AN EFFICIENT MODEL FOR INDOOR RADIO SIGNAL PREDICTION AND COVERAGE ESTIMATION

MD. SUMON SARKER

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ABSTRACT

The potential implementation of Wireless Radio Networks and Personal Communication Systems (PCS) inside buildings requires a thorough understanding of signal propagation within buildings. Empirical approaches in this regards offer computational simplicity with low accuracy, while the deterministic models based on the numerical calculation of electromagnetic field provide higher accuracy as well as very high computational intensity which should not be expected now-a-days. So, the ray-tracing technique, which accelerates the computation while achieving the reasonable accuracy, is an appropriate selection for wireless signal prediction. Ray tracing is of vast use in the field of computational electromagnetic, such as the well known shooting and bouncing ray (SBR) algorithm. While designing the wireless networks, it is also crucial to obtain the optimum coverage for indoor environment by using minimum number of transmitting antennas. The purpose of this study is to propose a model that efficiently predicts the trajectory of the radio signal and at the same time can provide optimum wireless coverage. In this regards, this study explores two algorithms. The first algorithm is an efficient and faster ray-tracing technique based on binary angle division for radio signal prediction in indoor environment. And the second algorithm is the optimization technique for indoor wireless coverage. It minimizes the number of transmitters in the corresponding indoor area using a novel integrated approach of the proposed ray-tracing and genetic algorithm (GA). The study mainly focuses on the single floor of a typical building while describing the proposed model. Genetic algorithm is combined with the Breath First Search (BFS) algorithm incorporated with Branch-And-Bound terminology while exploring the search space tree to achieve the

optimum coverage solution. BFS is used to generate the search space tree and Branch-And-Bound terminology is to avoid the unnecessary generation of the sub-tree using proposed bounding functions. Some termination criteria have also been presented to make sure the successful termination of the proposed coverage algorithm. The simulation results generated from the proposed ray-tracing technique are compared with the conventional ray-tracing and the ray launching techniques to prove the superiority of the proposed algorithm in terms of both computational efficiency and accuracy. And it is also found that the proposed ray tracing system achieves better performance in terms of higher computational efficiency of about 22.17% and superior average accuracy of 94% in case of signal prediction compared to other existing techniques. On the other hand, the proposed coverage algorithm outperforms the existing algorithm in terms of both space and time complexities. The proposed coverage algorithm also proves that the computation time is much less than that of the existing algorithm and the difference of computation time between the existing and the proposed algorithm is proportional to the number of total receiving points used in the indoor environment. Moreover, it is also revealed that the proposed coverage algorithm is capable of reducing the computation time as high as 99% because of strong bounding functions as well as the concept of magnificent coverage pattern.

ABSTRAK

Potensi pelaksanaan Rangkaian Radio Wireless dan Sistem Komunikasi Personal (PCS) di dalam bangunan memerlukan pemahaman yang menyeluruh perambatan isyarat dalam bangunan. Pendekatan empiris dalam hal ini menawarkan kesederhanaan pengiraan dengan ketepatan yang rendah, manakala model berketentuan yang berdasarkan pengiraan berangka medan elektromagnet memberikan ketepatan yang lebih tinggi serta sangat tinggi keamatan pengiraan yang tidak boleh dijangka kini-satu hari. Jadi, teknik ray-mengesan, yang mempercepatkan pengiraan masa yang sama mencapai ketepatan yang munasabah, adalah pilihan yang sesuai untuk ramalan isyarat wayarles. Ray mengesan penggunaan yang luas dalam bidang elektromagnetik pengiraan, seperti menembak yang terkenal dan sinar memantul (SBR) algoritma. Ketika mereka bentuk rangkaian wayarles, ia juga penting untuk mendapatkan perlindungan optimum untuk persekitaran tertutup dengan menggunakan nombor minimum pemancar antena. Tujuan kajian ini adalah untuk mencadangkan satu model yang cekap meramalkan trajektori isyarat radio dan pada masa yang sama boleh memberikan liputan tanpa wayar yang optimum. Sehubung dengan ini, kajian ini meneroka dua algoritma. Algoritma pertama yang cekap dan cepat teknik-kerja mencari sinar berdasarkan pembahagian sudut perduaan untuk ramalan isyarat radio dalam persekitaran tertutup. Dan algoritma yang kedua adalah teknik pengoptimuman untuk liputan tanpa wayar dalam bangunan. Ia mengurangkan bilangan pemancar di kawasan yang sama dalam bangunan yang menggunakan pendekatan bersepadu novel algoritma yang dicadangkan ray-mengesan dan genetik (GA). Kajian ini terutama tertumpu kepada satu tingkat bangunan yang biasa pada masa yang sama menerangkan model yang

dicadangkan. Algoritma genetik digabungkan dengan Search Nafas algoritma Pertama (BFS) yang ditubuhkan dengan Cawangan-Dan-Bound istilah pada masa yang sama menerokai pokok carian ruang untuk mencapai penyelesaian perlindungan optimum. BFS digunakan untuk menjana pokok carian ruang dan Cawangan-Dan-Bound istilah adalah untuk mengelakkan generasi yang tidak perlu sub-pokok yang menggunakan dicadangkan Mengehad fungsi. Beberapa kriteria penamatan juga telah dikemukakan untuk memastikan penamatan berjaya algoritma liputan yang dicadangkan. Keputusan simulasi yang dihasilkan dari teknik yang dicadangkan sinar-mengesan berbanding dengan konvensional sinar-mengesan dan sinar melancarkan teknik untuk membuktikan keunggulan algoritma yang dicadangkan dari segi kecekapan dan ketepatan kedua-dua pengiraan. Dan ia juga mendapati bahawa sinar sistem yang dicadangkan mengesan mencapai prestasi yang lebih baik dari segi kecekapan pengiraan yang lebih tinggi kira-kira 22,17% dan ketepatan purata yang lebih tinggi sebanyak 94% dalam kes ramalan isyarat berbanding teknik lain yang sedia ada. Sebaliknya, algoritma liputan yang dicadangkan melebihi performa algoritma yang sedia ada dari segi kedua-dua kerumitan ruang dan masa. Liputan Algoritma yang dicadangkan juga membuktikan bahawa masa pengiraan adalah lebih kurang daripada algoritma yang sedia ada dan perbezaan masa pengiraan antara yang sedia ada dan algoritma yang dicadangkan adalah berkadar kepada jumlah mata menerima jumlah yang digunakan dalam persekitaran yang tertutup. Selain itu, ia juga mendedahkan bahawa liputan algoritma yang dicadangkan mampu mengurangkan masa pengiraan yang setinggi 99% kerana fungsi Mengehad kukuh serta konsep corak liputan yang mengagumkan.

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CHAPTER 1

INTRODUCTION

The generation that is familiar with the sci-fi movie characters on “Star trek” and “Matrix” speaking to each other and sending data over handheld, pocket-sized personal communicators expects to have such devices made available to them. Personal Communication Services (PCS) promise to deliver on that expectation. In recent years, the advancement of the Personal Communication Systems has generated a great deal of interest among the researchers in characterizing radio propagation inside buildings. In this regard, radio waves are the greatest discovery that truly has changed our world. The history of wireless communications begins with the first experiments of the radio pioneers. The first demonstrations of Hertz in 1880s inspired the entrepreneur Guglielmo Marconi to seek a market for this amazing new service. In the present world, the human beings depend completely on spin-offs of this basic discovery.

1.1 OVERVIEW AND MOTIVATION

The challenges of the propagation modeling in indoor environments have increased enormously in recent years. The main reason is the large amount of competition that exists in the field of wireless communication at the moment. This makes it very important to have an efficient way to predict the signal propagation in indoor area and to carry out a prior analysis to allow minimizing the number of base stations to give an efficient service with the economical saving. The faster evolution of wireless communications has directed to the use of smaller cell sizes, higher frequency bands and smart antenna systems, making the issues of propagation prediction more challenging.

On the other hand, the accuracy of radio propagation prediction in indoor environment involves many aspects. They include the accuracy of locations and sizes of buildings and proper knowledge of the behavior of walls, furniture and other objects involved. They also include the focusing on the prediction of the significant trajectories of the signals and ignoring the computation of hundreds of irrelevant paths. So, the first challenge is the successful modeling of wireless communication networks for indoor environments and this modeling should be based on accurate prediction of the paths of the signals between fixed transmitting antennas and the receivers. Another challenge of propagation prediction is shown in Figure 1.1 where it is shown that small inaccuracies in the analysis of building structure can lead to totally different prediction results. As angular criterion is considered during the prediction of the propagation path of the signals, the orientation of the walls is extremely important. Moreover for effective indoor propagation prediction, it is also important to account for the building database with high accuracy including precise description of the indoor features. These factors make it very difficult to obtain good predictions while modeling indoor radio propagation. To meet these challenges and accurate characterization of the complex indoor environment, it is needed to modify the existing methods as well as develop new procedures and techniques.

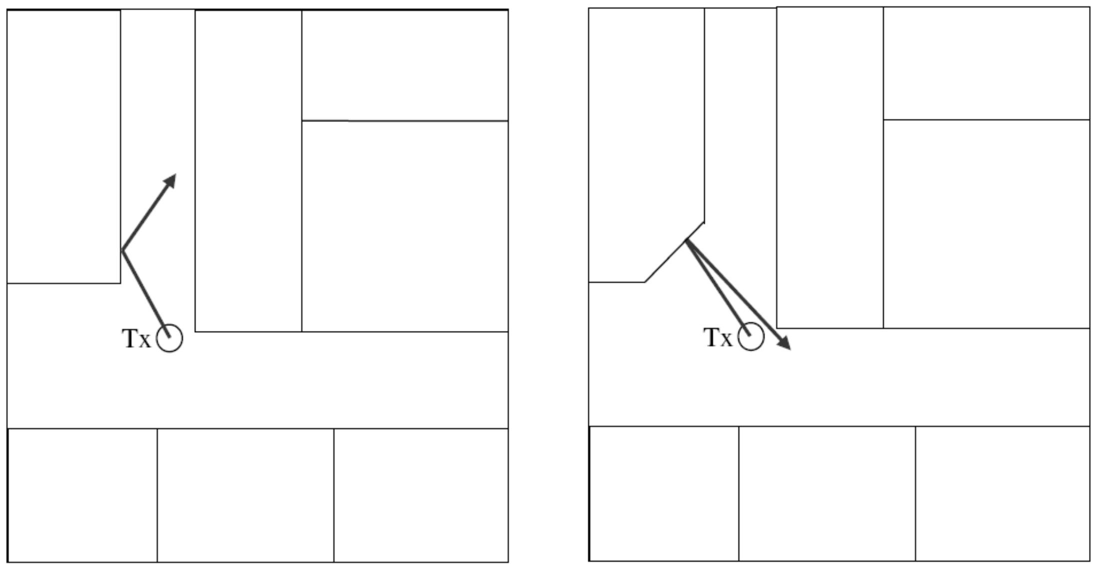


Figure 1.1: Accuracy of building structure.

The use of wireless systems in indoor area poses one of the biggest design challenges, as indoor radio propagation is essentially a subject of intense investigation and the research in this area has been proliferated. Although a Personal Communication System (PCS) or Wireless Local Area Network (WLAN) can be designed either by estimation or through extensive field measurements, taking field measurements can be more time consuming and difficult in some cases to achieve accurate results, which can lead to costly services. On the other hand, propagation modeling based on simulation can save time, money, and can also offer the similar parameters required to design the wireless communication systems. Therefore, more accurate site-specific indoor propagation model is required to design optimum wireless systems that will provide reliable and low-cost service. In this regards, a novel ray-tracing algorithm based on the proposed Binary Angle Division technique has been developed and applied for indoor radio signal prediction and the obtained results confirm that the proposed system is capable of achieving better performance in terms of higher computational efficiency and superior average accuracy in case of signal prediction compared to other existing algorithms.

On the other hand, the optimum coverage problem is a classical issue in computational complexity theory. This kind of problems is widely taught in approximation algorithms. Because of ever increasing demand of this field, the well-known brute force algorithms are systematically going to be replaced by the state-of-the-art optimization techniques. Here, several sets are given as input and a number *k*. The sets may contain some elements in common. The target is to select at most *k* of these sets so that the number of covered elements is the maximum, i.e. the union of the selected sets has the maximum size. To obtain the optimum wireless coverage like this, it is necessary to incorporate the ray-tracing technique with the proper optimization algorithm. In this regards, Genetic Algorithms (GA) are being successfully used in optimizing antenna locations and solving electromagnetic problems over the years. Here GA is a heuristic approach that usually leads to an approximate (but often good) solution, in tractable time. The word heuristic comes from the Greek "heurisko" (I find). ("eureka"=> I have found it!). The area coverage can be approximated as point coverage. That is, if all the sampling points are covered by the minimum number of transmitters, the entire area will be considered as covered optimally. In this study, the problem of selecting the minimum number of transmitter to cover the whole indoor propagation area has been addressed and it is observed that the proposed coverage algorithm has less space and time complexities. It is also found that the proposed coverage algorithm is competent of reducing the computation time while comparing with the other existing algorithm.

1.2 PROBLEM DEFINITION AND ANALYSIS

In mobile radio communication system, the human-made structures play a major role in the system design aspect, especially the mobile communication within the buildings. In general, the signal penetration through the building walls in residence houses or 2-3 story buildings is usually low and therefore, we can use the outside cell sites to serve the in building communications. But when the buildings are higher than four stories, the signal penetration through the buildings experience a big loss and therefore, in building mobile radio system should be installed in each building. Since the concrete floors isolate the signal propagation between floors, this study focuses on the signal propagation between the transmitter and the receiver on the same floor.

There are several distinguished scenarios inside the buildings of modem construction. One scenario is the free space loss between transmitter and receiver. A second scenario is reflection and reception from interior walls. Since all the floor plans in each building are different and so is the construction material, the use of deterministic models like ray tracing technique appearing in certain literatures becomes hard to apply. Therefore, the purpose of this research is to introduce an accelerated algorithm for predicting the indoor radio propagation in order to contrive a more computationally efficient model.

