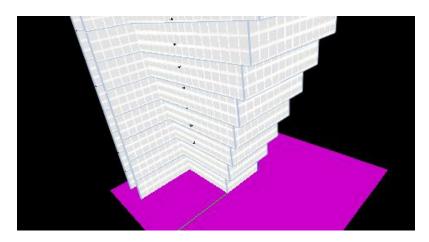


Fig. 3-3-9 Increasing room-size models combined into one 3D-view

Simulation Results

With Coverage factor calculated in each model, a curve of coverage factor is generated as Fig. 3-3-10:

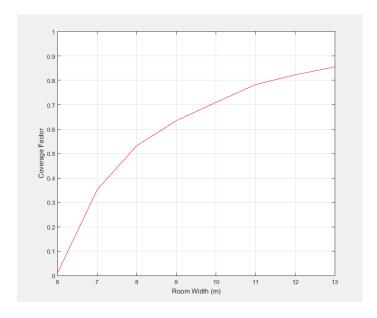


Fig. 3-3-10 Coverage factor with different room sizes

From the result, it is considered that the coverage factor is increasing significantly at the beginning of modelling, and then the increasing rate slows down and approaches to its maximum value because the limitation is met when the room is large enough to be taken as an open space. The simulation result matches with the prediction that the coverage factor is influenced by not only door position but also room size. The degree of the influence can also be clearly told from the curve in the figure.

Summary

With a bigger room, the same source is harder to cover the entire space. With a larger room, the coverage rate will decrease while the coverage factor is increased, and with a room that large enough,

the coverage rate of given building will approach the coverage rate of open space, while the coverage factor will approach to 1.

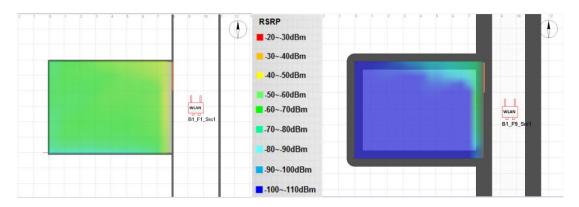
3.3.3 Thickness of Wall

The property of walls is also a key parameter in indoor environment. In [30], both the thickness and material of walls are taken into consideration in the complex wall effect research. Therefore, in this part, the influence to coverage factor caused by the thickness of wall will be analysed and calculated. The adopted model is still the simple model with one room and one source used in the two previous sections.

Modelling

In Fig. 3-3-11, two extreme conditions of the thickness of wall are presented. In the figure on the left, the thickness of wall is set to be 0.1 meters and in the right, the thickness of wall is set to be 1M. The position of door and the position of signal source are all fixed and there is no other variable in the comparison. Clearly, the overall coverage rate in the left is much more satisfactory than the condition that the wall thickness is 1m. The simulation result matches with the assumption. Other thicknesses are also considered and a linear step of 0.1m is taken to do simulation with thickness between 0.1 and 1 meter.

Parameters of the model except the thickness of walls are the same as the smallest room in Table. 3-2-4.



- (a) Signal strength distribution with wall thickness of 0.1m
- (b) Signal strength distribution with wall thickness of 1m

Fig. 3-3-11 Comparison of the Signal power intensity with different thickness of wall

Simulation Results

The simulation result is shown as below. As we can see, the tendency of influence is that as the wall thickness increases, the coverage factor increases correspondingly. In another word, the coverage rate decreases in this procedure and the performance of the indoor wireless communication system becomes worse. As we see in detail, the velocity of change is also varied in different phases in the change. When the thickness of wall is extremely small, the influence of wall thickness does not show apparently. It is because that in this range of wall thickness, the signal is easy to go through and the

performance will not be largely affected. In the range of 0.6 to 0.9 meters of wall thickness, the rate of increase for coverage factor is large because in this range, the characteristic of signal propagation experiences a threshold and the propagation of signal through wall becomes much harder. When the thickness of wall is larger than 0.9 meters, the rate of increase becomes slow again. In this phase, the propagation for signal is hard anyway so the influence of wall thickness becomes not dominant.

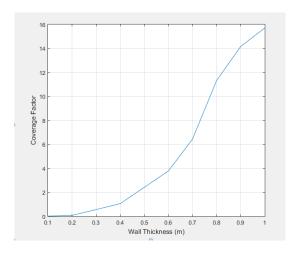


Fig. 3-3-12 Coverage factors affected by wall thickness

Summary

The coverage factor is in general positively correlated with wall thickness which means the coverage rate becomes more unsatisfactory when the wall is thicker. The further influence of wall thickness will be conducted further research in chapter 4 to be considered on the basis of optimisation of source deployment. What's more, in chapter 5, two typical examples of indoor wireless communication environment will be introduced. In the model of office building, which is a typical environment that has a good indoor wireless communication system, the influence of wall thickness will be further presented. Even in a system with an outstanding wireless communication performance, wall thickness still needs to be carefully chosen. What's more, the thickness of wall may also be varied even in a certain room. In one of the essay in the literature review, mid wall, heavy wall and other kinds are used together in the floor plan of a university building. The adoption of multiple thicknesses of wall is another way to approach the real situation. In some cases, it is necessary to take this factor into consideration. It is worth attempting but in this thesis, it is neglected for simplicity.

3.3.4 Material of Wall

Modelling

The consideration of the wall material is based on the previous cognition on several literature. Different from the previous simulations, information from the simulation about material is not able to do the fitting. Discrete value of coverage factor is got from each simulation so we cannot figure out a relationship between coverage factor and material. On the other hand, each material of wall has a corresponding value of attenuation value. This is a value that measures how much the intensity of the signal will be affected because of the propagation behaviour through the wall. The degree of

attenuation is expressed in the form of the proportion of intensity of signal after wall-through and the intensity of signal before wall-through in a logarithmic scale. A relationship between the attenuation value and the coverage factor can be set up. The adopted model is still the simple model with one room and one source used in the three previous sections.

Simulation Results

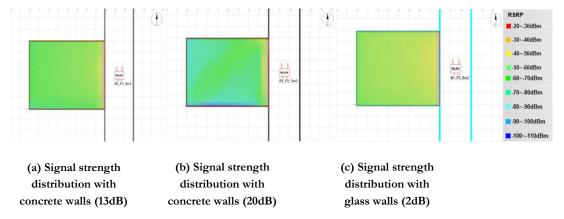


Fig. 3-3-13 Coverage factors affected by material of wall

Parameters of the model except wall material are the same as the smallest room in Table. 3-2-4.

In Fig. 3-3-13, the coverage factors that in the condition of three different materials are presented. In the first case, the wall is made of normal concrete and the corresponding attenuation value is 13dB. In the second case, the wall is made of another kind of concrete whose attenuation value is 20dB. In the third case, walls are made of glass whose attenuation value is only 2dB. Because the simulation model is a most simple one in the single room, the signal source is fixed and the door position and room size are all the same in the simulation of different materials, all of the differences are caused by the material of wall. The difference is tiny but we can still tell the difference. In the case with a 20dB attenuation value, the coverage rate has a noticeable disadvantage compared to the other two and the coverage rate in wall with 2dB has an extra tiny advantage compared to 13dB concrete wall. This is according with our cognition because glass is always used in occasions like office to ensure a satisfactory wireless communication environment.

Summary

Based on the situation that the difference in simulation of coverage factor in single room is not noticeable, extra analysis of influence of wall material will be further conducted in chapter 5. In chapter 5, real cases of typical indoor wireless communication system will be presented and analysed. These models are more complicated in the structure than the simple models in this chapter so the effects of different factors are easy to show. In the first case, material will again be taken as a variable to prove its importance in differentiating the indoor wireless communication performance.

3.3.5 Dormitory Building Environment: Window Size Influence

Modelling

For most dormitory environment, the signal sources are routers inside rooms. Most students would prefer to own their own routers in their own dormitories because signal from routers next door often performances unsatisfactorily. It is different from the previous models in which sources are outside the room. To study the influence made by windows, simple models like Fig. 3-2-1a is unavailable to get results in simulation. Therefore dormitory building model in Fig. 3-2-1b is introduced in this part.

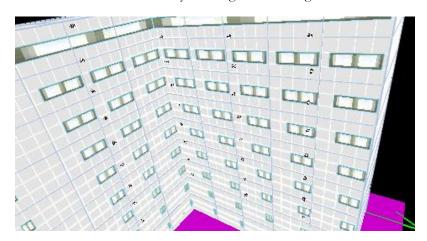
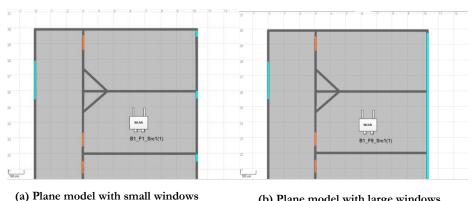


Fig. 3-3-14 Dormitory model with increasing window size in upper floors

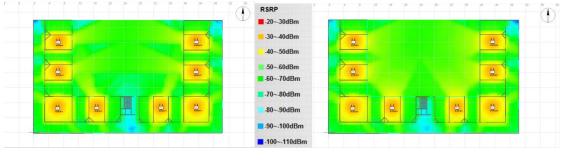
Simulation Results

In models with sources outside target areas, the neighbouring rooms without sources will be affected when parameters of structures change. The window size will be changed in linear step too to be analysed about its influence on the coverage rate of both the room with source and the nearby rooms without source. The two extreme situations of window size are shown in Fig.3-4-15. The simulation result is shown in Fig.3-4-16.