Indoor wireless communication associated with Personal Communication Systems (PCS) and Wireless Local Area Networks (WLANs) - is exploding rapidly. It has become one of the fastest growing fields and has been a subject of intense investigation. One important problem in this area is the propagation of the wireless signal from the transmitting antenna of the base station to a mobile receiver through a very complex and convoluted indoor environment. So, both computation time and accuracy are still an open issue in terms of ray tracing technique. And for this reason, the need for an efficient way to evaluate radio propagation in indoor area is increasing.

It is also critical to optimize the locations of the base stations to ensure satisfactory wireless coverage. So, determining the optimal locations of the base stations to meet a given performance criteria is therefore, an important research topic and to achieve this standard, an easy-to-use and reasonably accurate propagation model is necessary which can be employed to make planning and installation of personal communication systems as easy and as cheap as possible.

Therefore, the opening of the proposed model in this study promises an excellent alternative for radio signal prediction and optimum wireless coverage in indoor area. Moreover, this research work has been performed at the deterministic level with the aim of characterizing the propagation path of the radio signal in the indoor communication channel.

1.3 THESIS OBJECTIVES

The objective of this research is to develop an efficient model for simulation of indoor radio propagation. The model will fulfill the following purposes:

(i) Efficient radio signal prediction in indoor environment using computational geometry and binary angle division technique.

(ii) To find the global optimal solution, an optimization algorithm will be developed that will outperform the existing algorithms in terms of space or time complexities and computation time.

(iii) To determine the optimal locations of the base stations to meet a given performance criteria, an easy-to-use and reasonably accurate propagation model will be developed which can be employed to make planning and installation of Personal Communication Systems as easy and cheap as possible.

1.4 THESIS CONTRIBUTIONS

The unique contribution of the study can be summarized as follows:

(i) The basic contribution of this study is to forward concepts and ideas on indoor radio signal prediction and coverage optimization towards new world views.

(ii) An introduction of triangular geometry that gives the guideline of how to build the ray emanated from the transmitter. Binary Angel Division technique has been implemented to avoid redundant computation as well as accelerate the simulation process.

(iii) This study will provide more reliable solutions while designing distributed antenna system to achieve optimum wireless coverage in an indoor zone. It will be helpful to make planning and installation of distributed antenna system. The outcome of this study will be supportive for analyzing the wireless radio networks and personal communication services inside buildings. This study will also be a viable alternative to several existing techniques.

1.5 THESIS OUTLINE

This study describes a novel model for efficient radio signal prediction based on accelerated ray tracing algorithm and provides optimum wireless coverage for an indoor environment. The proposed model considers the physical layout and construction of the structures observed in the typing buildings while implementing ray tracing technique and use the concept of Genetic Algorithm for providing optimum wireless coverage. The organization of the study can be portrayed as the following chapters.

The current chapter briefly focuses on the research work. It describes modern challenges and limitations regarding indoor radio propagation modeling. The motivation and purposes of this study has been presented here. A concise overview of the research work, simulated results and corresponding discussions has been depicted. This chapter also addresses the future scope of the study.

Chapter 2 describes the basic issues regarding wireless communication as well as the current research work. It also discusses on the relevant literature in the field of radio propagation modeling in indoor area. This chapter also outlines the advantages and disadvantages associated with the previous works and find the necessity and scopes of the future works in this area.

Chapter 3 provides a comprehensive discussion about the proposed methodology on radio signal prediction and coverage optimization in indoor area. It concentrates on the propagation characteristics of radio waves to present a new ray tracing technique. It also proposes an algorithm to optimize indoor wireless coverage.

Chapter 4 analyzes the generated results of both ray tracing and wireless coverage algorithms and describes the various aspects of them. The complexities of the proposed coverage algorithm have been derived here. Some simulation results of both ray tracing and coverage algorithms have also been presented.

Chapter 5 deals with the comparative study of the proposed methodology with the existing ones. The ray tracing technique has been proved superior in terms of execution time and accuracy of signal prediction. On the other hand, the coverage algorithm has been proved better in case of time complexity, space complexity and computation time.

Finally, Chapter 6 states the overall conclusions drawn from this study. It presents summary of the generated results found so far from the discussion of the previous chapters to prove the superiority of the proposed algorithms. It also suggests about the applications and future scopes of this study.

CHAPTER 2

LITERATURE REVIEW

In the previous days, it was all about getting the radio signal transmitted over longer and longer distances. We are now on the brink of a whole new era in the world of wireless communication, an era where mobile communication network will be an integrated part of any building. People expect wireless coverage and immaculate wireless data service everywhere. So, these days, however, the radio channel between the network and the mobile user is getting shorter and shorter due to the stricter demands on the quality of the radio channel in order to perform the higher data rates. Marconi struggled to get his radio transmission to reach a mile. These days we are struggling to get a service range from an indoor base station to mobile users at 20-40 meter distance with high speed data including good quality service. The network elements are also moving closer to the mobile users in order to afford the requirements for quality of voice and data.

The area of indoor radio propagation is relatively new as the first wave of research in this domain started in the early 1980s. (Cox et al., 1983) at AT&T Bell Laboratories and (Alexander, 1982) at British Telecom were the first to carefully study indoor propagation of radio waves for a large number of homes and office buildings. In general, a complete design of indoor radio propagation model consists of radio propagation prediction and coverage optimization using minimum number of transmitting antennas. In this regards, ray-tracing algorithms as mentioned in (Tayebi et al., 2009; Blas et al., 2008; Cocheril and Vauzelle, 2007; Razavi & Khalaj-Amirhosseini, 2008; Liang et al., 2008; Lee, 2009; Kim

& Lee, 2009; Mphale & Heron, 2007; Gomez et al., 2010; Teh et al., 2006; Alvar et al., 2008; Tao et al., 2008; Bang et al., 2007; Martini et al., 2007; Jin, 2006; Xia et al., 1996) are used to trace the propagation paths of the radio signals emanated from the transmitter and optimization methods described in (Anderson & McGeehan, 1994; Hu & Goodman, 2004; Yun et al., 2008) are used to determine the locations of those transmitting antennas.

Indoor wireless communication has been a subject of intense investigation and voluminous research work has been done in this area. So, according to (Hashemi, 1993; Molkdar, 1991; Seidel & Rappaport, 1992; Honcharenko et al., 1993) there is considerable interest in prediction of the propagation mechanisms for indoor environments. All the models regarding indoor propagation prediction are based on the a priori knowledge of the locations of the base stations or the transmitters. In order to design wireless communication systems for an indoor environment, determining the optimal locations of the base stations to meet a given performance criteria is also an important consideration.

2.1 BASIC RADIO PROPAGATION ISSUES

It has been noticed that radio propagation within buildings is not influenced by weather conditions, such as rain, snow, or clouds, as is outdoor propagation, but it can be strongly influenced by specific features such as the building types, the construction materials and the layout of the buildings as shown in Figure 2.1. Though the mechanism of indoor radio propagation is about similar to that of outdoor, the conditions are much more dynamic. For illustration, signal levels are very different depending on whether the interior doors are open or closed inside a building. The mounted locations of the antennas also impact large-scale propagation. The received signal by the antennas mounted at the desk level in a partitioned office is much different from those mounted on the ceiling. So, there are two aspects that differentiate the indoor radio channel from the traditional mobile radio channel. These aspects are as follows:

(i) The distances covered are very small in comparison with the outdoor area.

(ii) For very small separation distance between transmitter and receiver, the variability of the environment is much higher.

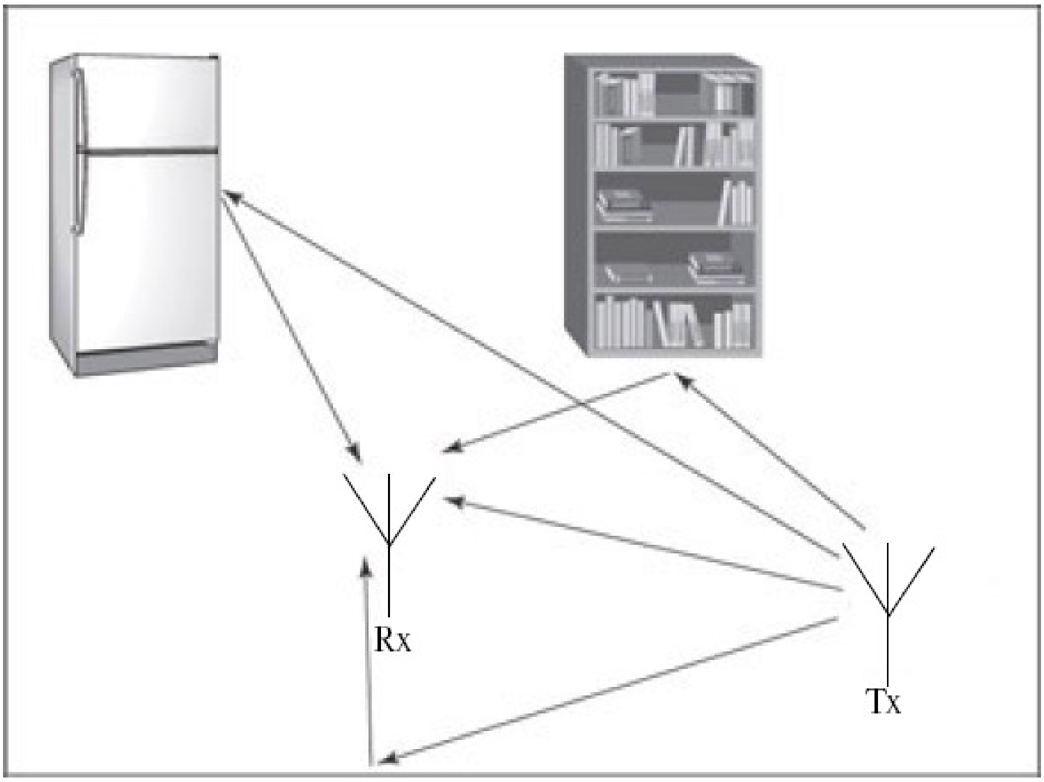


Figure 2.1: Radio signals received by the receiver in indoor area.

2.1.1 COMMUNICATION SYSTEMS

Since the derivation of the equations to analyze the electromagnetic medium by James Clerk Maxwell, and the subsequent inventions regarding radio communications, the electromagnetic spectrum is being widely used for many real life applications. Lots of efforts have been carried out while analyzing how communication takes place between two entities. The objective of such studies is to maximize the rate of transferred information between two communicating devices. Any communication system can be viewed as a link as reported in Figure 2.2 between a source and a destination where information is sent from the source to the destination. The intervening stages of this type of communication system are shown in Figure 2.3.

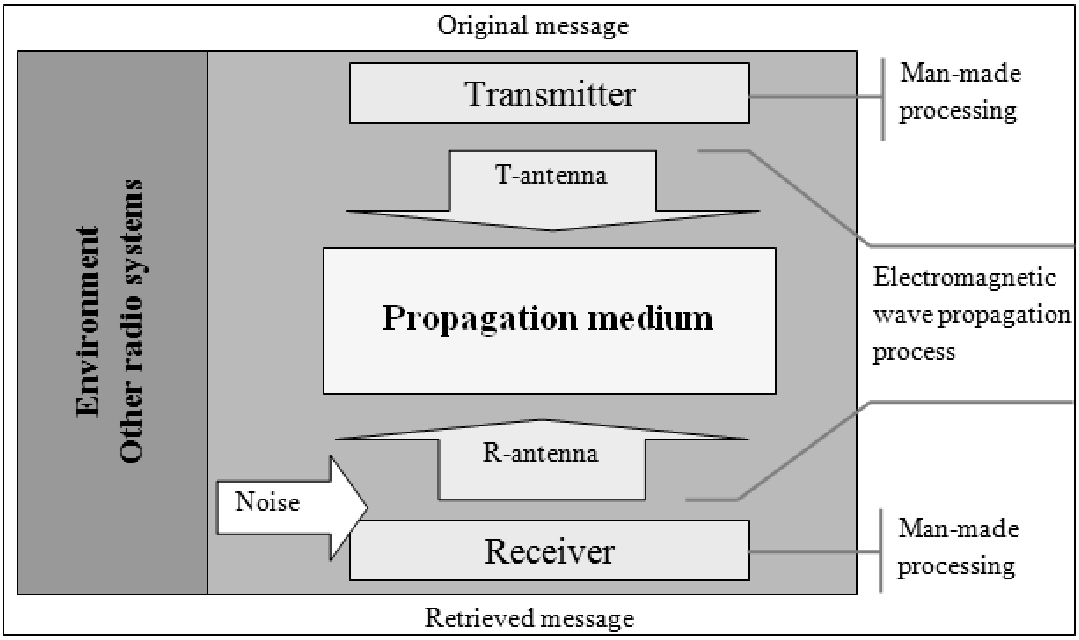


Figure 2.2: Basic radio link model.

Referring to Figure 2.3, the transmitter takes the information from the source device and encodes that information which is suitable for transfer over the channel such that the transmission cost is minimized. Here, cost is a function that refers to the time taken to perform the communication, the bandwidth used, the degree to which the transmission interferes with other transmissions and the amount of error that occurs in the communication process. The channel describes the process of altering signal that is being transmitted through the communication channel of the corresponding environment. Finally, the receiver receives those signals that have been altered by the communication channel, and tries to recover the original message that was sent from the source. Then the received information is passed to the destination.

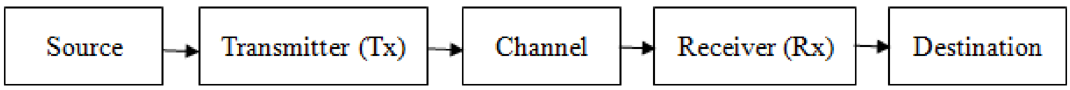


Figure 2.3: Basic communication system.

2.1.2 ADVANTAGES AND DISADVANTAGES OF WIRELESS NETWORKS

Wireless networks have both advantages and disadvantages when compared with wired networks. To add or move workstations are much flexible for wireless LAN. It is much easier to provide connectivity where it is difficult to use cable. The installation of wireless network is easier and faster than the wired network. It also eliminates the need to pull cable through walls and ceilings. In historic buildings, where cabling could compromise the facade, the wireless LAN can avoid the need to drill holes in walls. For dynamic environments where frequent moves and changes of the objects are required, long term cost benefits can be achieved using wireless network.

On the other hand, it may be necessary to replace wireless cards or access points with the change of standards. Its communication speed is lower than the wired network that makes it less reliable. There is a great security issue that is very difficult to guarantee and need proper configuration. The devices in the wireless environment operate at a limited distance from the access point. It is much affected by the surroundings, e.g. walls those work as blocking entity. Wireless network cannot provide complete wireless service. A wired LAN is to be required to provide a backbone to the wireless LAN. That is, a wireless LAN can be a supplement to a wired LAN instead of a complete solution provider. Moreover, in wireless networks, there is the risk of having dead spots where the signal is either weak or not existed.

2.2 RADIO PROPAGATION PREDICTION MODELS

A Radio wave propagation model, also known as Radio frequency propagation model, is the mathematical formulation for characterizing radio wave propagation as a function of distance, frequency and other conditions. A single model is generally developed to predict the behavior of propagation of the radio signals under some constraints. The goal of predicting the way radio waves are propagated from a transmitter to a receiver is to predict the propagation path and the efficient coverage area of a transmitter. A simplified flow diagram of a ray-tracer has been shown in Figure 2.4.

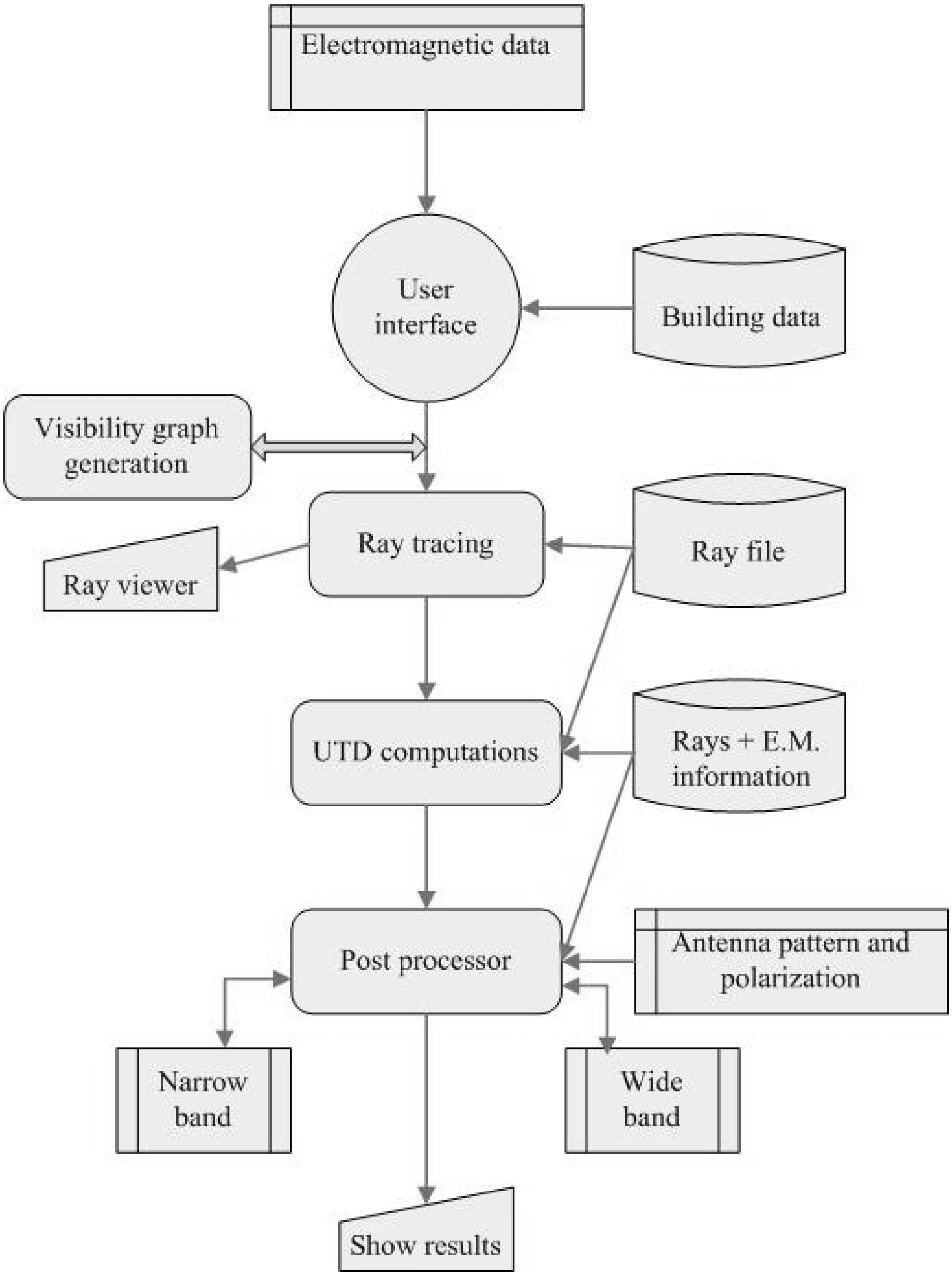


Figure 2.4: Sample flow diagram of a ray tracer.

To meet the needs of realizing the propagation behavior of radio signals in different conditions, different models have been developed in the past years for various types of environments. Most common types of models regarding indoor radio propagation prediction include:

(i) Free Space Model

(ii) 2-Ray Model

(iii) Shooting And Bouncing Ray (SBR) Model

(iv) Image Method

(v) Hybrid Method

(vi) Ray Launching Method

(vii) Beam Tracing Method

(viii) Ray Splitting Method

Based on (Pechac et al., 2000; Widyawan et al., 2007) there are two classical approaches regarding radio signal propagation modeling. They are

1. Empirical models
2. Deterministic models

Radio propagation models are empirical in nature, which means, they are developed based on large collections of data collected for the specific scenario. For any model, the collection of data has to be sufficiently large to provide enough scope to describe all kind of situations that can happen in that specific scenario. On the other hand, deterministic models (Iskander & Yun, 2002) try to follow physical principles of electromagnetic wave propagation. These models are very accurate, site-specific and can predict wide-band parameters as well. The most popular models in this category are optical models using ray tracing as reported in (Tayebi et al., 2009; Blas et al., 2008; Cocheril & Vauzelle, 2007; Razavi & Khalaj-Amirhosseini, 2008; Liang et al., 2008; Lee, 2009; Kim & Lee, 2009; Mphale & Heron, 2007; Gomez et al., 2010; Teh et al., 2006; Alvar et al., 2008; Tao et al., 2008; Bang et al., 2007; Martini et al., 2007; Jin, 2006; Xia et al., 1996; Mohtashami & Shishegar, 2010) or ray launching technique as reported in (Hoppe et al., 1999; Raida et al., 2008; Lawton & McGeehan, 1994). To deal with very complex propagation environments, deterministic models are developed based on ray-tracing techniques. The major task in a basic ray tracing program is to determine the trajectory of a signal emanated from the transmitter. This procedure also involves the calculation of the intersection between a ray and a surface of the obstacle in the environment. The computation time can be huge or may be beyond the capacity of the present computers if the corresponding propagation environment is very large or complex. Thus the computation time is the biggest issue against the development of the ray-tracing methods. So, an efficient ray-tracing algorithm is very important to improve the performance and the accuracy of signal prediction since more complex types of propagation environments are needed to be taken into account. Moreover ray tracing is widely used technique for propagation prediction in wireless communication environments, i.e. indoor picocells. Ray tracing algorithm is used to predict all possible ray paths available between a transmitter and a receiver in a communication channel. After identifying all possible paths, high frequency electromagnetic techniques in (Kouyoumjian & Pathak, 1974; Burnside & Burgener, 1983; Luebbers, 1984) are applied to evaluate each signal. As this study is mainly focusing on the deterministic models for analyzing indoor wireless propagation, some of the more commonly used deterministic models have been briefly described below.

2.2.1 FREE SPACE MODEL

The free space propagation model in (Friis, 1946) is developed assuming the ideal propagation condition in the provided environment. It assumes that there is only one clear line-of-sight path exist between the transmitter (Tx) and the receiver (Rx). Basically the free space model represents the communication range as a circle around the transmitter. The receiver receives all signals if it remains within the circular range. Otherwise, all signals are lost. The antennas are kept in unobstructed free space and there will be no multipath propagation between them as shown in Figure 2.5.

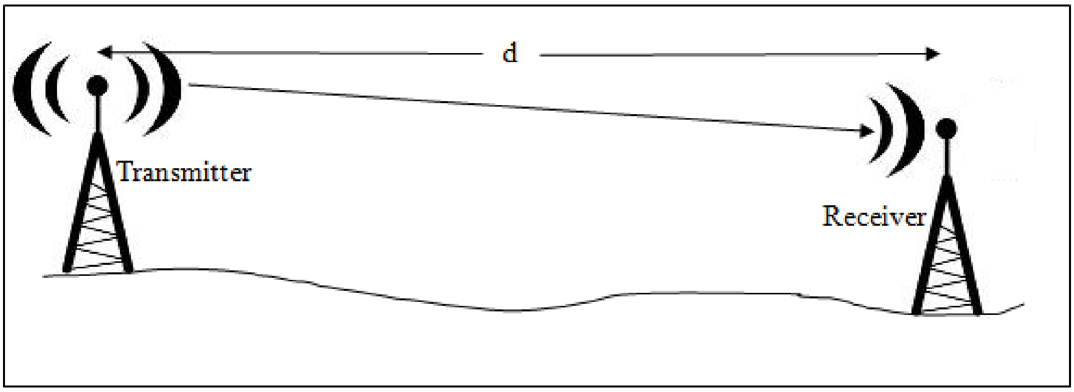


Figure 2.5: Free space propagation.

The transmitters and the receivers are correctly aligned and polarized accordingly. The bandwidth of the signal is supposed to be narrow enough so that a single value of the wavelength can be considered. In the absence of any reflection or multipath, free space propagation can be modeled as follows:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \quad (2.1)$$

The above equation was derived by (Friis, 1946) where P_t is the transmitted signal power and P_r is the received signal power. G_t and G_r are the gains of the transmitter and the receiver respectively. λ is the wavelength and d is the distance between the transmitter and the receiver in the same unit of wavelength. The inverse of the factor in parentheses on Equation (2.1) is the so called free space path loss (FSPL). In the field of wireless communication, free-space path loss is the loss of signal strength of an electromagnetic wave. Here the signal propagates through a line-of-sight path in free space, with no obstacle on the path to cause any kind of obstruction. FSPL doesn't consider factors such as the gain of the transmitter and the receiver, not any loss that is associated with hardware imperfections. Free-space path loss is proportional to the square of the distance between the transmitting and the receiving antenna, and also proportional to the square of the frequency of the transmitted radio signal. The equation of FSPL can be expressed as follows

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2$$

$$= \left(\frac{4\pi df}{c}\right)^2 \qquad (2.2)$$

Where λ is the wavelength in meters, f is the signal frequency in hertz, d is the distance between transmitter and receiver in meters and c is the speed of light in the vacuum that is equivalent to 2.99792458×10^8 meters per second. A convenient way to express FSPL in terms of dB is as follows:

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

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

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

$$= 20\log_{10}(d) + 20\log_{10}(f) - 147.55 \qquad (2.3)$$

where the units are similar to the previous ones. For the calculations of the typical radio applications, f is measured in MHz and d in km. So, the modified FSPL equation becomes

$$FSPL(dB) = 20\log_{10}(d) + 20\log_{10}(f) + 32.45 \qquad (2.4)$$

Alternatively, the Equation (2.1) can be expressed in dB units by taking $10\log_{10}$ on both sides as:

$$P_r(dB) = P_t(dB) + G_t(dB) + G_r(dB) + 20\log_{10}\left(\frac{\lambda}{4\pi}\right) - 20\log_{10}(d) \qquad (2.5)$$

The first two terms of the right hand side combined are called Effective Isotropic Radiated Power (EIRP). The last two terms of Equation (2.5) combined are called Free-space path loss (FSPL). Using these definitions, the Equation (2.5) can be rewritten as

$$P_r(dB) = EIRP(dB) + G_r(dB) - FSPL(dB) \qquad (2.6)$$

In practical, it is almost impossible to achieve the ideal conditions in normal terrestrial communication, because of obstructions and most importantly the occurrence of reflections from the ground. The situation where this model works accurately is in satellite communications when the atmospheric absorption is very negligible. This model also works properly while designing anechoic chambers to minimize reflections. But in a mobile communication channel, a single direct path between the transmitter and the receiver is seldom the only physical means of propagation, and hence the free space propagation model is inaccurate in most of the cases. Thus, for propagation conditions in non free space, the path loss (PL) can be modified by

$$PL = A + B\log_{10}(R) \qquad (2.7)$$

Where A is the median path loss in dB at 1km, B is the rate of falling signal strength and R is the range in km.