(b) Plane model with large windows

Fig. 3-3-15 Building models with least window size and largest window size



(a) Signal strength distribution with small windows

(b) Signal strength distribution with large windows

Fig. 3-3-16 Simulations with least window size and largest window size

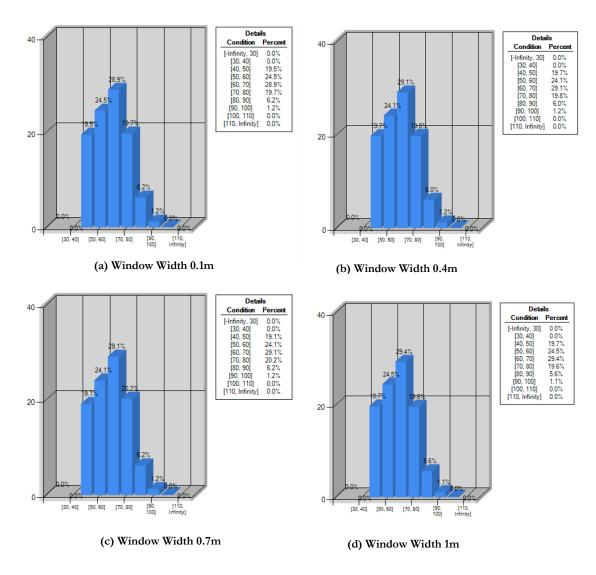


Fig. 3-3-17 Path loss histograms on some models in window size modelling

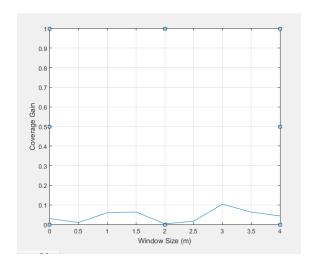


Fig. 3-3-18 Coverage factor with different window sizes

Summary

From the simulation result in the above figures, though the signal in the middle area has some difference, the target area, which is inside the building, has not been greatly affected. It is considered that those window sizes will not affect the wireless performance significantly, and probably will only work when all parameters changing together. The reason for this phenomenon can be that the direction of window is always vertical to the neighbourhood, which means that even signal can leak through window, it does not leak to the dormitory nearby but to the outside window, which can also be seen in the comparison in Fig. 3-3-16. The wireless performance in the rooms without source may be affected more by the characteristic of wall which separates the two rooms, like the thickness or material and so on. The rooms with or without sources inside are neither affected by the window size significantly. In real cases, the allocation of sources in dormitory is more changeable, but the conclusion can be applied to them too because of continuity. To proceed analysis, simulated annealing algorithm would be introduced in my second stage of work in next chapter.

3.4 Further Analysis and Conclusion

3.4.1 Further Analysis

The basic direction of optimisation has been all presented after each analysis of factors that can influence the coverage factor. The respective pattern of function has been derived. However, methods used for those building models before can only evaluate the buildings' wireless communication performance when sole variable is analysed, but with multiple variables of the building structure working together, the optimisation of the building communication performance need a probability algorithm to support and solve solution problems. To process further optimisation after the evaluation, the application of certain algorithm for coverage factor is more convincing because optimisation algorithm is capable of dealing with multiple variables together.

After the evaluation, if a formula of coverage factor can be obtained, the calculation of coverage factor will be possible with input from some basic parameters such as door widths, room sizes, room numbers etc. from a building. A preliminary equation for calculating coverage rate C_b is proposed after the simulations in section 3.3.1-3.3.4:

$$C_b = \begin{cases} \frac{(11w_r - 9|2x_d + w_d - 2x_t|)(26 - w_r)}{200w_r} \times 100\%, & |x_d - x_t| \geqslant \frac{w_d}{4} \\ \frac{26 - w_r}{20} \times 100\%, & |x_d - x_t| < \frac{w_d}{4} \end{cases}$$
(3-4-1)

where w_r is the width of the room, x_d is the position of the door, x_t is the position of the transmitter, w_d is the width of the door. When the transmitter is in the front area of the door $(|x_d - x_t| < \frac{w_d}{4})$, the influence made by door and source is negligible.

However, this equation has several limitations: when the w_r is lower than the minimum of 6m, the C_b stays in 100% since the entire room is covered; and this equation does not work for any other building structures, for instance, the dormitory building in section 3.3.5 is not suitable for this equation. Therefore, equation (3-4-1) is not usable in future optimisation for other different building structures, further studies are still needed.

3.4.2 Conclusion

With different simulations, the curves of coverage factors are obtained for each building model. The door position simulation and room size simulation gave results that match the prediction, while more research will be needed to dig in the influence of window size with optimisation algorithms.

The previous simulations are generated in iBuildNet® and its reliability has been discussed before. As a result, the simulation data are persuasive and reliable. The previous models are all simplified before by controlling variables and using classic structures of room so the conclusion is not complete because complex structures and multiple variable models are not taken into consideration. The analysis of the complex models is similar to simple models so the rough process can be used for reference and the simulation process can be reappeared when given enough parameters. For multiple variable models, more advanced algorithm is necessary and further study is needed in the second stage of research.

All of the simulations before are based on the assumption that coverage factor is a metric that can reflect the wireless communication performance of building structures, which has been proved before by giving relative references and providing its expression. This metric is one of the main goals of the research to be optimised and has great importance and meaning. It should be taken into consideration in further analysis of all kinds of models in the realm of indoor wireless communication.

In the next step, simulation and analysis of capacity factor will be discussed in detail. In real indoor wireless communication system, the capacity factor is what should be put emphasis on. It mainly deals with SINR which will be discussed in chapter 4. In an environment that several signal sources are deployed, signal from other sources is taken as interference and noise for the received point. That

is why that the SINR in indoor system may be larger than open space because signal from other sources will propagate more easily in open space as well as the target signal source. The final result will still depend on several factors like the thickness and material of wall, the position of door and windows, the competition of target signal source and other signal sources. The situation in this is much more complicated compared to the monotonic characteristic of influence of factors on coverage factor. As a result, the optimal capacity factor will be figured out using optimisation algorithm in a higher necessity.

As a conclusion the optimal process of coverage factor and capacity factor are extremely different. The optimisation of coverage factor will finally be immersed in an embarrassing situation of extreme value while the optimisation of capacity factor is not only more practical but also more close to truth. The optimisation of capacity factor will be taken as the dominant part in this chapter will be introduced in the next part.

Chapter 4 Evaluation and Optimisation of Capacity factor

In this chapter, the definition of another important metric will be introduced first. Based on some of the analysis and conclusion before, optimisation of the capacity factor will be conducted. Annealing Algorithm is mainly used here to finish the optimisation. The conclusion will be made and related discussion will also be presented.

4.1 Metric Design: Capacity Factor

To define a metric that can reflect the status of the wireless capacity performance in the building, we propose capacity factor G_{cap}

$$G_{cap} = \frac{C_b}{C_0} \tag{4-1-1}$$

Where C_b is the average capacity of a network in the given building, C_0 is the average capacity of the same network in an open space. Capacity factor is for research related to SINR. It is a parameter that can take both the interference and white noise into consideration. The detailed meaning of it will be elaborated later.

4.2 Theoretical Basis on Capacity Factor

Previous simulations in chapter 3 focus mainly on coverage factor to measure the performance of wireless communication system in simple models and real building cases. The evaluation and simulation in previous are all intended to prove that coverage factor will change as the building structure changes so it is able to be taken as a metrics of the building structure. The optimisation part can use coverage as a target in this way. The analysis before is not only used simply to evaluated different building structures but also to evaluate the metrics. So does the capacity factor. Actually, as mentioned in the introduction and definition parts, capacity factor is another important specification to measure the performance. As the name indicated, it takes the capacity of the signal into main consideration. It focuses on the quality of the signal. Coverage factor mainly deals with whether the signal can be received or not and what is the range it can possibly to cover while capacity factor pays more attention to whether the signal is clear and strong enough to be useful and whether users can have a wonderful user experience. The ratio of signal to noise (SNR) is what capacity rate represents the quantitative level. SINR is a publicly recognised specification that indicates the quality of signal in various kinds of realms and this will be introduced in detailed next.

4.2.1 Channel Capacity and SINR

In [52], the relationship between channel capacity and SINR is presented. The Shannon-Hartley law states that the channel capacity of a band-limited Additive White Gaussian Noise (AWGN) channel can be expressed as in Equation (4-2-1-1):

$$C = Blog_2(1+\gamma) \tag{4-2-1-1}$$

Where *B* is the channel bandwidth, γ is the signal to noise ratio (SNR), and *C* is the channel capacity in bits/sec. The SNR γ is defined as $\gamma = \frac{s}{N}$, where *S* is the received signal power and *N* is the AWGN power within the channel bandwidth.

In most mobile radio systems, however, the channel exhibits Rayleigh fast fading, aggravated by typically log-normally distributed shadowing or slow fading, resulting in a time-variant channel capacity. [53] derived an estimate of the channel capacity in Rayleigh fading environments and showed that when using diversity in a Rayleigh fading environment, the average channel capacity can approach that for a Gaussian channel. The normalised channel capacity can be expressed as in Equation (4-2-1-2):

$$\eta = \frac{c}{R} = \log_2(1 + \gamma) \tag{4-2-1-2}$$

An upper bound approximation, which has to be replaced by Lee's estimate in case of Rayleigh channels:

$$\eta = \log_2 C * C^{-\frac{1}{\gamma}} (-E + \ln \gamma + \frac{1}{\gamma})$$
 (4-2-1-3)

Where $E \approx 0.577$ is the Euler constant. An evaluation in [52] displays a 32% channel capacity reduction in comparison to the Gaussian channel at an SNR of 10 dB.

In a cellular re-use structure the effect of co-channel interference must be included in the channel capacity estimate. Hence the definition of γ in Equations (4-2-1-1) to (4-2-1-3) must be modified by replacing the SNR by the signal to noise-plus-interference ratio (SINR). The SINR is defined below in Equation (4-2-1-4), where S is the received signal power, I is the received interference power and N is the AWGN power within the channel's bandwidth:

$$\gamma = \frac{S}{I+N} \tag{4-2-1-4}$$

Therefore the normalised channel capacity for a band-limited, interference-contaminated Gaussian channel is defined in Equation (4-2-1-5):

$$\eta = \frac{c}{B} = \log_2(\frac{S + I + N}{I + N}) \tag{4-2-1-5}$$

In a noise-limited radio system without power-control one would expect the SINR to reduce with distance from the transmitter, when using an omnidirectional aerial. However, in an interference-limited system the pattern of SINR is less regular.

4.3 Algorithm Realization

4.3.1 Choosing an Optimisation Algorithm

Traditional optimisation algorithms thrived since long time ago because many important problems in real life involve the choice of a best goal or choosing some kinds of parameters and values to realise the goal. These problems can all be concluded as optimisation problems. An optimisation problem consists of several elements like the solution space and solution restriction and is focused on finding a minimum or maximum value. And because maximum value can be converted to minimum value so they are identical in essence. To deal with nonlinear problems, people used linear optimisation theory at the very beginning, but the result is not satisfactory. Afterwards, nonlinear problems are mostly based on quadratic function. Quadratic functions are used to approach other nonlinear functions. Many classic optimisation algorithms are proposed based on this, including some non-constrained optimisation algorithms like steepest, Newton Algorithm and some constrained algorithms like Augmented Lagrangian Algorithms and SQP.

As the development of the society, practical problems became more and more complicated, like global optimisation problems. Most of the classic algorithms use local information like the differential coefficient at certain point to solve problems. This makes classic algorithms unable to avoid the problem of local optimisation. In another word, most of the classic algorithms can only find the minimum value in local but unable to find the minimum value in global. On the other hand, global optimisation problem is an NP-Hard problem. In polynomial time, the absolute optimisation value cannot be obtained anymore. Strategies should be taken to get approximated optimisation solution in acceptable time. The original classic algorithm should be improved or combined with heuristic algorithm. Heuristic algorithms are those which are based on experience or perceptual intuition. It can work out an approximated optimisation solution in duration of time and with cost that is acceptable. However, the deviation of the solution with the real optimisation solution is hard to calculate or we can say, it is hard to elaborate the degree of similarity between two solutions. In the 1970s, Holland proposed Genetic Algorithm based on the biological evolution on earth. And in the 1980s, Simulated Annealing Algorithm, Artificial Neural Network and Tabu Search occurred one after one. At the beginning of the 21 century, Evolutionary Algorithm, Ant Algorithm and many new algorithms thrived to reach the high ride of researching on heuristic algorithm. Because of the efficiency and simplicity of these algorithms, they became an important bridge between scientific calculation and human being. Genetic Algorithm simulates the procedure of choice, intersection and variation of gene chromosomes in which individuals with better gene have a high chance to survive. Artificial Neural Network simulates the neural processing procedure of human brain. By associating the competence and collaboration of neurones, it realises the process of choice and variation. Tabu Search simulates the experience of person. By searching the history information in the Tabu table to avoid the road back and jump out of the local optimisation solution. Ant Algorithm simulates the collective behaviour of ants and contributes a lot to problems concerned about shortest routine. Though all of these algorithms are optimisation algorithms, they have their own characteristic and preferred applicable situations too.

The purpose of the thesis in this phase is to evaluate the capacity factor for an indoor wireless communication system. Variables are designed according to content in previous chapters. Some of these variables are continuous, like the room size, thickness of wall, door position and window size. Some of the variables are discrete, like the material of the wall. Each material maps a parameter and these parameters are discrete. The mentioned variables do not compose the final version set of variables because some of them may be taken as constant ultimately by extra consideration and extra variables can be introduced too. All of the plans of choosing variables take the real case into vital consideration.

One of the main characteristics of Genetic Algorithm is its outstanding performance in dealing with discrete variables. When talking about continuous variables, discrete values should be sampled from continuous value to be applied to Genetic Algorithm. The density of sampling determines part of the accuracy of the optimised result so we do not take Genetic Algorithm as the most applicable algorithm in this thesis and put it aside temporarily. Though in literature review, the optimal deployment of Wi-Fi wireless access point using genetic algorithm was mentioned. Because of the discrete characteristic talked about before, the essay divided the area into 180*180 small squares. The precision of dividing the targeted area directly determines the precision of optimised result. It is worth attempting using genetic algorithm in this thesis too. However, because of the better continuity of simulated annealing algorithm, genetic algorithm is placed in a lower priority. Artificial Neural Network is based on the principle of learning. By learning, the chance of making mistake in the next movement decreases. It is mainly used in realms related to biology and psychology, or in realms that related to artificial intelligence because learning process is one of the main characteristics. In this thesis, learning feature is not remarkable and it has no biological property so we focus on the next possible solution. Tabu Search is an algorithm targeted mainly on avoiding local optimal solution as it is indicated by its name. It has a table to record the local optimal solutions which have already arrived and chooses not to search these points anymore. It is an algorithm that worth trying in this thesis. Ant Algorithm, on the other hand, is somewhat similar to Artificial Neural Network because it is also about learning. The experience of ants in the front provides information for the ants behind to help them find a more close way. The learning process is realised in group and Ant Algorithm is mainly used to solve the shortest routine problems. There are various other algorithms that may be applicable to the problem in this thesis and the negative evaluation given to some of the above algorithms does not mean they are not possibly used in this thesis. They are only given a rough evaluation and the comprehension to the algorithms by me may lead to some deviation of the actual function of them. What's more, they may have unexpected effect after small improvement.

4.3.2 Simulated Annealing algorithm

Simulated Annealing algorithm is a heuristic algorithm that came from the principle of solid annealing. When the solid goes through the procedure of heated to certain temperature and calmed down slowly, the particles in the solid becomes out of order and the internal energy becomes larger because of the rising temperature while particles become in order again and internal energy drops to the lowest in the cooling. The cooling procedure has a great similarity with optimisation problems. It starts with a high temperature and the global optimal solution is being searched combined the

probabilistic jumping property and continuous dropping of the temperature parameters. This material is subjected to high temperature and then gradually cooled. The gradual cooling allows the material to get into a state in which there are few weak points. It achieves a kind of global optimum wherein the entire object achieves a minimum energy structure. If the material is rapidly cooled, some parts of the object are easily broken (areas of high energy structure). With rapid cooling, the object has achieved some local areas of optimal strength but is not strong throughout. The simulated annealing is derived from the physical heating of a material. It is a random searching for optimisation algorithm based on Monte-Carlo iteration for solution. This method can successfully jump out of the local optimum and finally verge to the global optimal value. It was used in the realm in combination optimisation by Kirkpatrick first. Now it already has a wide application in realms like VLSI, control engineering, machine learning, signal processing and so on.

To give a more clear explanation of annealing algorithm, another algorithm Hill Climbing is introduced to be used as comparison. As the name indicated, Hill Climbing is a simple greedy algorithm. It chose the optimisation solution in the adjacent solution space of current solution as the new current solution until it gets a local optimisation value. It is just like that a rabbit that is climbing the mountain always goes into the direction that is higher than its position. Finally, it will come to place that is the highest nearby, but it cannot promise that it is the highest place in the world. On the contrary, annealing algorithm introduces the element of random though it is also a greedy algorithm. It accepts certain possibility of a worse solution compared with the current solution. In this way, it has the chance to jump out of the local optimum and reaches the global optimum. It is just like that the rabbit is drunk and jumps randomly during a long time. In this period, it jumps to higher place or lower. However, it gradually becomes sober and jumps to the highest mountain top.

In [30], the professional definition and plain explanation of annealing algorithm have been presented and then, a concise description of the algorithm using math expression will be given.

If $J(Y(i+1)) \ge J(Y(i))$ accept the move.

If J(Y(i + 1)) < J(Y(i)) accept the move in certain possibility and the value of possibility decreases as the time going.

Where J is the targeted value and is the function of Y which is needed to be optimised. Here, we define that the larger of it, the better.

The certain possibility here takes the reference of metal annealing procedure and it is also one of the reasons for the name of the algorithm. When the temperature is high, the possibility of temperature dropping is high and when the temperature is low, the possibility of temperature dropping is low. The possibility is always between 0 and 1. In practical, the movement towards a worse value is taken as a procedure that the temperature jumps to another level and this movement is accepted in a changeable possibility which is indicated before.

In the indoor wireless communication thesis, annealing algorithm is applicable. The values that need to be optimised are coverage factor and capacity factor. They are equalised to the height of mountain in the example of rabbit and the temperature in the metal cooling. Taking the capacity factor as an

example, the SINR changes as the elements like the thickness of wall and door position change. Only if the function relationship is not linear, the optimisation cannot be implemented by Hill Climbing algorithm. Taking the condition that SINR is affected by multiple factors generalised in last chapter into consideration, annealing algorithm is necessary and suitable to be used here. When the multiple possible affecting factors are changing together in small steps, the worse SINR in the neighbourhood of current value should be accepted in certain possibility to ensure the avoidance of stuck in local optimal SINR. As the current value approaching the final value, the possibility of acceptance of worse neighbour should be set lower and lower. SINR will gradually be optimised in the global scale. The coverage factor can be optimised by the same way too.

4.4 Optimisation of Capacity factor

4.4.1 Distinctive Perspective

In the part of optimisation of capacity factor, a distinctive series of steps are adopted to finish the optimisation. In an optimisation process, the first thing needs to be confirmed is which parameter is constant value and which is variable. At the previous chapter of this thesis, the focus of the research is determined to be building structure and the source deployment is considered as a lower priority here because there are large amounts of research on it and considering both the building structure and the source deployment is too complicated to analyse. In the optimisation part of this thesis, another way is used. The simulated annealing algorithm is applied to optimise the source deployment and then with the optimised source deployment scheme, the SINR of the building is calculated; after that, the building structure will be changed and a new optimised source deployment scheme will be calculated again for the new structure, and a new SINR for the changed building will be calculated. After enough data gathered, the analyse for the variety of SINRs will be given.

One of the main advantages of this method is that more parameters can be considered into the list of which can affect the SINR, mostly are those discrete parameters like material of wall. In regular optimisation process, the variables need to be continuous so the adjacent situations can be compared with the current solution to find a potentially better solution. In this case, discrete parameters cannot be simulated. For walls of glass, concrete, wood or other materials, the signal propagation characteristic of them can be evaluated by penetration loss. However, not all the penetration loss value derived after optimisation exists in real life. For example, the penetration loss of glass is 2dB and the penetration loss of concrete is 13-20 dB. Assuming that there is no other material that has a penetration loss value between them, if the optimised value of penetration loss is 0 dB, no corresponding material can be reflected, so the result is useless because it does not exist in real life and it is either hard to tell whether glass or concrete is more close to the optimal situation.

Another advantage of this method is that it avoids many extreme situations. Unlike coverage factor, SINR can be derived by path loss of targeted point minus sum of path loss of other sources. The interference from other sources is decreased when the thickness of wall is increased. In another word, the change tendency of coverage factor is monotonic because it is only affected by path loss of

targeted point while the change tendency of capacity factor is varied and uncertain because the path loss of targeted point and sum of path loss of another point jointly affects the result.

It is worth mentioning that using this method the optimisation process will be conducted several times. Luckily, for discrete variables the total amount of value is finite so the simulation can be done in finite time. The detailed optimisation process using this method will be introduced in the form of flow chart below.