2.2.2 2-RAY MODEL

This model as reported in (Rappaport, 1999; Yang et al., 2007) considers a ray bounced back from the ground. It uses free space path loss model for near sights. The 2-ray model shown in Figure 2.6 is comparatively useful propagation model that is based on geometric optics. It considers both LOS and reflected propagation paths between the transmitter and the receiver. The major weakness of this model is that it can't be suited for those environments where multipath propagation is needed to be considered. Here the total received E-field; E_{TOT} is the result of the LOS component, E_{LOS}, and the reflected component, E_g. Referring to Figure 2.6, h_t is the height of the transmitter and h_r is the height of the receiver. If the free space E-field at a reference distance d_0 from the transmitter T_x is E_0, then the free space propagating E-field for $d > d_0$ can be expressed from (Rappaport, 1999) as

$$E(d,t) = \frac{E_0 d_0}{d} \cos\left(w_c \left(t - \frac{d}{c} \right) \right) \qquad (d > d_0) \tag{2.8}$$

Where $|E(d,t)| = E_0 d_0 / d$ represents the value of E-field at d meters distance from the transmitter. The receiver can receive two types of rays from the transmitter. One is the LOS wave having distance d' and the other is the reflected wave having distance d''. The E-field due to the LOS component can be expressed as

$$E_{LOS}(d',t) = \frac{E_0 d_0}{d'} \cos\left(w_c \left(t - \frac{d'}{c} \right) \right) \tag{2.9}$$

And the E-field due to the reflected wave having distance $d^{''}$ can be expressed as

$$E_g(d^{''},t) = \frac{E_0 d_0}{d^{''}} \cos\left(w_c \left(t - \frac{d^{''}}{c} \right) \right) \tag{2.10}$$

According to the laws of reflection from dielectrics reported in (Rappaport, 1999)

$$\theta_i = \theta_0 \tag{2.11}$$

And

$$E_g = \Gamma E_i \tag{2.12.a}$$

$$E_t = (1+\Gamma) E_i \tag{2.12.b}$$

Where Γ is the reflection coefficient. Assuming the case of perfect ground reflection, i.e. Γ=-1 and E_t=0, the resultant E-field envelope is given by

$$|E_{TOT}| = |E_{LOS} + E_g| \tag{2.13}$$

The total received E-field, $E_{TOT}(d, t)$, is also the sum of Equations (2.9 & 2.10) and can be expressed as

$$E_{TOT}(d,t) = \frac{E_0 d_0}{d^{'}} \cos\left(w_c \left(t - \frac{d^{'}}{c} \right) \right) + (-1) \frac{E_0 d_0}{d^{''}} \cos\left(w_c \left(t - \frac{d^{''}}{c} \right) \right) \tag{2.14}$$

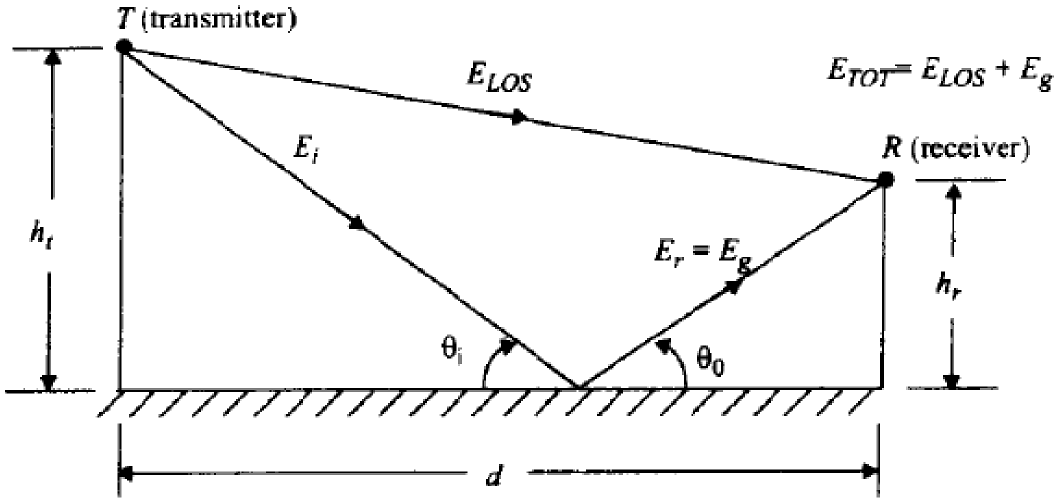


Figure 2.6: 2-ray model (Rappaport, 1999).

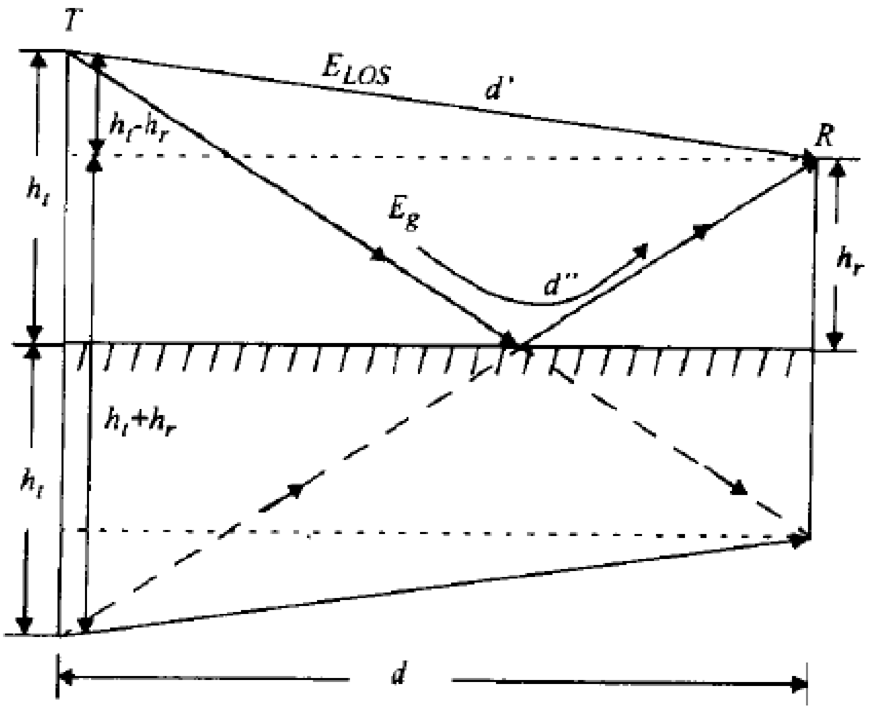


Figure 2.7: The calculation of path difference between the line of sight and the reflected ray (Rappaport, 1999).

From the geometry of the model in Figure 2.7, the path distance difference between LOS and reflected rays can be calculated as follows

$$LOS\ ray\ \ d' = \sqrt{d^2 + (h_t - h_r)^2}$$

$$= d\sqrt{1 + \left(\frac{h_t - h_r}{d}\right)^2} \qquad (2.15)$$

$$\text{Re}\,flected\ ray\ \ d'' = \sqrt{d^2 + (h_t + h_r)^2}$$

$$= d\sqrt{1 + \left(\frac{h_t + h_r}{d}\right)^2} \qquad (2.16)$$

According to binomial theorem we know

$$\sqrt{(1+x)} = 1 + \frac{1}{2}x - \frac{1}{2}\frac{1}{4}x^2 + \frac{1}{2}\frac{1}{4}\frac{3}{6}x^3 - ... \approx 1 + \frac{1}{2}x,\ \ if\ \ x = 1 \qquad (2.17)$$

Applying the binomial theorem of Equation (2.17) to Equations (2.15 & 2.16) respectively, we have

$$LOS\ ray\ \ d' \approx d\left[1 + \frac{1}{2}\left(\frac{h_t - h_r}{d}\right)^2\right] \qquad (2.18)$$

$$Reflected\ ray\ \ d'' \approx d\left[1 + \frac{1}{2}\left(\frac{h_t + h_r}{d}\right)^2\right] \qquad (2.19)$$

$$\Delta paths = d'' - d' \approx d\left[1 + \frac{1}{2}\left(\frac{h_t + h_r}{d}\right)^2\right] - d\left[1 + \frac{1}{2}\left(\frac{h_t - h_r}{d}\right)^2\right]$$

$$\approx \frac{(h_t + h_r)^2}{2d} - \frac{(h_t - h_r)^2}{2d}$$

$$\approx \frac{h_t^2 + 2h_t h_r + h_r^2 - h_t^2 + 2h_t h_r - h_r^2}{2d}$$

$$\approx \frac{2h_t h_r}{d} \qquad (2.20)$$

2.2.3 SHOOTING AND BOUNCING RAY (SBR) MODEL

The conventional procedure for ray tracing is the SBR algorithm as reported in (Ling et al., 1989; Wang et al., 2008; Dikmen et al., 2010; Saeidi et al., 2009; Tao et al., 2010; Buddendick & Eibert, 2009; Mohtashami & Shishegar, 2010; Kipp, 2010; Amornthipparat et al., 2007; Geng et al., 2008; Gao, 2010). This model is based on geometrical optics to predict signal propagation within buildings for Personal Communication System (PCS) design. This technique incorporates both brute force ray tracing and uniform geometrical theory. At first, a ray is emanated from the transmitter (*Tx*), and then the path of the ray is traced to determine if it hits any obstacle or is received by the receiver (*Rx*). If any ray is received by the receiver, the received power associated with the corresponding ray is calculated. An illustration of the SBR is shown in Figure 2.8. In Figure 2.8, it is shown that some rays are emanated from the transmitter *Tx* and a fewer number of them may be received by the receiver *Rx* at the end of the process after reflected by the walls.

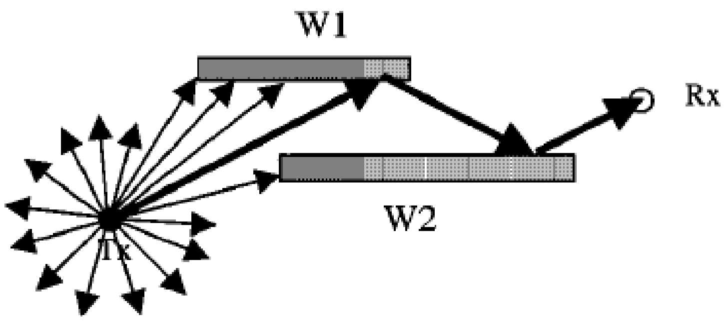


Figure 2.8: Ray tracing procedure (Tran-Minh & Do-Hong, 2008).

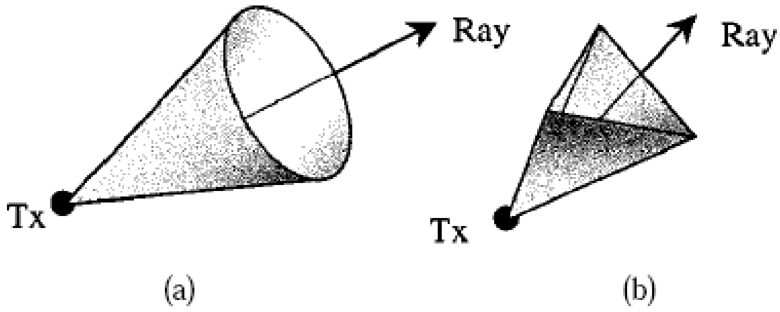


Figure 2.9: Illustration of ray cone and ray tube. (a) Ray cone. (b) Ray tube (Tran-Minh & Do-Hong, 2008).

This algorithm has some fundamental issues that are needed to be clarified. The first is how to transmit a ray. The second is how to determine whether a ray hits an obstacle. According to third issue, if there are several obstacles on the way of the ray, how to determine which obstacle is really hit. And the fourth is how to determine if a ray is received by the receiver. There are some reviews on SBR algorithm exist to clarify the above issues.

Refer to Figure 2.9; a ray is actually a ray tube or a ray cone as reported in (Chen & Jeng, 1997; Yang et al., 1998; Suzuki & Mohan, 1997). When ray cones as shown in Figure 2.9(a) are considered, the spherical wave front at the receiving antenna has to be overlapped (Seidel & Rappaport, 1994) with those ray cones. On the other hand, if ray tubes as shown in Figure 2.9(b) are used, the spherical wave front can be covered by the ray without overlapping of ray tubes. To determine whether a receiving antenna has received a ray, it is needed to check if the receiving point resides in the ray cone or ray tube. If it resides, the signal will be received by the receiver; otherwise it will be considered as lost signal. Under ray-cone scheme, the reception test of the signal can be carried out by considering a reception sphere with radius equal to $\frac{\alpha d}{\sqrt{3}}$ (Seidel & Rappaport, 1994) at the receiving point, where α is the angular distance between two adjacent rays and d is the total length of the path of the ray. The concept of overlapping of ray cones generates errors if a receiving point is located in the overlapping area between the ray cones. In this situation, the Rx will receive two rays and ray double counting will occur (Durgin et al., 1997). There are some procedures proposed in (Durgin et al., 1997; Yun et al., 2001) to handle this issue.

To test the intersection of a ray with an object is a classical problem in computational geometry and graphics (O'Rourke, 1993). The SBR algorithm tests all the objects to determine whether a ray intersects with an object. If the number of obstacles are large in the indoor environment, the intersection test can be very time consuming and inefficient. It is noticed in (Catedra et al., 1998) that the intersection test can take more than 90% of CPU time for a general SBR algorithm. Currently this algorithm is being widely used while modeling indoor radio propagation. But the computation time and accuracy of signal prediction are still open issue for this model.

2.2.4 IMAGE METHOD

The image method described in (Iskander & Yun, 2002; Tran-Minh & Do-Hong, 2008; Zhuang et al., 2008) is one of the deterministic approaches for ray-tracing in indoor environment. It is a simple and accurate method to predict the ray trajectory between the transmitter and the receiver. This method computes reflection paths by considering virtual sources taken by mirroring the location of the source over each polygonal surface of the environment. For each virtual source, a complete reflection path can be constructed by considering iterative intersection of a line segment from the source to the receiver with the reflecting surfaces. Specular reflection paths can be computed up to any order by generating virtual sources recursively.

Figure 2.10 shows the working principle of the image method for a simple case. Here rectangles labeled by *W1* and *W2* are walls working as reflectors for the rays. *Tx* and *Rx* are the transmitter and the receiver respectively. For this simple scenario, the image (*Tx1*) of the transmitter (*Tx*) due to *W1* is first determined. Then the image (*Tx2*) of *Tx1* due to *W2* is calculated. The reflection point *P2* on the wall *W2* can be found out by connecting *Rx* and *Tx2*. Another intersection point *P1* on the wall *W1* can be found out by connecting the points *P2* and *Tx1*. Thus the path of the signal from the transmitter to the receiver is traced by connecting the points *Tx*, *P1*, *P2* and *Rx* respectively.