4.4.2 Flow Chart and Illustration

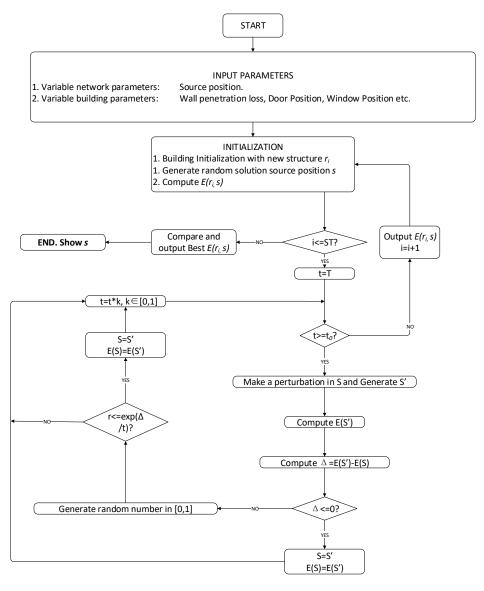


Fig. 4-4-1 Simulated Annealing Algorithm Process Programming

The flow chart of processing Simulated Annealing algorithm is displayed in Fig 4-4-1. Here is the brief explanation of the flow of the program. Capacity factor is optimised during this process using simulated annealing algorithm.

First of all, input parameters are being inputted. The variable related to network parameters is mainly source position and the variables related to building parameters are wall penetration loss, door position, window position and so on.

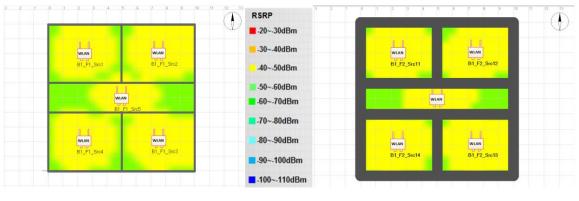
The initialization is the second part of the whole model. It sets the initial values and generates random solution source positions. The architecture models that needed to be compared are r_i . For example, we set 20 models in which the attenuation value of wall varies from 20dB to 1dB, so we have 20 models. $E(r_i, s)$ represents the present solution which is solved from the present source position and structure of the wall, which is also called SINR as we talked before, where r represents different models and i represents which model is it. s represents the position of signal source.

The condition of comparison " $i \leq ST$?" represents the judgment of whether the tests to all the models have been finished. If i has reached the exit value ST, the deployment with best SINR is compared and output. "t = T" means that the initial temperature of simulated annealing algorithm is T. The condition of comparison " $t \geq t_0$?" represents the judgment that whether the cooling temperature has been achieved. If it is the case, the simulated annealing algorithm goes back to the upper class and output the optimal value in current structure.

"Make a perturbation in S and Generate S'" is the procedure of forging. In this process, the current signal source position is swayed and the new adjacent solution is being calculated. "Compute Δ = E(S') - E(S)" is used to calculate which of the current solution and the new solution is better. $\Delta >$ 0 means that the new solution is better, so the old solution is replaced by the new solution. At the same time, the temperature is cooled into a new value using the expression t = t * k. k is a constant value between 0 and 1. A larger k is corresponding to a slower speed of cooling and a better chance of getting the optimal value. At the same time, the speed of calculation will also be slowed down. The cooling speed is faster if the value of k is small and the calculation will be correspondingly faster, but the possibility of entrapping into the local optimal value will be larger. If $\Delta \leq 0$, the current solution will be replaced with a chance of $exp(\Delta/t)$. $\Delta \leq 0$ means that the new solution is not better than the current solution, but there is still a chance to accept the new solution. The purpose of it is jumping out of the local optimal value which has been introduced before. The value of $exp(\Delta/t)$ will be larger if the initial temperature is set to be higher and the Δ is smaller and at this time, the chance of replacing the old solution with a worse new solution will be larger. As the cooling procedure going on, this chance will be smaller and smaller and the solution will approach the value of optimised value.

Finally, when the final temperature is the same with t_0 , $E(r_i, s)$ is being output as the optimal value in current situation. The value of i is added with 1 and the next group of building architecture is being calculated and optimised.

4.4.3 First Model: All Rooms with Source



(a) Rooms with wall penetration 2dB

(b) Rooms with wall penetration 20dB

Fig. 4-4-2 Optimisation of the Model All Rooms with Sources

Modelling

The first simulated model is a simple office floor plan. All the rooms are occupied with signal source according to the necessity of communication. It is a common structure in real life because in regular office building or some other places that have a high necessity of wireless communication system, signal sources are deployed in each room. The optimisation is realised by using the simulated annealing algorithm.

The flow of program is described as followed: First of all, set the parameters of the rooms and the walls. Then the initial sources are deployed randomly. In the third step, the simulated annealing algorithm is used to optimise the position of sources to get an optimal capacity factor. In this optimised situation, the average SINR and capacity factor in the room are calculated. After this, the building structure is changed and the first step is repeated. At last, the average SINR of different building structure is compared and the optimised result is derived.

The parameters of simulation environments are provided as follows:

- 1) FDD-LTE 2.6GHz with 20MHz bandwidth
- 2) Channel 2 used in cells with centre frequency of 2670MHz
- 3) Source position height: 1.5m. Transmitter power: 33dBm, gain: 0dBi
- 4) User equipment (receiver) height: 1.5m, sensitivity: -106dBm
- 5) Wall material: concrete. Highest wall penetration loss: 20dB; Lowest wall penetration loss: 1dB.
- 6) Room size: 5x4m; Corridor size: 10x2m.

Simulation Results

Fig. 4-4-3 shows the simulation results using iBuildNet®. When the thickness of office wall becomes larger, the interference signal and targeted signal are supposed to be affected both. However, the result seems to be monotonic.

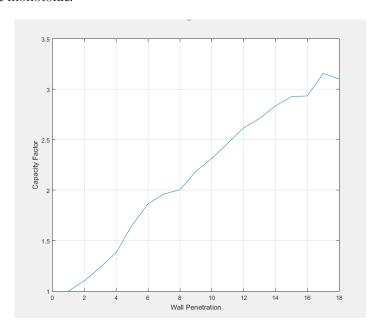


Fig. 4-4-3 Simulation results of Capacity factor

The size of each room is 5*4 (meter), and the corridor is 10*2 (meter), The X-coordinate is the wall penetration loss. It is a property of wall and the value increases with the thickness of wall increases. The Y-coordinate is the capacity factor which is decided by the average SINR. The result shows that when the wall penetration loss increases, which also means that the wall is thicker, the corresponding average SINR becomes larger too. The monotonic relationship deviates from the anticipation. However, after careful consideration, the simulation result is reasonable. When all the rooms are occupied with signal source, the targeted signal in each room is not influenced by the thickness of wall in large degree because the targeted signal in this model does not need to penetrate wall to get to targeted areas. On the other hand, as the interference of one of the room, signal sources from other rooms are obstructed by the wall. When the thickness of wall becomes larger, the obstruction effect becomes more noticeable and the interference effect becomes lighter. In this way, the proportion of signal and interference becomes larger and the SINR becomes more optimal. If not all the rooms are occupied with sources, it can be entirely different, and it is one of the situations that will be discussed in 4.4.4.

Summary

The proportion of signal and interference becomes larger and the SINR becomes more optimal when the thickness of wall is larger.

4.4.4 Second Model: Source on Corridor Shared by Classrooms

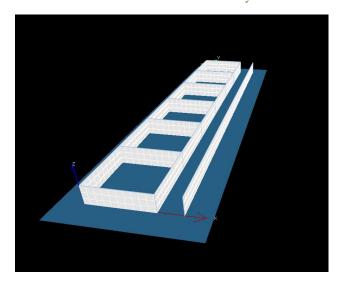


Fig. 4-4-4 3D version of model Source on Corridor Shared by Classrooms

Modelling

This model contains one corridor and several cascaded classrooms. The size of each room is 10*10 (meter), and the corridor is 60*4 (meter) It is a simplified version compared to the version in chapter 3. It is chosen as a typical environment here to finish the optimisation because it is a common building structure which is often used in dormitory building, office building and classroom building. What's more, the characteristic of each room with a signal source has been simulated and analysed, so it is necessary to focus on a model with signal source outside the room. In this model, a source is shared by two classrooms so the optimisation of source positions is extremely necessary.

The parameters of simulation environments are provided as follows:

- 1) FDD-LTE 2.6GHz with 20MHz bandwidth
- 2) Channel 2 used in cells with centre frequency of 2670MHz
- 3) Source position height: 1.5m. Transmitter power: 33dBm, gain: 0dBi
- 4) User equipment (receiver) height: 1.5m, sensitivity: -106dBm
- 5) Wall material: concrete. Highest wall penetration loss: 20dB; Lowest wall penetration loss: 1dB.
- 6) Room size: 10x10m; Corridor size: 4x60m.

Simulation Results

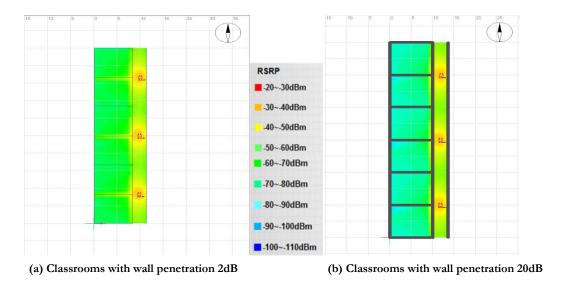


Fig. 4-4-5 Simulation Result of wall with 10dB and 20dB attenuation value

The above figure is the simulation result of model with different thickness of walls. The situation on the left is when the wall attenuation value is set to be 10dB and the situation on the right is when the wall attenuation value is set to be 20dB. The relationship between average SINR and wall penetration loss is shown.

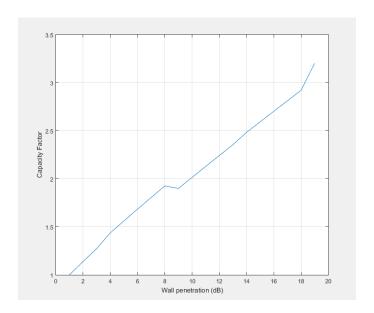


Fig. 4-4-6 Relationship between Average SINR and Wall Penetration Loss

The relationship is still close to being monotonic. Capacity factor increases with the average SINR as the wall penetration loss increases. There is an abnormal point when the wall penetration reached 9dB, which the capacity factor decreased slightly. After checking the data generation process, it is

found that the optimisation process of source deployment has not reached the optimise position before the annealing algorithm stopped, which is rare to happen but normal due to the small chance that the algorithm cannot reach the optimise position. Therefore, the point does not affect the overall tendency.

This phenomenon does not conform with the expectation again but can be explained from an aspect. Since the optimisation algorithm optimises the source positions, which is also called the distribution of the signal source, the number of wall going through is minimised and the final received power is maximised. In this situation, the accepted signal is optimised. On the other hand, when the wall thickness is larger, the interference will be affected to a larger degree than the targeted signal because propagation of targeted signal is optimised while the propagation of the interferential signal is not optimised. In addition, the target signal source only goes through one wall, and interference sources go across multiple walls, therefore, the thicker of the walls, the smaller the interferences of the other source are. From this prospective, the SINR then will only be better when the wall is thicker. This explains the unanticipated result and shows that it is reasonable.

Summary

The average SINR is optimised when the wall penetration loss is larger. The wall penetration loss is a function of both the wall thickness and the material.

Besides the above simulation results and analysis, there are two considerations that need to mention: Firstly, all the SINR got before is the average SINR and this average SINR is calculated by adding all the SINR value of 100 random points in the room and divides the sum by 100. This is not scientific to some degree because the average value may not precisely present the SINR in the room and randomly picking up points can lead to uncertainty. In the next step, the distribution of the 100 SINR will be shown and analysed to make further conclusion. Secondly, one thing that can be sure of is that the interference becomes lighter as the thickness of wall becomes larger. Other elements like the door position and window position may not have a monotonic effect like this and will be discussed in the following sections.

4.4.5 Distribution of SINR

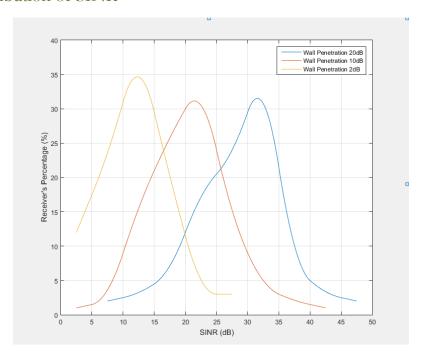


Fig. 4-4-7 Distribution of Value of SINR in the Model

The size of the room is 5*4 meters, and the transmission power of each signal source are 33dBm, The X-coordinate is the SINR of receivers. The Y-coordinate is the percentage that how many receivers are in the area of different SINR values. As mentioned before, the way to calculate SINR is to use the average value of which randomly selected from positions in the room. It is not very scientific actually because of the following reasons. Firstly, the selected points are randomly selected so the representativeness is worth a doubt. However, when the number of selected points is large enough, it will not be a problem anymore. Secondly, the average cannot describe all the characteristic and performance of SINR. This point is also what I want to mainly discuss. In math problems, there are many specifications to measure the characteristic of a group of values. Average value, median, mode and variance are all included. In this problem, the SINR can only be thoroughly conducted if its distribution is achieved, by which we can achieve average value, median, mode, variance and so on to comprehensively conduct the characteristic of SINR.

The above figure is the distribution of SINR by randomly receiving signal in different positions in the room under three circumstances of building structure. In these three building types, the attenuation values of wall are respectively 2dB, 10dB and 20dB. The reflective relationship has been shown in the legend of the figure.

According to our cognition that the scale of value in the middle area is larger. The overall distribution is similar to the Normal Distribution but because of the complexity of the building structure, it is not exactly the same with Normal Distribution. It can be clearly seen from the figure that the curve of SINR integrally moves to the right when the thickness of wall is getting larger. That means the overall SINR is larger and the signal received by users has a better quality.

It is easy to draw a conclusion here because the shapes of the distribution of SINR in these three situations are similar while the curve of one with a penetration of 20dB is integrally on the right so it is the optimised situation. However, it is not always the case. Imagine two curves that one of them mainly owns a small SINR value but the distribution is concentrated while another has an overall larger SINR value but the distribution of it is scattered and in some extreme low value of SINR, the percentage even exceeds the previous situation. It is hard to tell which has a better capacity performance now. In this first case, the SINR is stable while the overall value is not much satisfactory while in the second case, dead end of wireless communication exists even most areas in it have a satisfactory performance. It is worth mentioning that in the first chapter, the introduction of femtocell, the judgement "How to distribute the signal in largest degree and in most even way in every place in the indoor system is a key point in optimisation" is made, which means that intensity of SINR is no less important than the average value of it. Intensity can ensure the stability of wireless communication service so variance is in great necessity imported here to balance the consideration of average value and centralization, or we can say that the distribution of SINR is the one can comprehensively measure the performance instead of a single value of average or variance.

The purpose of elaborating the importance of distribution of SINR is directly associated with the method used in optimisation. As mentioned in the beginning of optimisation of capacity factor, the distinctive perspective determines that the optimisation of source deployment is used first then the optimisation of building structure is conducted. Besides the reason talked about before, the following consideration is vital too. It is not possible for all the variables that need to be taken into consideration to be included in the algorithm. In common optimisation problems, the metric that needed to be optimised is always a quantitative value. In this case, however, every time the variables change, one curve is drawn. There will be thousands of curves overlapping together so it is hard to observe and analyse. Because of this consideration, thousands of combination of variables can be simulated to analyse the average value of SINR while only a few cases can be drawn on the same figure to do the analysis of SINR distribution, so one variable will be considered at one time.

From the evaluation of chapter 3, the capacity factor of received signal can be affected by the door position, the attenuation of walls and the position and width of windows. In one optimisation process, 3 to 5 improved model will be realised. They are different from each other in various aspects like the door position, the attenuation of walls and the position and width of windows. Different combination of variables will be considered to analyse the overall tendency. The distribution of SINR will be drawn and the SINR will be analysed integrally. For example, a conclusion like the distribution of SINR is optimal when the wall is thicker, window is larger, door is wider and in the centre of the wall will be achieved.

4.5 Summary

The second metric capacity factor is introduced in this chapter and thoroughly analysed. All of the simulations are based on the premise of optimisation of signal source. This method enables a more proper environment for the optimisation of SINR and combines the research of source deployment and building structure. The relationship between SINR and capacity factor is clarified firstly. Then

two models are set up to do the simulation. One is a model in which all rooms are deployed a signal source and the other is a model in which several rooms share a source and the source is in the corridor. Both of the simulation results show that the thickness of wall has a positive effect on the capacity performance of building, which is different from the conclusion drawn when evaluating the effect on coverage rate. The reason for the difference is that signals from other sources are taken as interference when calculating capacity factor while it is not this situation when calculating capacity. Thick walls are able to block interference and enhance the performance of SINR. Last but not least, the defect of using the average SINR as the optimising goal is elaborated and the distribution of SINR is introduced to the assist demonstration and the same conclusion is made.

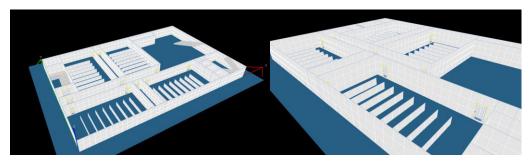
Chapter 5 Practical Application of the Model

In real cases, the indoor wireless communication system is still in developing stage compared to outdoor wireless communication system. On the other hand, it is a much more promising research topic because it stands on the initial stage of development. Models in previous chapters are simplified and still have same differences compared to real cases. The condition of real indoor wireless communication varies by cases. Office buildings, airports and classrooms are typical successful cases in indoor wireless communication. The structures of them are designed to fully consider the signal propagation performance because of necessity. And parking garage and cinemas are typical cases in which wireless communication does not work well, even always out of use. This chapter will discuss the typical real examples of indoor wireless communication and comprehensively analyse the reason for them to be good or not.

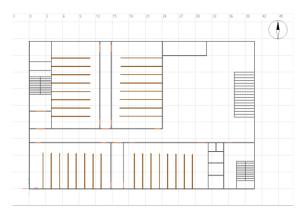
5.1 Case Study 1: indoor wireless communication system in cinema

Most people have the experience of using mobile phone in the cinema. In most cinemas, signal from femtocell is very weak and in most cases a long time will be taken to connect to the network. "Connecting" will always show on the top of phone. Sometimes this will be extremely inconvenient because most people need to deal with personal affairs even when they are in entertainment places like cinema. Considering about the reason for it, the following several explanations can be counted on. Firstly, the cinema itself is designed to be a place that takes audience' concentration on the movie as granted. Blockers are common in cinemas to block the signal from transmitters and help audience concentrate. And because of the low necessity of using phone in cinema, the sources deployed in cinemas are extremely few. Because of the large room space and the lack of sources, the coverage rate and the capacity of signals in cinema become both unsatisfactory.

The model of a typical cinema is shown as below. It is composed of several rooms. In this case, the number of room is set to be four. Each room has two doors and the seats in them are modelled as wooden wall which is 1 meter high. Sources are not deployed in each room because of the consideration of the necessity of concentration for audience as discussed before. In this model, the only two sources are deployed at the left end of the corridor and in front of the counter bar as shown in Fig. 5-1-2.



(a) Three-dimensional model of a cinema



(b) Plane model of a cinema

Fig. 5-1-1 Model of a Typical Cinema

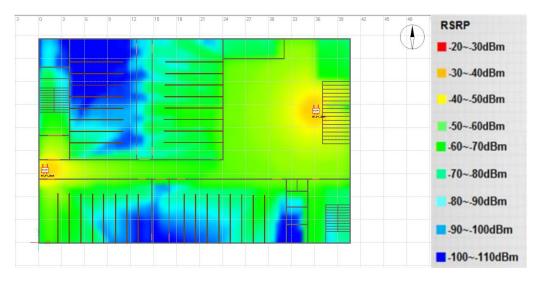


Fig. 5-1-2 Simulation result in a Typical Cinema

The result is obvious. The coverage rate in a typical cinema is not satisfactory. Except for the room on the top right, the network systems in other rooms are almost out of use. If there are extra blockers, the result will be even worse. The figure clearly shows that how the structure of building and deployment of rooms can affect the wireless communication system negatively.

Admittedly, the bad performance of wireless communication is not only affected by the building structure or material but also by the source deployment, especially in this case in which number of sources is cut down on purpose to weaken the signal. However, even with the same number and position of sources, the arrangement of rooms also contributes to the final purpose of cutting down signals. Taking the room on the left top as an example, the long and narrow space on its left side plays an important role in blocking the signal from the source at the left end of the corridor. Even the room is close to the source, the performance of the wireless communication in it is the worst of the four.