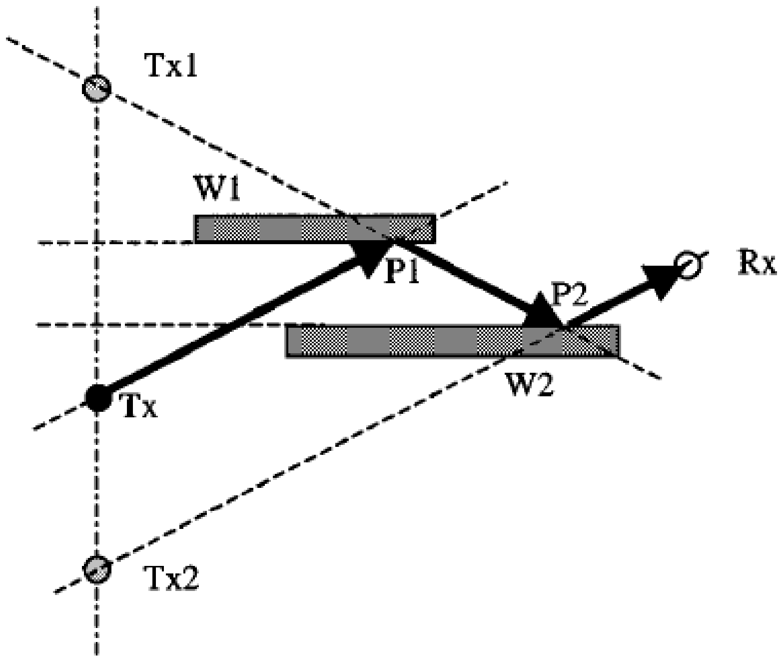


Figure 2.10: Signal prediction using image method (Tran-Minh & Do-Hong, 2008).

The basic advantage of the image source method is its robustness. It can guarantee that all the specular paths up to a given order will be found. Though the image technique is accurate, it suffers from inefficiency. When the number of walls and obstacles involved is large and there are lots of reflections for a single path from transmitter to receiver, this method suffers from large computation time. Its computation complexity has exponential growth. In general, $O(n^r)$ virtual sources are generated for r reflections with n surface planes in the environments. For real life applications, special techniques such as the acceleration and hybrid methods have to be used to minimize the computation time. Moreover this method can handle very simple environments having few obstacles. But many indoor environments with which we are concerned in our daily life are furnished and complex. The image method is not adequate to analyze those environments. Therefore, the application of the image method is very limited for indoor radio propagation prediction.

2.2.5 HYBRID METHOD

(Tan & Tan, 1996) proposed a hybrid model combining both image and SBR techniques. The SBR method is used for faster identification of a possible ray trajectory from a transmitter to a receiver. If the trajectory of the emanated ray is found, a series of walls involved on the way can be determined. The accurate reflection positions can then be found by the image method. This method has the advantages of both SBR (efficient) and image (accurate) methods but still suffers from computational inefficiency.

2.2.6 RAY LAUNCHING METHOD

Ray launching model reported in (Hoppe et al., 1999; Raida et al., 2008; Lawton & McGeehan, 1994; Sato & Shirai, 2008; Sato & Shirai, 2009) is basically a ray-path searching algorithm. That is, the ray-tracing program is applied only to those areas where rays are likely to be existed (Agelet et al., 2000). This method consists of casting rays from the transmitter in a discrete set of directions in the channel. The number of selected rays must be large enough to properly characterize multipath propagation in the corresponding environment. Here a small constant angular distance (θ) between the launched signals from the transmitter must be specified to generate reliable results. The concept of ray launching technique has been shown in Figure 2.11. This technique is computationally efficient and its efficiency is further increased since rays falling below a given threshold or exceeding a given number of interactions with the objects in the environment can be discarded. But the accuracy of this model is greatly reduced for those rays traveling long distances from the transmitter. As this model launches the rays from the transmitter with a constant angular increment (θ), there is huge possibility of neglecting an object, which is very small and located in the middle between the trajectories of two signals. Thus, it can be said that, ray-launching technique is suffering from accuracy in terms of signal prediction.

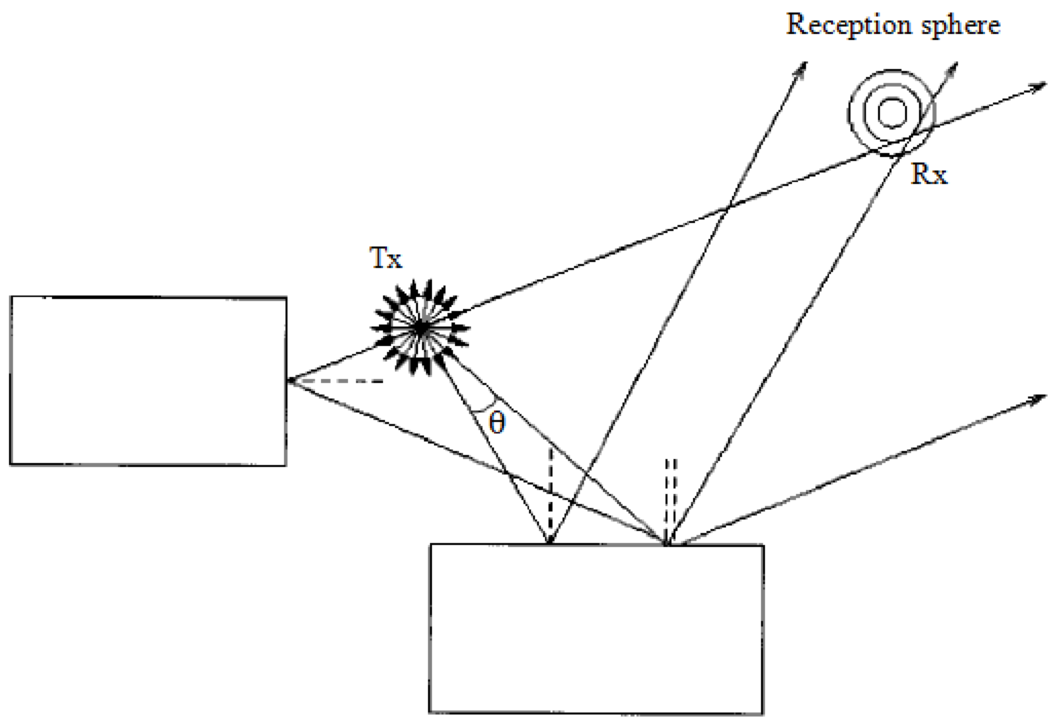


Figure 2.11: Illustration of ray launching technique.

2.2.7 BEAM TRACING

In order to describe the working procedure of beam tracing technique reported in (Fortune, 1998; Rad et al., 2009; Chung et al., 2004), select a sequence W of walls $w_1, w_2, \ldots, w_k$. The reflection cone C_w refers to all points in three-dimensional space reached by propagation paths from the base station that reflects off exactly the walls in W in order. Figure 2.12 shows a reflection cone C_w, for a sequence consisting of a single wall w. Suppose v is the reflection of the base b in the plane of wall w. C_w is a truncated polyhedral cone: the apex of C_w is v; the facets of C_w are each a portion of the plane through v and an edge of w. C_w is truncated by the wall w which forms the only bounded facet of C_w. Both of the line segment vp and the reflecting path from b to p intersect wall w at the same point.

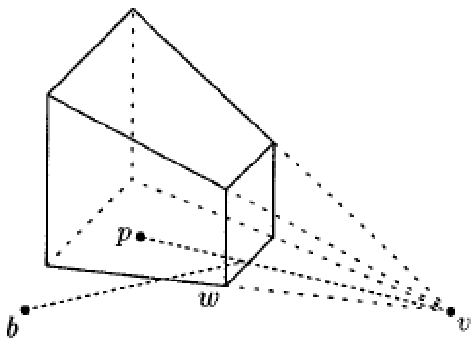


Figure 2.12: Reflection cone (outlined in solid lines). *b* is base, *v* is virtual transmitter. Reflecting path from *b* to *p* intersects *w* at the same point as line segment *vp* (Fortune, 1998).

If $W = w_1, w_2, \ldots, w_k$ consists of more than one wall, C_w is again a truncated polyhedral cone (if it is nonempty). C_w is not empty exactly if for each of $i = 2, \ldots, k$, wall w_i intersects with the reflection cone generated by walls $w_1, \ldots, w_{i-1}$. The apex of C_w is the virtual transmitter generated by successive reflection of the base in the planes of the walls $w_1, \ldots, w_k$. Assuming *a* priori bound on the number of reflections (to keep the algorithm finite); the pseudo code of beam tracing algorithm (Fortune, 1998) can be given simply as

```
for each reflection cone C
        for each sample point p inside C
                compute power of path to p .
```

The significant advantage of beam tracing algorithm over conventional ray tracing method is the efficiency in reducing the computation time. Only for small number of reflections, beam tracing technique is competitive with the conventional ray tracing algorithm in running time, largely as a consequence of the extensive filtering of propagation paths. This algorithm is also useful for the calculation of the field strength at different heights of the receiving antennas. But this algorithm cannot handle complex environment having large number of obstacles. As the number of reflection increases, the manipulation of reflection cones becomes harder which lead to the dominant cost.

2.2.8 RAY SPLITTING METHOD

Refer to (Fortune, 1998; Liu et al., 2008); according to ray splitting method consider a small spherical area around the transmitter. Points on the sphere are interpreted as direction vectors pointing away from the transmitter. Divide the sphere into triangles of reasonably uniform size and shape. This model launches a sample ray for each triangle on the sphere. Each ray contains a canonical path, which generates the path followed by the ray. It also has a capture cone, which determines the sample points captured by the ray. The initial direction of the ray is considered as centered of the triangle. The initial capture cone is formed by all points reachable from the transmitter in a direction that lies within the triangle. If any canonical path intersects with a wall, a reflected ray is generated. Its capture cone refers to the reflection of the capture cone of the original ray truncated by the plane of the wall.

For each ray, the algorithm keeps record of all the reflection determined by the canonical path. The algorithm also can assign power to any point on the canonical path using the accumulated product and the distance along the path to the transmitter. If there is a sample point inside a capture cone, the algorithm assumes that there is also a path to the sample point that is similar to the canonical path. The sample point is assigned the power of a neighboring point on the canonical path. The ray tracing algorithm stops the process of tracing a ray if it leaves the boundary of the corresponding environment, or if the power assigned to the canonical path falls below a threshold value.

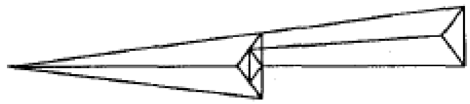


Figure 2.13: Ray splitting to maintain spatial separation (Fortune, 1998).

The spatial distance between two adjacent rays increases linearly with the increase of distance travelled by the rays. If the spatial separation exceeds a bounding value, the ray is split again into four sub rays, halving the spatial separation of rays. The capture cone is also split into four pieces. Referring to Figure 2.13**,** assume that each initial ray is split at least once. Then the total number of emanated rays counting reflected, transmitted, and split rays respectively, can be bounded by

$$\frac{4\pi\beta_{1m}}{A\beta_t} \tag{2.21}$$

where β_{1m} is the free-space power in one meter, β_t refers to the threshold power, and A is a cross-sectional area of a ray just after a split in meters squared. This bounding condition can be shown by a conservation-of-power argument, comparing the minimum threshold power of a ray with the power leaving the transmitter. For the typical parameter values β_{1m} = -23dBm, β_t = -90dBm, A = 1 and for a spatial separation of two meters, the bound is about 63 x 10^6 which is very large value. This large bound is pessimistic for most of the environments as rays leave the propagation environment rather than die because of the threshold power.

2.3 INDOOR WIRELESS COVERAGE OPTIMIZATION

There are several optimization techniques as proposed in (Anderson & McGeehan, 1994; Hu & Goodman, 2004) to determine the locations of the transmitters and ray tracing methods as reported in (Tayebi et al., 2009; Blas et al., 2008; Cocheril & Vauzelle, 2007; Razavi & Khalaj-Amirhosseini, 2008; Liang et al., 2008; Lee, 2009; Kim & Lee, 2009; Mphale & Heron, 2007; Gomez et al., 2010; Teh et al., 2006; Alvar et al., 2008; Tao et al., 2008; Bang et al., 2007; Martini et al., 2007; Jin, 2006; Xia et al., 1996) to optimize the positions of the base stations in the indoor environments. But according to (Yun et al., 2008), none of them provides any integrated approach that can help to obtain the optimized wireless coverage by removing the bad receiving signal areas. Bad receiving signal areas in indoor environments refer to those areas where the sampling points cannot receive any signal from the transmitter or the signal strength is very low. To address the issue of wireless coverage optimization, the algorithm proposed by (Yun et al., 2008) describes an integrated approach of Ray Tracing and Genetic Algorithm. This method exploits the advantages of the ray-tracing technique and genetic algorithms and presents a new method that determines the minimum number and locations of transmitters to ensure effective wireless coverage for an indoor propagation environment.

The ray-tracing method used for this optimization model avoids the ray-wall intersection tests like the conventional shooting-and-bouncing-ray algorithm (Yun et al., 2002). This model, therefore, avoids routine search methodology and has been proved accurate and computationally efficient in the calculation of wireless. This model considers a typical office building as depicted in Figure 2.14 where the sampling points are labeled from 1 to 79. The size of the floor is assumed as 60m by 45m. The transmitter(s) are placed to the left of the sampling points by 36 cm to avoid the overlapping of transmitter and sampling points. As for GA calculations, each chromosome contains information of transmitter(s) as the optimization variable. The GA reruns the ray tracer for each generated chromosome to calculate the field distribution at each sampling point from the location of transmitter(s) as provided by the chromosome. The cost function is chosen as the number of sampling points where the received power from a transmitter is less than -50dB. These sampling points are marked as bad sampling points and the areas associated with them are identified as bad receiving-signal area. Therefore, GA finds the optimum positions of a given number of transmitters to minimize bad receiving-signal areas.

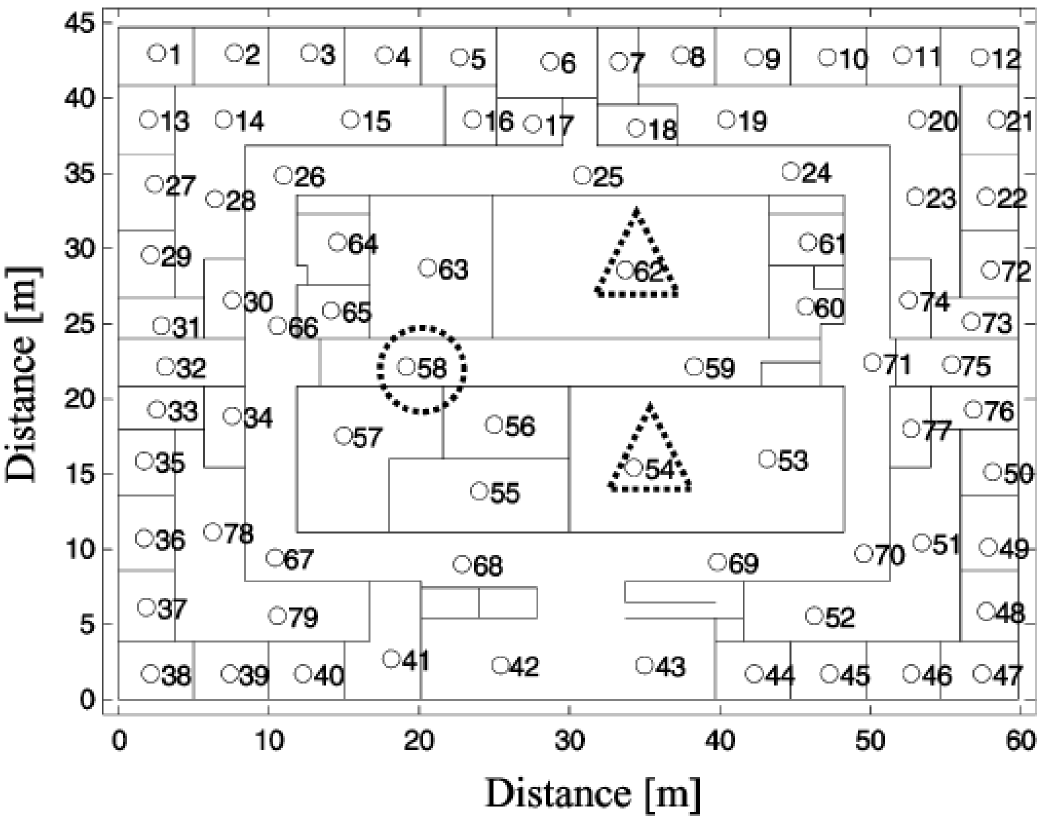


Figure 2.14: A floor plan for a typical office building and the locations of sampling points. (O) Optimized transmitter position in case of one transmitter. (Δ) Optimized transmitter positions in case of two transmitters (Yun et al., 2008).

At first, only one transmitter is considered and its position is optimized. In Figure 2.14, the sampling point 58 surrounded by a dotted circle is chosen as the optimum transmitter position by GA. In this case, four bad receiving signal areas are found including (not highlighted) the sampling points 8, 45, 46, and 47. To minimize the bad receiving area, another GA is run with two transmitters. After the GA optimization, the sampling points 54 and 62 surrounded by dotted triangles are chosen as the two optimum transmitter locations and for this case, there is no bad receiving-signal area exists. This result shows that two transmitters are sufficient to provide complete wireless coverage over the entire indoor area.

2.4 SUMMARY

Empirical models are based on very simple and straightforward formulas (Yarkoni & Blaunstein, 2006) and derived from extensive field measurements. These are fast and simple to use, only simple input is needed, and the formulas are easy to apply. However, empirical models provide poor site-specific accuracy and cannot predict the wide-band parameters of the communication channel. On the other hand, deterministic models are very accurate, site-specific and they can predict wide-band parameters as well. But usually the deterministic models are very slow or they need some pre-processing and simplifications to be faster. In addition, they need very precise input database of obstacles and a site geometry including the electrical parameters of used materials, which are often unavailable or too expensive to obtain. Now it is a big challenge to search for a new propagation model and design tool that will avoid the disadvantages and combine the advantages of the above models at the same time.

Moreover, the above algorithms have been used for accurately predicting the site-specific radio propagation characteristics, in spite of its computational intensity. A naive implementation of these models can be computationally expensive. In a large building there may be lots of possible propagation paths between base and sampling points, though only a few contribute significant power, and received by the receiver and others are lost. The above discussed ray tracing algorithms are not concern about identifying the lost signals before processing of them. The ignorance of the processing of unnecessary signals can reduce the computation time significantly. The proposed ray tracing algorithm is concern about this aspect. A typical obstacle can be considered as consisting of four edges. While calculating the intersection point, it is not needed to consider all four edges. Only few edges of an obstacle should be considered based on the direction of the ray .There is no proper guideline by the existing algorithms to manage this kind of situations. The proposed algorithm will strictly take into account this kind of conditions to reduce the computation time.

On the other hand, the wireless coverage model as discussed in section 2.2 reruns the ray tracer for every generated chromosome. So, there is huge possibility of rerunning the ray tracing program multiple times for the same transmitter position which is time consuming. This model also cannot reuse the information of a transmitter position instead of running the ray tracer repeatedly. So, this model has more space and time complexities as well as more computation time. The proposed wireless coverage algorithm has been developed to outperform the existing coverage algorithm in terms of space complexity, time complexity and computation time.

CHAPTER 3

RESEARCH METHODOLOGY

This study presents two different types of algorithms intended for modeling indoor radio propagation. These algorithms are as follows:

(i) Proposed ray-tracing (RT) technique for indoor radio signal prediction.

(ii) Proposed coverage algorithm for optimum indoor wireless coverage.

The proposed RT technique is developed to offer successful prediction of radio signals. And the coverage algorithm is used to find the optimal positions of the transmitters to cover the whole indoor environment. Here, the coverage algorithm uses the proposed ray-tracing technique for calculating the field distribution among the sampling points and Genetic Algorithm to optimize the overall performance.

3.1 PROPOSED RAY-TRACING TECHNIQUE

The purpose of this section is to introduce an accelerated ray-tracing technique based on the proposed Binary Angle Division mechanism. The Binary Angle Division algorithm equally divides the angular distance between two consecutive signals emanated from the transmitter. The proposed ray-tracing technique will be used to predict the signal trajectory. Triangular geometry will provide specific guideline to define the propagation path emanated from the transmitter. On the other hand, the proposed Binary Angel Division technique will be used to increase the efficiency in terms of computation time and accuracy. Lastly, the precedence of the proposed technique will be proved by comparing with the relevant methods in terms of computational efficiency and accuracy. Thus, it can be said that the attractive features of the proposed ray tracing technique will be ease of implementation, computationally efficient, and more accurate than the existing ray-tracing models reported in (Iskander & Yun, 2002; Ling et al., 1989; Wang et al., 2008; Dikmen et al., 2010; Saeidi et al., 2009; Tao et al., 2010; Buddendick & Eibert, 2009; Mohtashami & Shishegar, 2010; Kipp, 2010; Amornthipparat et al., 2007; Geng et al., 2008; Gao, 2010) and ray-launching techniques in (Hoppe et al., 1999; Raida et al., 2008).

In this study, the proposed ray-tracing technique based on the Binary Angel Division has been developed by C# 2008 of .NET framework 3.5, an object oriented programming language. The program can perform an intersection test for a ray and an object. Although the algorithm to determine the intersection is different for different objects, the same subroutine may be called to perform the intersection test.

For ease of understanding, this study will consider a two dimensional (2D) space for a typical indoor environment. Suppose, there is a transmitter (*Tx*) and a receiver (*Rx*) placed in the indoor area as shown in Figure 3.1. Before describing the proposed algorithm, the procedure to predict the path of the emanated ray from the *Tx* is explained as follows:

(i) Launch the ray from the *Tx* at an angle θ.

(ii) Build the ray using triangular geometry. Assume a ray *TxN1* that has been launched from *Tx* at an angle θ with the base line *TxB1* as shown in Figure 3.1. It forms a triangle $\Delta TxB1N1$. To compute the end point *N1* of the ray, it is required to compute the length of the normal *B1N1* of the triangle $\Delta TxB1N1$. The overall triangular formula to compute the end point *N1* of the ray *TxN1* has been stated in the following Equations (3.1-3.6).

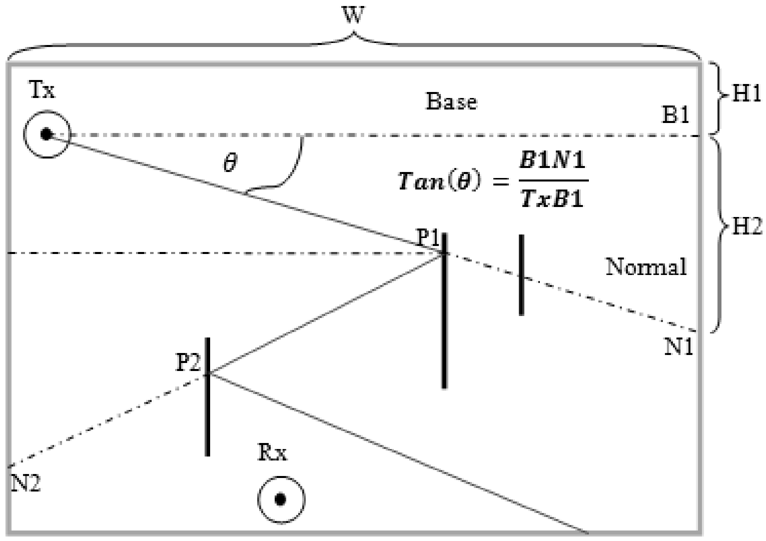


Figure 3.1: To build a ray using triangular geometry.

$$Tan(\theta) = \frac{Normal}{Base} = \frac{B1N1}{TxB1} = \frac{H2}{Width(W) - X \text{ value of } Tx} \tag{3.1}$$

where *H2* is obtained from the following equation:

$$H2 = Tan(\theta) * (Width(W) - X \text{ value of } Tx) \tag{3.2}$$

The value of *H1* is as follows:

$$H1 = Tx(Y) = Y \text{ value of } Tx \tag{3.3}$$

Next, the point $N1(x, y)$ can be computed as follows:

$$N1(X) = X \text{ value of } N1 = \text{Width of the measurement area} = W \tag{3.4}$$

$$N1(Y) = Y \text{ value of } N1 = H1 + H2 \tag{3.5}$$

Therefore,

$$N1(x, y) = N1(W, H1 + H2) \tag{3.6}$$

(iii) Find all object intersections with the ray.

(iv) Compute the hit point (reflection point), where the ray hits the object. The algorithm stated in Figure 3.2 can be used to compute the hit point.

```
/// <summary>This method calculates the hit point</summary>
/// <param name="start1">start point of the ray</param>
/// <param name="end1">end point of the ray</param>
/// <param name="start2">start point of the obstacle</param>
/// <param name="end2">end point of the obstacle</param>
/// <returns></returns>
public static PointF FindHitPoint(PointF start1, PointF end1,
PointF start2, PointF end2) {
    float denom = ((end1.X - start1.X) * (end2.Y - start2.Y))
                - ((end1.Y - start1.Y) * (end2.X - start2.X));
    // the lines are parallel
    if (denom == 0)return PointF.Empty;
    float numer = ((start1.Y - start2.Y) * (end2.X - start2.X))
                - ((start1.X - start2.X) * (end2.Y - start2.Y));
    float r = numer / denom;
    float numer2 = ((start1.Y - start2.Y) * (end1.X - start1.X))
                - ((start1.X - start2.X) * (end1.Y - start1.Y));
    float s = numer2 / denom;
    if ((r < 0 || r > 1) || (s < 0 || s > 1)) return PointF.Empty;
    // Find intersection point
    PointF result = new PointF();
    result.X = start1.X + (r * (end1.X - start1.X));
    result.Y = start1.Y + (r * (end1.Y - start1.Y));
    return result;
}
```

Figure 3.2: Algorithm to find the hit point of the object.

(v) Identify the closest object intersection based on the distance from the ray's emanating point. In Figure 3.1, the closest intersection point for the ray *TxN1* is *P1*.

At the beginning, from the position of *Tx*, divide the whole space into four quadrants as illustrated in Figure 3.3. The size of each quadrant is 90 degree. To trace the rays emanated from the *Tx*, the proposed algorithm will be applied for those four quadrants individually. Referring to Figure 3.4, there are some obstacles (*R1*, *R2*, *R3*), working as reflectors. The target is to predict the paths of the significant signals that are being emanated from *Tx* and received by *Rx*. As presented in Figure 3.4, the receiver is placed on the fourth quadrant and thus, the proposed algorithm is applied on the fourth quadrant as illustrated. By launching two signals *L1* and *L2* from the *Tx*, a polygon consisting of the points *L1*, *Tx*, *L2*, and *Q4* will be formed. The next step is to check if there is any obstacle within this polygon. To do this, consider only one point of each obstacle (e.g., top left corner point) and determine if the point lies on the interior of the polygon using the *PNPOLY* (point inclusion in polygon test) algorithm as shown in Figure 3.5.

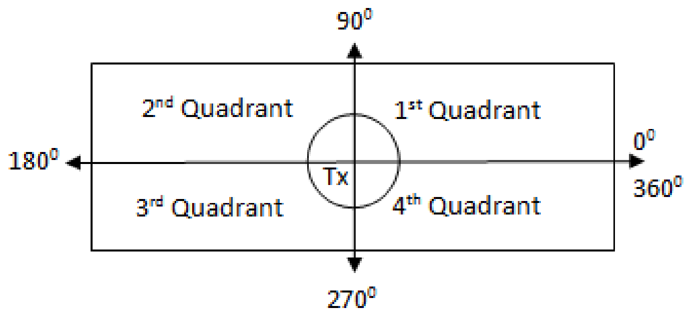


Figure 3.3: Four quadrants in 2D space.