Many similar buildings of cinema can be found. The deployment of signal sources and the arrangement of rooms may vary. But the performance of wireless communication system is unsatisfactory universally. They may have common points in building structure or source deployment and at the same time they each have their own characteristic. An optimisation part will be unnecessary here because cinemas are designed to be in this way.

In the above case, the material of the wall is chosen to be the most common type of concrete. The Attenuation Value is 13dB. The attenuation value is one of the most official standards to measure the penetration performance of material and the attenuation value here is used for reference to analyse the coverage factor of each situation.

Other two materials are used here to do the simulation. One is another kind of concrete whose attenuation value is 20dB and one is an all-glass wall whose attenuation value is only 2dB, which means the loss through the signal propagation is very little. The below two figures are the simulation results of the two situations. In cinema with concrete wall whose attenuation value is 2dB, the coverage factor is similar to the previous 13dB concrete wall and in cinema with all-glass wall whose attenuation value is 2 dB, the performance improves a lot. In a cinema with a wall that has 13dB or more attenuation value, the attenuation value is not in the dominant place. In spaces that are open to the signal sources, the wall material has no chance to interfere in the signal propagation. In space that is separated with signal source by the wall, the type of concrete still has some influence on the coverage rate. On the other hand, in the case that the concrete wall is all glass and with an attenuation value of 2dB, the simulation result is entirely different. As we can see, the dark blue area totally turned into green. It matches with our direct feeling. In offices, glass is used often as the main material to divide rooms instead of concrete because of its excellence performance both in propagating wireless signals and blocking sound. Cinema will not adopt this kind of material because of its necessity of blocking the light and sound.

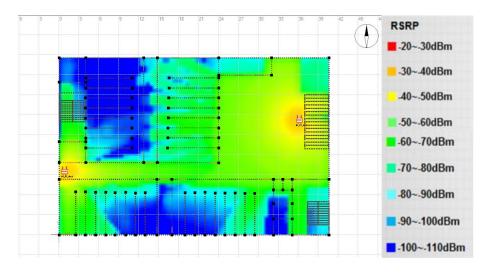


Fig. 5-1-3 Simulation results in Cinema with concrete wall with 20dB attenuation value

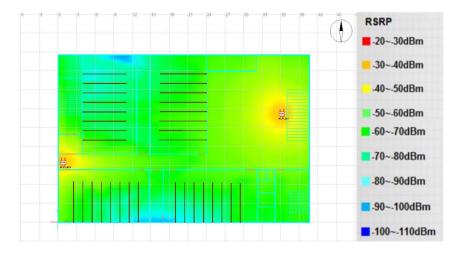


Fig. 5-1-4 Simulation results in Cinema with all-glass wall with 2dB attenuation value

5.2 Case Study 2: indoor wireless communication system in office building

Most of the business of indoor wireless communication happens in office buildings, and it is necessary to conduct a thorough research on these places to determine factors that make their communication system outstanding and find out ways to do further optimisation.

Here, office building is used as the example to do the case study. The following figures are a 3D version of a typical office building and its floor plan which can tell the distribution of rooms and other facilities. There are mainly four large rooms on this floor. Doors are set in each office in the corner and windows are deployed in the surrounding of the whole building. In the middle, there are stairs and elevators. The model uses a real office floor plan as a reference and this ensures that the model in the thesis is close to the real situation. This is an improved version compared to the simple office model in chapter 4 and it is much more close to the situation in real life.

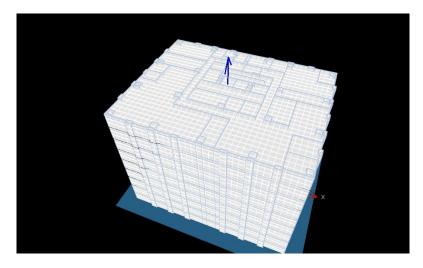


Fig. 5-2-1 3D Model of a Typical Office Building

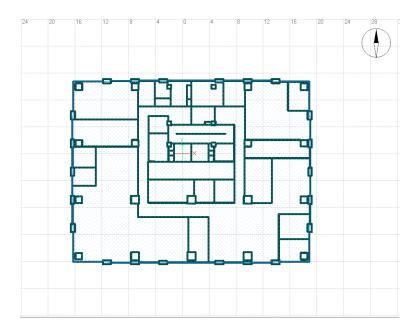


Fig. 5-2-2 Floor Plan of ah Typical Office Building

After the deployment of four signal sources respectively in the centre of four main rooms, the result of coverage rate of the building can be clearly seen in Fig. 5-2-3. According to the assumption, the intensity of signal in the centre of the four large rooms is strongest and decreases in the farther places. The intensity of signal in small rooms which do not have sources deployed is normally and stable.

In this model, signal sources, windows and doors are all fixed. The only variable is set to be the thickness of wall. Wall is served as the main part in this model because nearly all rooms are separated mainly by walls. The doors are already set in minimum sizes so even the sizes of doors are changeable, no worse case exists. In the simulation, the thickness of wall is changed solely to see the change of coverage rate of the signal.

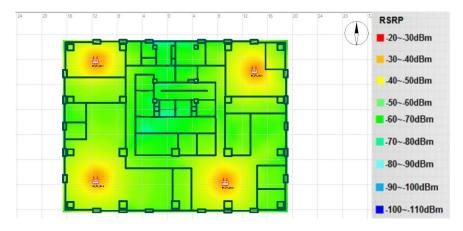


Fig. 5-2-3 Simulation Result of a Typical Office Building

Two extreme conditions are shown in Fig. 5-2-4. In Fig. 5-2-4(a), the thickness of the wall is set to be 0.1m and the thickness of the wall in Fig. 5-2-4(b) is set to be 1m. In the first case, the coverage rate has no big difference compared to the default case before. It is because in the default case, walls are already thin enough for signal to go through. In the second case, striking differences appear. Not only are the rooms without sources completely out of service, the rooms with sources in them perform unsatisfactorily too. The thick wall blocks the signal from propagating to rooms nearby and at the same time, make the room where it is in shielded by the wall.

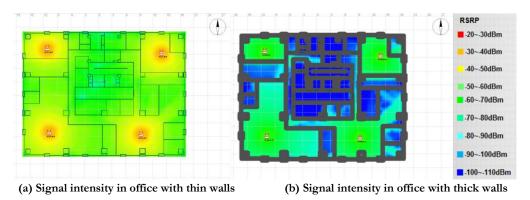


Fig. 5-2-4 Changing the wall thickness of a Typical Office Building

The curve of coverage factor is shown below. With the increasing wall thickness, the coverage factor becomes larger, which also means that coverage rate becomes smaller. And we can also see the detail that on the bottom of the left side of the figure. When the wall thickness is small enough, the coverage factor is not affected by the wall thickness much. It also matches with the simulation result in the floor plan before.

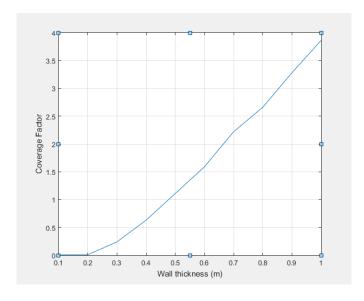


Fig. 5-2-5 Coverage Factor with Changing Wall Thickness

5.3 Summary

In the two models which are respectively in the environment of a cinema and the office building, the simulation results show a consistency. When the wall is thicker or the attenuation value is larger when using a different material, the overall SINR is better while the coverage rate decreases in a large degree. When the thickness of wall is smaller or the attenuation value is smaller when using the material like the glass, the value of coverage rate is more optimal while the interference from another signal source is similar to interfere under free space, the corresponding capacity rate is not satisfactory under this situation. Therefore, the design of building structure should consider both of the metrics, like the demand for coverage rate to achieve a value of 95%. It is not realistic to optimise one metric on the basis of sacrificing another. Further considerations of designing a synthetical metric will also be introduced in chapter 6.

The case study in this chapter is a kind of extension and supplement to the previous chapters. Simple models simulated in previous chapters are somewhat digressed from the real life because the structures are simplified in large degree. In this chapter, the complex distributions of rooms and other entities in the floor plan are all adopted from cases in real life. This makes the research show more direct value in real and it also proves that the modelling method used in the research can be easily applied to more complex cases. The continuity can be seen from this perspective. Certain elements that will affect the metrics are conducted further simulation in this chapter, like the thickness and material of the wall, because in a more complex environment, the effect of these elements is more noticeable. In chapter 3, the compared results of the simulation of material and thickness of wall in a single room in the simple model have little difference that one is hardly to tell or unable to draw decided conclusion from the result. In real cases, the noticeable difference makes the conclusion before more convincing and it is directly perceived.

Chapter 6 Conclusion and Future Work

The simulations for the evaluation and optimisation are complete in the 3-5 chapters, and results of those have been analysed at the end of each chapter. The main content of this chapter is to generate the conclusion of this thesis, and present the deficiency in definition, demonstration and evaluation which can be improved in the future work.

6.1 Conclusion

This thesis has designed two metrics: coverage factor and capacity factor, for the purpose of evaluating and optimising wireless communication performance for typical buildings. After the definition, several simulations are presented to reveal that the two metrics can be used in the evaluation and optimisation for building structure. Simulation results for different metrics are analysed and concluded in chapter 3 and 4, and two typical buildings have been discussed in chapter 5 to reveal the future possibility for using the metrics in optimising building structures. As a conclusion, coverage factor and capacity factor can provide reliable results in the evaluation of communication performance for indoor environment.

6.2 Future Work

There are still several deficiencies in the thesis due to the lack of time. There are three parts that can still be improved as follows.

6.2.1 Deficiency in Definition

The main definitions in this thesis are the two metrics, coverage factor and capacity factor. These metrics have been proved to have the ability to efficiently reflect the quality of indoor wireless communication system while the following things are worth considering: is there a chance that a second definition can be applied to the metrics or is there a third metric that should be taken into consideration? The coverage factor is the function of coverage rate. It is directly affected by the distance between transmitter and receiver, and the signal frequency. However, there exists the chance that other factors have the influence on this metric too, like the altitude difference though clarification has made before. There may be other factors that have been left out and caused inaccuracy between the simulation results and manual calculation. From this perspective, a third metric may be necessary to be introduced to make the evaluation of indoor wireless communication system more complete.