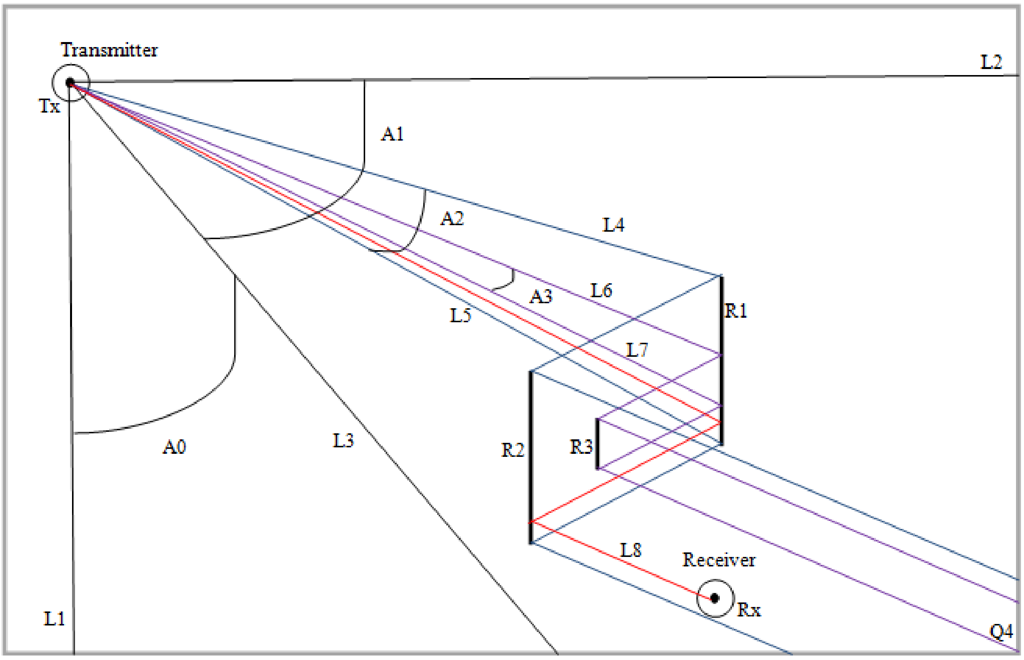
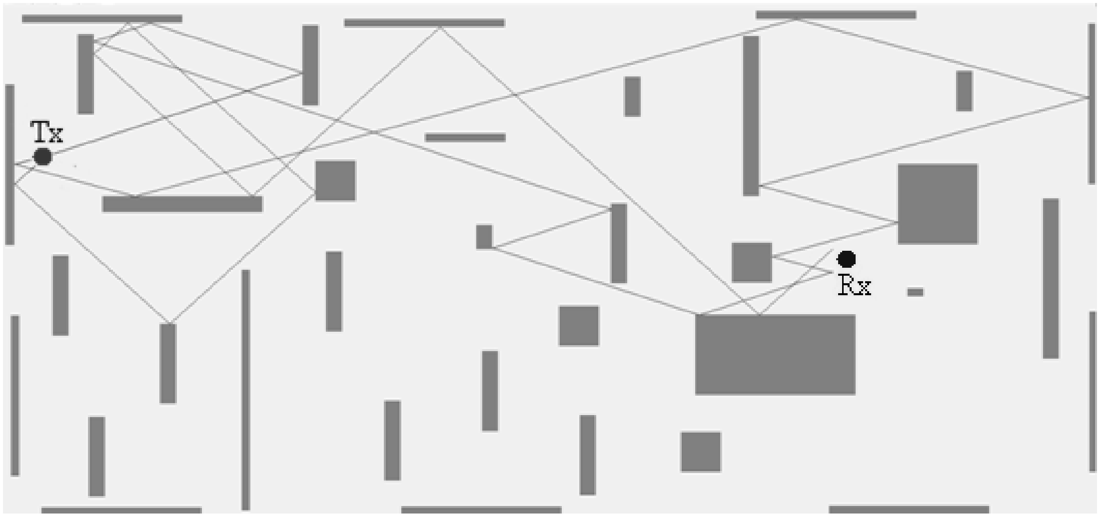


Figure 3.4: Radio signal prediction in 2D space of indoor environment.

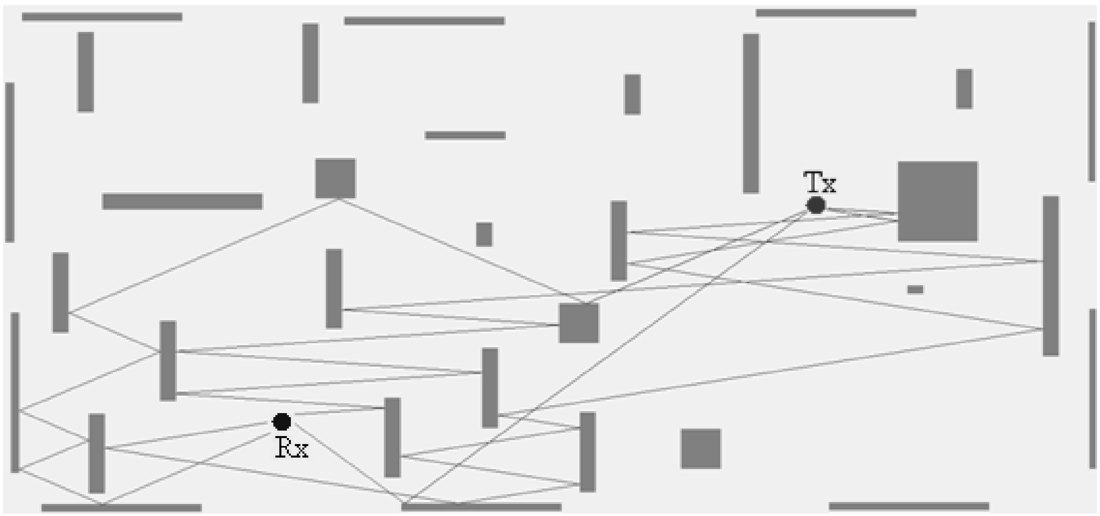
If any obstacle is found on the interior of the polygon, the angular distance between *L1* and *L2* will be divided equally by launching another signal *L3* from the *Tx*. As a result, two new polygons will be formed for the regions *L1TxL3* and *L3TxL2*, marked by *A0* and *A1*, respectively. If the *PNPOLY* algorithm in Figure 3.5 is applied for the regions *A0* and *A1*, it will be seen that there is no obstacle as well as no receiver exist for *A0*. Thus, it can skip the processing of all other signals within *A0* because all the signals within this area will be lost as well. That is, *A0* is an invalid region. However, there are obstacles exist for the region *A1*. Therefore, *A1* is considered as a valid region and is to be divided equally by launching a signal *L4*. The path of the signal *L4* is followed in case of intersection as well as reflection until it passes away the propagation area. Here, signal *L4* reflects on two obstacles *R1* and *R2*, respectively and finally, passes away the propagation area. Another signal *L5* passes through the middle of the angular distance of the signals *L3* and *L4* and passes away the indoor area after reflecting on the obstacles *R1* and *R2*. Similarly, consider signals

```
public static bool pnpoly(List<PointF> polygon, PointF p){
float xinters;
int counter=0,N = polygon.Count;
PointF p1 = polygon[0], p2;
for (int i = 1; i <= N; i++){
p2 = polygon[i % N];
if (p.Y > MIN(p1.Y, p2.Y)){
if (p.Y <= MAX(p1.Y, p2.Y)){
if (p.X <= MAX(p1.X, p2.X)){
if (p1.Y != p2.Y){
xinters = (p.Y - p1.Y) * (p2.X - p1.X) / (p2.Y - p1.Y) + p1.X;
if (p1.X == p2.X || p.X <= xinters) counter++;
}}}}
p1 = p2;
}
//outside
if (counter % 2 == 0)return false;
//inside
else return true;
}
```

Figure 3.5: C# function to determine if a point lies on the interior of a polygon with N points.



(a) Three significant signals.



(b) Four significant signals.

Figure 3.6: Simulation in a sample indoor environment.

L6 and *L7* based on analogous Binary Angle Division that are passing through the indoor area after reflecting on the obstacles *R1* and *R3*. Here, the region *A3* covered by the paths of the signals *L6* and *L7* contains no obstacles. Hence, *A3* can be marked as invalid region and all other signals within this region can be ignored. Now, consider another signal *L8* that is being passed through the middle of the signals *L5* and *L7*, and after consecutive reflections with the obstacles *R1* and *R2*, it reaches to the receiver. Consider this signal as a significant signal. Figure 3.6 shows some significant signals generated by the proposed algorithm for four different scenarios. In Figure 3.6, the circles labeled by Tx and Rx represent the transmitter and the receiver, respectively and the rectangles are the obstacles. The path of the signals from Tx to Rx is composed of connected line segments, where the first line segment is the emanated ray and the others are the reflected rays. To trace the paths of the signals from the transmitter to the receiver, the above Binary Angle Division algorithm is applied in other quadrants as well. In this way, by applying the proposed ray tracing algorithm in all four quadrants, it is possible to identify the invalid regions to skip the processing of all unnecessary signals and predict the significant signals received by the receiver in an indoor environment. The following recursive algorithm brings out the whole radio signal prediction technique for an individual quadrant. The signal prediction algorithm is included as follows:

(i) At the position of *Tx*, let *Start* and *End* represent the starting and the ending angles, respectively.

(ii) Launch the signals from the *Tx* at angles *Start* and *End* respectively and follow the paths until they become weaker or pass away the indoor environment or they are received by the receiver after reflections with the obstacles.

(iii) If the emanated ray is received by the *Rx*, consider it as a significant signal.

(iv) Check the trajectories of two signals emanated at angles *Start* and *End*, if they create valid polygon. If there is same number of reflections and corresponding reflectors are same, then it can be assumed that the region covered by the paths of these two signals forms a valid polygon.

(v) If the polygon is valid and there is no obstacle within the polygon, skip all other signals within the angles *Start* and *End*. Otherwise, continue to the following steps.

(vi) Set *Start* = *Start* and *End* = (*Start* + *End*)/2 and go to the step (ii).

(vii) Set *Start* = (*Start* + *End*)/2 and *End* = *End* and go to the step (ii).

3.2 PROPOSED COVERAGE ALGORITHM

In general, the coverage area can be approximated as point coverage. That is, if all the sampling points are covered by the minimum number of transmitters, the entire area will be covered optimally. The problem of selecting the minimum number of transmitters, however, is NP-hard (Yang et al., 2006). Although there are existing optimization methods reported in (Anderson & McGeehan, 1994; Hu & Goodman, 2004; Yun et al., 2008) to determine the locations of transmitting antennas and ray-tracing methods reported in (Tayebi et al., 2009; Blas et al., 2008; Cocheril & Vauzelle, 2007; Razavi & Khalaj-Amirhosseini, 2008; Liang et al., 2008; Lee, 2009; Kim & Lee, 2009; Mphale & Heron, 2007; Gomez et al., 2010; Teh et al., 2006; Alvar et al., 2008; Tao et al., 2008; Bang et al., 2007; Martini et al., 2007; Jin, 2006; Xia et al., 1996) to design and optimize the base stations, none of them provides an efficient integrated approach that can lead to the achievement of an optimum wireless coverage. To achieve this goal, it is necessary to incorporate the RT technique with the proper optimization algorithm. In this regards, genetic algorithm (GA) reported in (Yun et al., 2008; Rahmat-Samii & Michielssen, 1999; Choo & Ling, 2002; Lim & Ling, 2006; Lim & Ling, 2007; Agastra et al., 2008; Meng, 2007; Lucci et al., 2004) is being successfully used in optimizing many antenna design and electromagnetic problems over the years. In this study, the problem of selecting the minimum number of transmitters and their locations to cover the whole propagation area has been addressed.

The proposed coverage algorithm uses both ray-tracing as proposed in this study and GA incorporated with Breath First Search (BFS) of (Russel & Norvig, 2003; Knuth, 1997) to provide an efficient coverage for indoor environment. Here, each chromosome is represented by a coverage pattern that keeps the coverage information of the corresponding transmitter. In BFS, the live node refers to that node, which has been generated and all of whose children have not yet been generated. The live node whose children are currently being generated is called E-node. This study applies branch-and-bound terminology while generating search tree using BFS. Basically, branch-and-bound is a backtracking process, where bounding functions are used to help avoid the generation of sub-trees that do not contain an answer node. The proposed coverage algorithm generates less number of nodes in the search tree by applying bounding functions that reduces both time and space complexities of the algorithm, which lead to minimum number of iterations as well as less computation time. The proposed algorithm also shows that, instead of rerunning the ray tracing method for the same transmitting position, an individual coverage pattern can be generated for each transmitter that will be reused for further iteration. This concept reduces the computation time as well. The overall efficiency of this algorithm has been proved by comparing with the existing relevant algorithm as reported in (Yun et al., 2008).

The basic idea of the proposed coverage algorithm is to select k number of transmitters for k positions from n number of available positions where each transmitter must have unique coverage pattern and the resultant pattern formed by recombination; will cover all the sampling points. To achieve this standard, this study integrates proposed ray-tracing as reported in section 3.1 with GA incorporated with BFS to optimize the indoor wireless coverage. For simplicity of discussion, the following notations will be used:

(i) t_i is the i^{th} transmitter where $1 \le i \le n$, if the number of sampling points (receiving points) in the indoor area is n.

(ii) p_i is the coverage pattern of t_i.

(iii) $G(i)$ is the number of good sampling point in p_i.

(iv) $B(i)$ is the number of bad sampling point in p_i.

(v) $N(g)$ is the number of good sampling point in a coverage pattern.

(vi) $N(b)$ is the number of bad sampling point in a coverage pattern.