6.2.2 Deficiency in Demonstration

In this part, the major reflection is made on the selection of algorithm.

The annealing algorithm used in the optimisation of capacity factor is a famous algorithm used in problems of optimisation. There are plenty of evidence to prove its efficiency and accuracy. The calculation process for simulated annealing algorithm is simple and it is widely applied in various kinds of topic without restriction. So it can be applied to solve complicated nonlinear optimisation problem. However, to make the optimisation more convincing, certain amounts of the demonstration of the validity of annealing algorithm are necessary too. After all, the simulated annealing algorithm has some known defects. Its velocity of convergence is slow and the execution time is long. This matches the experience during the simulation. Sometimes the performance of simulated annealing algorithm has a close relationship with the initial value. This characteristic determines that this algorithm is sensitive to the parameter and the sensitivity may cause inaccuracy because of small deviation of initial values or environmental parameters.

What's more, the literature review part has also indicated that there are dozens of algorithms used in optimisation problems in this realm in previous researches. Each of the algorithms has its distinguishing feature and more than half of them can be applied in this thesis as well because of the similarity of the thesis and previous researches. Actually, if there is enough time left for me, I would like to try some of the other algorithms used for optimisation problems and use the consistency of results in different algorithms to validate the reliability of my conclusion.

6.2.3 Deficiency in Evaluation

Reliability of Data

In the modelling and analysis procedure in chapter 3 and chapter 4, most parameters are fixed in the model for simulations. Some of the parameters are determined by referencing the literature or technical book in real building structures and some of the parameters are set only by experience. The reliability of data is doubtful. Even the data is derived from literature and technical book, the similarity of environment should be evaluated before the data is directly copied from those cases. In real engineering thesis, the premise proposed in defining the model and the fixed parameters all have the chance to change. The simulation results after the alteration of them may have a big difference between before. From this prospective, the reliability of these data should be further analysed if possible.

A synthetical metric

The two metrics, coverage factor and capacity factor are considered separately in this thesis. There is a chance that the following condition will be met: under a certain condition the coverage factor is more optimal and in the other case the capacity factor is more optimal when the two cases are compared with each other. It is hard to draw conclusion on which of the two cases is more optimal in general. From this perspective, there is certain necessity to design a synthetical metric to conduct general analysis, which can be called the figure of merit. In this thesis, both of coverage factor and capacity factor is negatively related to the performance of indoor wireless communication system so they should be multiplied or added in proportion together to compose the synthetical metric.

The synthetical metric is indicated before when talking about the necessity to evaluate the distribution of SINR instead of only evaluating the average value of SINR. The variance of SINR is as important as the average value of it because "How to distribute the signal in largest degree and in most even way in every place in the indoor system is a key point in optimisation". Intensity can ensure the stability of wireless communication service so variance is in great necessity imported here to balance the consideration of average value and centralization, or we can say that the distribution of SINR is the one can comprehensively measure the performance instead of a single value of average or variance. However, the introduce of distribution of SINR make the optimisation process more complicated because only few curve can be shown clearly in one figure. The advantage of figure shows here. If another metric is designed to take both the average and variance of SINR into consideration, the optimisation process will be much more convenient. The average is positively related to the performance while the variance is negatively related so using one to divide another with a little adjustment can design a new metric which can reflect the performance better. The same principle can be applied in designing a synthetical metric of the whole thesis.

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Reference

- [1] H. Hashemi, "The indoor radio propagation channel," Proceedings of the IEEE, vol. 81, no. 7, pp. 943–968, 1993.
- [2] T. Rappaport, Wireless Communications: Principles and Practice, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2001.
- [3] N. Moraitis, P. Constantinou, and D. Vouyioukas, "Power angle profile measurements and capacity evaluation of a simo system at 60 ghz," in Personal Indoor and Mobile Radio Communications (PIMRC), 2010 IEEE 21st International Symposium on, Sept 2010, pp. 1027–1031.
- [4] R. Janaswamy, "Angle and time of arrival statistics for the gaussian scatter density model," Wireless Communications, IEEE Transactions on, vol. 1, no. 3, pp. 488–497, 2002.
- [5] J.-M. Gorce, K. Jaffres-Runser, and G. De La Roche, "Deterministic approach for fast simulations of indoor radio wave propagation," Antennas and Propagation, IEEE Transactions on, vol. 55, no. 3, pp. 938–948, 2007.
- [6] Z. Lai, G. De La ROCHE, N. Bessis, P. Kuonen, G. CLAPWORTHY, D. Zhou, and J. Zhang, "Intelligent ray launching algorithm for indoor scenarios," Radioengineering, vol. 20, no. 2, pp. 399, 2011.
- [7] V. Degli-Esposti, V. Kolmonen, E. Vitucci, and P. Vainikainen, "Analysis and modeling on coand cross-polarized urban radio propagation for dual-polarized mimo wireless systems," Antennas and Propagation, IEEE Transactions on, vol. 59, no. 11, pp. 4247–4256, 2011.
- [8] Y. L. C. de Jong and D. V. Rogers, "Comparative evaluation of macrocellular and in-building wireless coverage performance at 700 and 2500 MHz," Antennas and Propagation (EuCAP), 2013 7th European Conference on, pp. 3974-3978, 2013.
- [9] D. Theckedath and T. J. Thomas, "The 700 MHz spectrum auction," Hillnote Number 2012-16E, Parliament of Canada, Apr. 2012.
- [10] C. Xue, Y. Zhu, L. Ni, M. Li and B. Li, "Optimal Relay Placement for Indoor Sensor Networks", Computer Communications and Networks (ICCCN), 2011 Proceedings of 20th International Conference on, pp. 1-6.
- [11] Y. Sun, Z. Yu, J. Ge, B. Lin and Z. Yun, "On Deploying Wireless Sensors to Achieve Both Coverage and Connectivity," Wireless Communications, Networking and Mobile Computing, 2009. WiCom '09. 5th International Conference on, pp. 1-4.
- [12] X. Bai, Z. Yun, D. Xuan, T. H. Lai, and W. Jia, "Deploying Four-Connectivity and Full-Coverage Wireless Sensor Networks," Proc. IEEE INFOCOM, 2008.
- [13] M. Hefeeda and M. Bagheri, "Randomized k-Coverage Algorithms For Dense Sensor Networks," Proc. IEEE INFOCOM, 2007.

- [14] Y. Zhao, H. Zhou and M. Li, "Indoor Access Points Location Optimisation Using Differential Evolution," Computer Science and Software Engineering, 2008 International Conference on, vol. 1, pp. 382-385.
- [15] Y. Zheng, O. Baala and A. Caminada, "Efficient design of indoor positioning systems based on optimisation model," Wireless Days (WD), 2010 IFIP, pp. 1-5.
- [16] Y. Xu, M. Zhou and L. Ma, "Optimisation of WLAN Indoor Location Network Based on Signal Coverage Requirement," Pervasive Computing Signal Processing and Applications (PCSPA), 2010 First International Conference on, pp. 162-166, 2010.
- [17] J. T. P. Yiin, M. J. Neve, and K. W. Sowerby, "Propagation Modeling for Indoor Wireless Systems Using the Electric Field Integral Equation," in Proc. IEEE APS/URSI Int. Symp., Toronto, Canada, July 11–17 2010.
- [18] M. Gustafsson, A. Karlsson, A. P. P. Rebelo, and B. Widenberg, "Design of frequency selective windows for improved indoor outdoor communication," IEEE Transactions on Antennas and Propagation, vol.54, pp. 1897-1900, 2006.
- [19] N. Qasem and R. Seager, "Frequency selective wall for enhancing wireless signal in indoor environments," in Antennas & Propagation Conference, 2009. LAPC 2009. Loughborough, 2009, pp. 573-576.
- [20] G. H. H. Sung, K. W. Sowerby, and A. G. Williamson, "The impact of frequency selective surfaces applied to standard wall construction materials," in IEEE Antennas and Propagation Society International Symposium, 2004, pp. 2187-2190 Vol.2.
- [21] Y. Maeda, K. Takaya, and N. Kuwabara, "Experimental investigation of controlling coverage of wireless LAN by using partitions with absorbing board," in International Symposium on Electromagnetic Compatibility, 1999, pp. 674-677.
- [22] L. Subrt and P. Pechac, "Controlling Propagation Environments Using Intelligent Walls", Antennas and Propagation (EUCAP), 2012 6th European Conference on, pp. 1-5, 26-30 March 2012.
- [23] D. I. Axiotis and M. E. Theologou, "An empirical model for predicting building penetration loss at 2ghz for high elevation angles," IEEE Antennas Wireless Propagat. Lett., vol. 2, pp. 234–237, 2003.
- [24] S. J. Hong, K. J. Kim and J. R. Lee, "Moisture effects on the penetration loss through exterior building walls," Vehicular Technology Conference, 1998. VTC 98. 48th IEEE, vol. 2, pp. 860-864, 1998.
- [25] Z. Yun, M. F. Iskander and Z. Zhang, "Complex-wall effect on propagation characteristics and MIMO capacities for an indoor wireless communication environment," Antennas and Propagation, IEEE Transactions on, Vol. 52, Issue 4, pp. 914-922, 2004.

- [26] C. L. Holloway, P. L. Perini, R. R. DeLyser, and K. C. Allen, "Analysis of composite walls and their effects on short-path propagation modeling," IEEE Trans. Veh. Technol., vol. 46, pp. 730–738, Aug. 1997.
- [27] M. F. Iskander, Z. Yun, and Z. Zhang, "Outdoor/indoor propagation modeling for wireless communications systems," in Dig. IEEE AP-S Int. Symp. USNC/URSI National Radio Science Meeting, vol. 2, July 8–13, 2001, pp. 150–153.
- [28] J. T. Zhang and Y. Huang, "Indoor channel characteristics comparison for the same building with different dielectric parameters," in Proc. IEEE Int. Conf. Commun., vol. 2, 2002, pp. 916–920.
- [29] Z. Yun and M. F. Iskander, "UWB pulse propagation through complex walls in indoor wireless communications environments," Wireless Networks, Communications and Mobile Computing, 2005 International Conference on, vol. 2, pp. 1358-1361, 2005.
- [30] Z. Yun, M. F. Iskander, and Z. Zhang, "Complex Wall Effect on Fading and MIMO Capacities for Wireless Communication Environments," Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th, vol.1, pp. 89-93, Oct 2003.
- [31] S. Kirkpatrick, Jr, C. D. Gelatt, M. P. Vecchi, "Optimisation by Simulated Annealing," Science 220 (4598): 671–680, 1983.
- [32] J. QI, "Application of improved simulated annealing algorithm in facility layout design," Control Conference (CCC), 2010 29th Chinese, pp. 5224 5227.
- [33] P. Sun, J. Ma and K. Ni, "A genetic simulated annealing hybrid algorithm for relay nodes deployment optimisation in industrial wireless sensor networks," Computational Intelligence for Measurement Systems and Applications (CIMSA), 2012 IEEE International Conference on, pp. 24-28.
- [34] X. Zheng, G. Bao, R. Fu and K. Pahlavan, "The performance of Simulated Annealing Algorithms for Wi-Fi Localization using Google Indoor Map," Vehicular Technology Conference (VTC Fall), 2012 IEEE, pp. 1-5
- [35] T. Jiang and G. Zhu, "Uniform Design Simulated Annealing for Optimal Access Point Placement of High Data Rate Indoor Wireless LAN Using OFDM", Personal, Indoor and Mobile Radio Communications, 2003. PIMRC 2003. 14th IEEE Proceedings on, vol. 3, pp. 2302-2306, 2003.
- [36] M. Matsunaga, T. Matsunaga and T. Sueyoshi, "An analysis of the effects of wall shapes on electromagnetic waves propagating around buildings," Proceedings of the 39th Microwave Conference, pp. 990–993, Sept. 2009.
- [37] M. Matsunaga and T. Matsunaga, "Electromagnetic Waves Propagating around Buildings," Wave Propagation edited by Andrey Petrin, INTECH, ISBN 978-953-307-275-3, Chapter 26, pp. 553–570, March, 2011.

- [38] M. Matsunaga, T. Matsunaga, M. Candotti and K. Inomata, "A Study of Electromagnetic Wave Propagation for the Estimation of Human Density inside Rooms," Proc. of CSIT vol.5, pp. 64–69, IACSIT Press, Singapore, May 2011.
- [39] M. Ghaddar et al., "A Conducting Cylinder for Modeling Human Body Presence in Indoor Propagation Channel," IEEE Trans. on Antennas and Propagation, vol. 55, no. 11, pp. 3099–3103, Nov. 2007.
- [40] M. Matsunaga, T. Matsunaga and M. Nakano, "Modelling and Measurement Techniques for Propagation of Indoor Wireless Communication Considering the Building's Structure and Human Bodies," Antennas and Propagation Conference (LAPC), Loughborough, pp. 1-4, Nov. 2011.
- [41] iBuildNet®, https://www.ranplan.co.uk/ranplan-product/ibuildnet, March 2015.
- [42] J. Liu, J. Wu, J. Chen, P. Wang and J. Zhang, "Radio Resource Allocation in Buildings with Dense Femtocell Deployment," Computer Communications and Networks (ICCCN), 2012 21st International Conference on, pp. 1-5.
- [43] M. A. A. Rahman, M. Dashti and J. Zhang, "Localization of unknown indoor wireless transmitter," Localization and GNSS (ICL-GNSS), 2013 International Conference on, pp. 1-6.
- [44] J. Wu, J. Liu, J. Chen and X. Chu, "Cooperative Interference Mitigation for Indoor Dense Femtocell Networks," Communications and Networking in China (CHINACOM), 2012 7th International ICST Conference on, pp. 93-98.
- [45] Z. Lai, G. D. L. ROCHE, N. Bessis, P. Kuonen, G. Clapworthy, D. Zhou, J. Zhang, "Intelligent ray launching algorithm for indoor scenarios", Radioengineering 20 (2), 398-408.
- [46] D. Umansky, G. D. L. Roche, Z. Lai, G. Villemaud, J. Gorce, J. Zhang, "A new deterministic hybrid model for indoor-to-outdoor radio coverage prediction", European Conference on Antennas and Propagation (EuCAP 2011), Rome, Italy.
- [47] Z. Zhang, X. Di, J. Tian, P. Chen, "A WLAN planning method for indoor positioning system," 2016 International Conference on Information Networking (ICOIN), Pages: 303 307.
- [48] D. Li, B Zhang, K. Huang, C. Li, "Measurement-Based Access Point Deployment Mechanism for Indoor Localization," 2015 IEEE Global Communications Conference (GLOBECOM), pp. 1-6.
- [49] Y. Shi, H. Osman, E. Hepsaydir; J. Wang, "Indoor wireless femtocell measurements," 2015 IEEE International Conference on Communications (ICC), pp. 2166-2171.
- [50] D. Plets; S. Aerts; W. Joseph; L. Martens, "Prediction of transmitted and received power of cellular devices in an indoor femtocell environment," 2013 IEEE Antennas and Propagation Society International Symposium (APSURSI), pp. 1954-1955.
- [51] C. Wang; L. Kao, "The Optimal Deployment of Wi-Fi Wireless Access Points Using the Genetic Algorithm," Genetic and Evolutionary Computing (ICGEC), 2012 Sixth International Conference on, pp. 542-545.

- [52] P. Cherriman, L. Hanzo, "Robust H.263 video transmission over mobile channels in interference limited environments," Wireless Image/Video Communications, 1996., First International Workshop on, pp. 1-7.
- [53] W. C. Y. Lee, "Estimate of channel capacity in Rayleigh fading environment," IEEE Transactions on Vehicular Technology (Volume: 39, Issue: 3), Aug 1990, pp. 187-189.
- [54] P Series, "Propagation data and prediction methods for the planning of indoor radio communication systems and the radio local area networks in the frequency range 900 MHz to 100 GHz", ITU-R Recommendations, Geneva, 2001.
- [55] A. Alhamoud, M. Kreger, H. Afifi, "Empirical investigation of the effect of the door's state on received signal strength in indoor environments at 2.4 GHz", Local Computer Networks Workshops (LCN Workshops), 2014 IEEE 39th Conference on, 2014.
- [56] S. Long, M. A. Khalighi, M. Wolf, S. Bourennane, Z. Ghassemlooy, "Investigating channel frequency selectivity in indoor visible-light communication systems", IET Optoelectronics, Volume: 10, Issue: 3, 6 2016.

Appendix

Program code for Simulated Annealing Algorithm:

```
static void Main(string[] args)
       System.Windows.Shapes.Line[] Room = new System.Windows.Shapes.Line[CountWall];
       Room = RoomBuilding(CountWall); //Room model built
       Random Rnd = new Random();
       System.Drawing.Point[] AccessPoint = new System.Drawing.Point[ApAmount];
       for (int i = 0; i < ApAmount; i++)
       {
         AccessPoint[i].X = Rnd.Next(RoomLength);
         AccessPoint[i].Y = Rnd.Next(RoomWidth); //Random Source positions
       }
       double[] SINR = new double[MaxWallFading];
       for (int i = MaxWallFading - 1; i > 0; i--)
         SimulateAnneal(Room, i, ref AccessPoint, out SINR[i]);
// use simulated annealing algorithm to optimise the source position and get best SINR
       }
       double BestSINR = SINR.Max();
       int BestFading = Array.IndexOf(SINR, BestSINR);
       PaintPrediction(Room, BestFading, TestRadius, AccessPoint);
```

```
/// <summary>
    /// Use simulated annealing algorithm to optimise the source position and get best SINR
    /// </summary>
    private static void SimulateAnneal(System.Windows.Shapes.Line[] Room, int WallFading, ref
System.Drawing.Point[] AccessPoint, out double BestSINR)
       double OldSolution, NewSolotion, Delta;
       for (int Temperature = Fire; Temperature > Cold; Temperature = (int)(Temperature *
CoolDown))
       {
         System.Drawing.Point[] OldAccessPoint = AccessPoint;
         OldSolution = CalculatedSINR(Room, WallFading, AccessPoint);
//calculate old SINR
         APShaking(Temperature, ref AccessPoint);
//change source position
         NewSolotion = CalculatedSINR(Room, WallFading, AccessPoint);
//calculate new SINR
         Delta = NewSolotion - OldSolution;
//calculate the difference
         if (Delta < 0) //if the new position is worse than the old one
            Random Rnd = new Random();
            double R = Rnd.NextDouble();
            double Judge = Math.Exp(Delta * Hurry / Temperature);
           if (R > Judge) //if the probability does not meet the requirement
              AccessPoint = OldAccessPoint; //revert to the old one.
            } //otherwise, take the new one as the solution even it is worse.
         }
       BestSINR = CalculatedSINR(Room, WallFading, AccessPoint); //output the best SINR
```

```
/// <summary>
    /// calculate the SINR of current building model
    /// </summary>
    private static double CalculatedSINR(System.Windows.Shapes.Line[] Room, int WallFading,
System.Drawing.Point[] AccessPoint)
       double SINR = 0;
       Random Rnd = new Random();
       int[,] Receiver = new int[ReceiversNumber, 2];
       for (int i = 0; i < ReceiversNumbe; i++)
         Receiver[i, 0] = Rnd.Next(RoomLength);
         Receiver[i, 1] = Rnd.Next(RoomWidth);
       }//random receivers' positions
       for (int i = 0; i < ReceiversNumbe; i++)
         double[] RPower = new double[ApAmount];
         for (int AP = 0; AP < ApAmount; AP++)
            System.Drawing.Point r = new System.Drawing.Point();
            r.X = Receiver[i, 0];
            r.Y = Receiver[i, 1];
            double distance = Distance2P(r, AccessPoint[AP]);
            int fade = WallCross(r, AccessPoint[AP], Room) * WallFading;
            double Pathloss = (20 * Math.Log10((double)distance / 10) + 20 * Math.Log10(2.4 *
1000000) - 87.55) + (double)fade;
            RPower[AP] = TxPower - Pathloss;
         }
         double maxpath = RPower.Max();
         int maxap = Array.IndexOf(RPower, maxpath);
         double IPower = NoisePower;
```

```
for (int AP = 0; AP < ApAmount; AP++)
{
    if (AP!= maxap)
        IPower = IPower + Math.Pow(10, (RPower[AP] / 10));
}
IPower = IPower / (ApAmount - 1);
IPower = 10 * Math.Log10(IPower);
SINR = SINR + maxpath - IPower;
}
return SINR / 100;
}</pre>
```