As for genetic calculation, each chromosome is represented by a coverage pattern to describe the coverage information of each transmitter. Before describing the proposed algorithm, the concept of the coverage pattern is considered necessary to be explained. Suppose, a set of n sampling points $S = \{s_1, s_2, ..., s_n\}$ has been deployed in the region to be covered by a set of k transmitting antennas $T = \{t_1, t_2, ..., t_k\}$, where $k \le n$ and each transmitter t_i has a coverage pattern $P_i = \{e_1, e_2, ..., e_n\}$, where $1 \le i \le k$. Here, the value of the element e_j is either “0” or “1” and $1 \le j \le n$. The value $e_j = 1$ refers to the j^{th} sampling point as good sampling point where the j^{th} sampling point is covered by the i^{th} transmitter. Thus, the existence of the relationship between the transmitter t_i and the sampling point s_j can be expressed as follows:

$$e_{i,j} = \begin{cases} 1 & \text{Sampling point } s_j \text{ is covered by the transmitter } t_i \\ 0 & \text{Otherwise} \end{cases}$$

The union of any two patterns $P^{'}$ and $P^{''}$ generates the resultant pattern P^{*}. That is,

$$P^{*} = \left\{ P^{'} \cup P^{''} \mid \sum_{i=1}^{n} e_i \geq 0 \right\} \tag{3.7}$$

In the optimal condition, the number of transmitter is minimized and the summation of the values of the elements of the resultant coverage pattern is *n*. That is,

$$P^{*} = \left\{ x \mid \sum_{i=1}^{n} e_i = n \right\} \tag{3.8}$$

For example, if there are 10 sampling points numbered from 1 to 10 and one transmitter covers the sampling points 1, 3, 4, 8, respectively, the coverage pattern of that transmitter will be as follows:

	e1	*e2*	*e3*	*e4*	*e5*	*e6*	*e7*	*e8*	*e9*	*e10*
$P^{'}$ =	1	0	1	1	0	0	0	1	0	0

And, for another transmitter covering the sampling points 2, 3, 7, 9, 10, the coverage pattern will be:

$P^{''}$ =	0	1	1	0	0	0	1	0	1	1

Therefore, $P^{'} \cup P^{''} = P^{*} =$

1	1	1	1	0	0	1	1	1	1

Here, the resultant pattern P^{*} is created by merging both $P^{'}$ and $P^{''}$ based on the concept of logical inclusive OR operation as shown in Table 3.1, where the result is “1” if the first bit is “1” OR the second bit is “1” OR both bits are “1”. Otherwise, the result is “0”.

Table 3.1: Truth table for bitwise OR operation.

1st value	2nd value	Result
0	0	0
0	1	1
1	0	1
1	1	1

Thus, for n sampling points if the set of unique coverage patterns is $P = \{p_1, p_2, ..., p_n\}$, the objective is to find a subset $P^{'} \subseteq P$, where the number of covered sampling points is $\left| \bigcup_{P_i \in P^{'}} P_i \right| = n$.

In this study, the BFS uses branch-and-bound terminology. That is, bounding functions as well as termination criteria are applied while expanding the search space. For n number of sampling points in the corresponding indoor environment, the proposed bounding functions are as follows:

(i) As a bounding function, the obvious criteria will be used such that if $T^{'} = \{t_1, t_2, ..., t_i\}$ is the set of transmitters that represents the path to the current E-node, then all children nodes with parent-child labeling t_{i+1} are $T^{''} = \{t_1, t_2, ..., t_i, t_{i+1}\}$, where the coverage pattern p_{i+1} of t_{i+1} will not be covered by the resultant pattern $\bigcup_{1 \le j \le i} P_j$ of the set $T^{'} = \{t_1, t_2, ..., t_i\}$.

(ii) The second bounding function for the proposed algorithm is $\left(N(b) \text{ in } \bigcup_{1 \le j \le i} P_j \right) \le \sum_{i+1 \le j \le n} g(j)$ where n is the maximum number of transmitters that can be considered while exploring the solution space and i refers to the i^{th}

transmitter that corresponds to the current E-node. So, $(i+1)$ refers to the child node of the E-node. That is the number of bad sampling points in the resultant coverage pattern generated from the set of transmitters that represents the path to the current E-node, should be less than equal to the summation of the good sampling points of the subsequent coverage patterns that correspond to the sub-tree where t_{i+1} forms the root node.

To make sure the successful completeness of the proposed algorithm, the following termination criteria has been proposed. The algorithm will be terminated if any of the following conditions becomes true.

(i) The set of transmitters $T^{'} = \{t_1, t_2, ..., t_i\}$ on the path to the current E-node have no bad sampling point in their resultant coverage pattern. That is, $P^{*} = \left(\bigcup_{1 \le j \le i} P_j \right)$ where $\left| p^{*} \right| = n$.

(ii) There is no live node exists in the solution space to be explored.

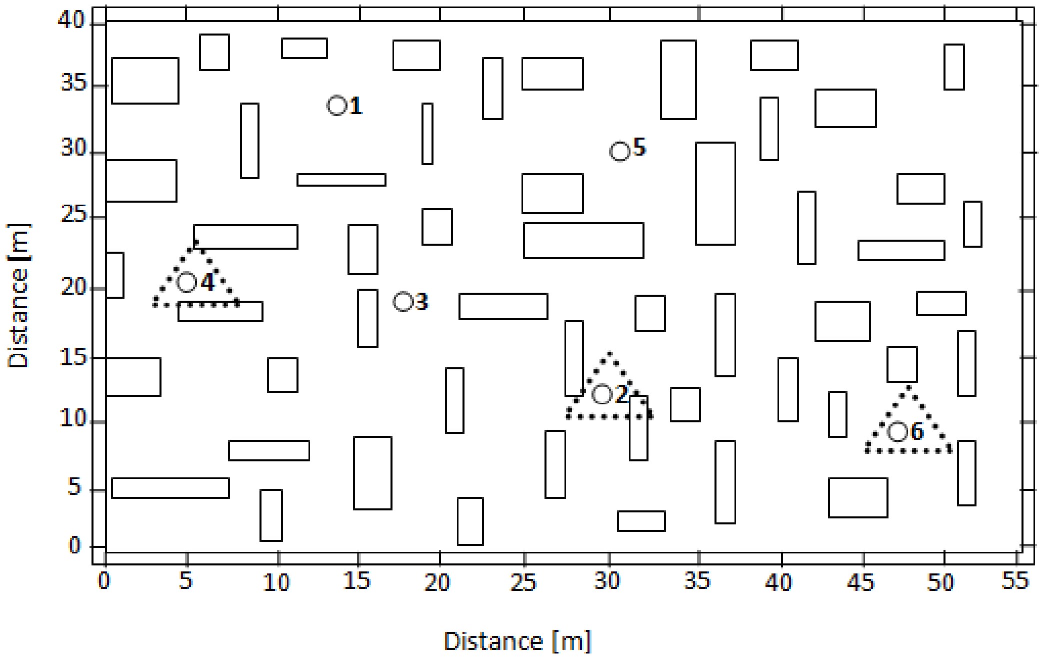


Figure 3.7: The floor plan of an office building including the locations of the sampling points (the optimized transmitter positions (Δ) when three transmitters are used).

To illustrate the proposed coverage algorithm, suppose, there are 6 sampling points labeled from 1 to 6 in the sample indoor propagation area as shown in Figure 3.7, that is, n=6. The received power at each sampling point is calculated by using the ray tracer. The transmitters are supposed to be positioned to the left of the sampling points by an arbitrary small distance of 36cm to avoid the possible overlapping between the transmitters and the receiving points (sampling points) at which the powers are being calculated. That is, if the position of the transmitter is same as the sampling point, both positions of transmitter and sampling point will be overlapped and the proposed algorithm will ignore that corresponding sampling point.

Now, run the ray tracer individually for each of the 6 positions to calculate the received power at each sampling point and generate the coverage patterns for the corresponding transmitters. Suppose the coverage patterns of the transmitters $t_1, t_2, ..., t_6$ are $p_1, p_2, ..., p_6$ as follows:

p_1 =	1	1	1	0	0	0
p_2 =	0	1	1	0	1	0
p_3 =	0	1	1	1	0	0
p_4 =	1	0	0	1	0	0
p_5 =	0	1	1	0	1	0
p_6 =	0	0	0	0	0	1

Here, the cost function to measure the effectiveness of the coverage pattern is chosen as the number of bad sampling points. The lower the number of bad sampling points, the higher the effectiveness. From the above patterns, it is seen that the values of the cost functions are 3, 3, 3, 4, 3, and 5 respectively. Here, both coverage patterns p_2 and p_5 are identical, that means, the sampling points covered by t_5 has already been covered by t_2. Hence, the proposed algorithm skips the pattern p_5 of t_5 by marking it as a duplicate pattern. Thus, the proposed algorithm considers only 5 coverage patterns $p_1, p_2, ..., p_6$ except p_5 of their corresponding transmitters $t_1, t_2, ..., t_6$ except t_5 and select minimum number of patterns from them, whose resultant pattern covers the whole indoor propagation area. The Figure 3.8 generates the state space search tree using different number of combinations of 5 transmitters to achieve the first optimal solution.

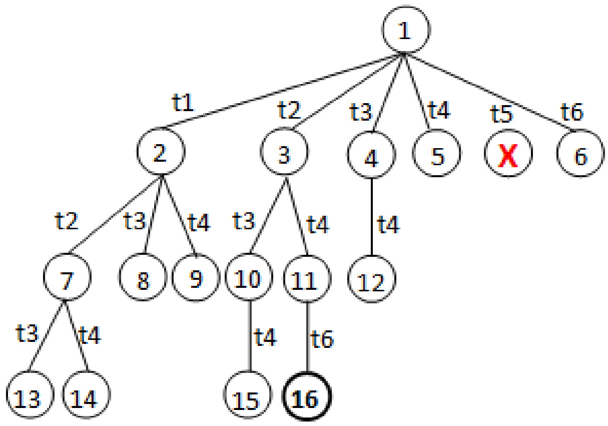


Figure 3.8: State space search tree generated by the proposed algorithm.

Referring to Figure 3.8, initially, there is only one live node, node 1. This represents the case in which no transmitter has been placed in the propagation area. This node becomes the E-node. It is expanded and its children, nodes 2, 3, 4, 5, and 6, are generated except the cross (X) marked node labeled by t_5 as its coverage pattern is already marked as duplicate. These nodes represent the solution space, where only one transmitter is considered at a time. The optimum solution is found in this state, which means, only one transmitter is sufficient for the optimum coverage of the corresponding area. Now, the only live nodes are 2, 3, 4, 5, and 6 respectively. If the nodes are generated in this order, then the next E-node is node 2 and the algorithm switches to the next level, where the optimization algorithm is based on two transmitters. Node 2 is expanded and t_2, t_3, t_4, and t_6 refer to the possible child nodes. The child node for t_6 is ignored using the second bounding function. The set of transmitters that represent the path to the current E-node 2 is $\{t_1\}$. The set has only one transmitter t_1, whose coverage pattern p_1 has 3 bad sampling points. The set of transmitters that form the sub-tree of root t_6 is $\{t_6\}$. This set contains only one transmitter t_6, whose coverage pattern has 1 good sampling point. Therefore, according to the second boundary function:

$$N(b) \text{ in} \{t_1\} \leq N(g) \text{ in} \{t_6\} \tag{3.9}$$

$$\Rightarrow 3 \leq 1 \tag{3.10}$$

The condition of the above Equation (3.10) is erroneous. As a result, the proposed algorithm will not generate the child node for t_6 from node 2. Only nodes 7, 8, and 9 will be generated that correspond to the transmitters t_2, t_3, and t_4 respectively. The node 3 of t_2 becomes the next E-node, which generates nodes 10 and 11 for t_3 and t_4, respectively and skips node for t_6 because of second bounding function as well. The next E-node 4 of t_3 generates only one node 12 for t_4 and skips node for t_6 because of second bounding function. The last node 6 on the same level (level 1) cannot generate any child node because of second bounding condition. Now, the algorithm proceeds to the next level (level 2), where the E-node 7 of t_2 generates child nodes 13 and 14, respectively. The possible child nodes for the next E-node 8 of t_3 should be of the transmitters t_4 and t_6. However, they cannot be generated because of the bounding functions. The set of transmitters that represent the path to the current E-node 8 is $\{t_1, t_3\}$, the resultant coverage pattern of which is as follows:

$P^* = P_1 \cup P_3 =$

1	1	1	1	0	0

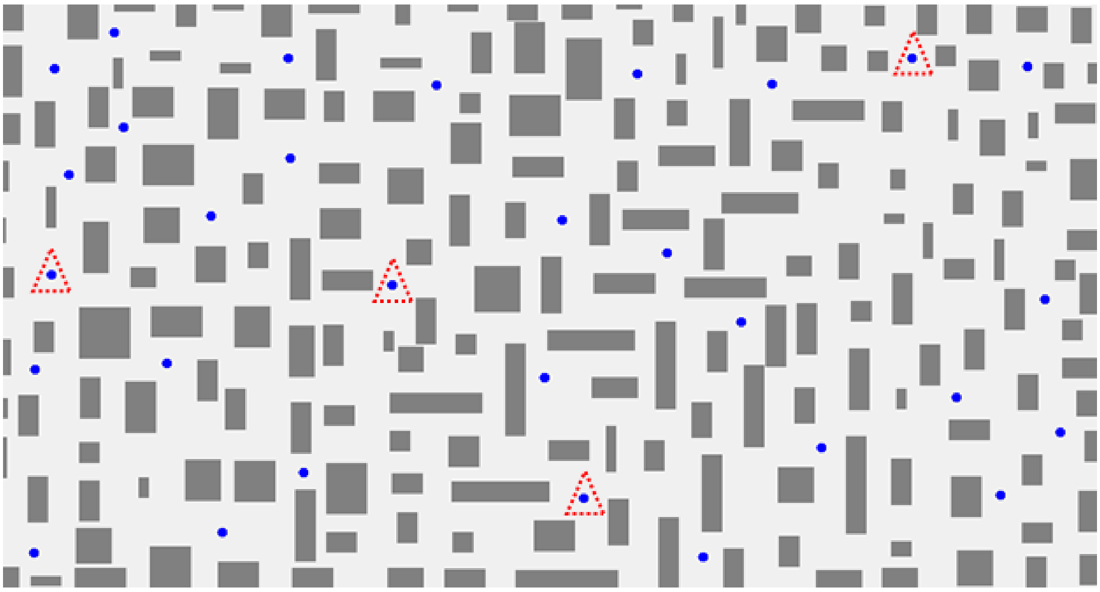
The above pattern also covers p_4 that violates the first bounding function. On the other hand, p_6 of t_6 violates the second bounding function. If the nodes are generated in this approach, the tree in Figure 3.8 will be generated based on the proposed coverage algorithm and the optimum solution will be formed by the transmitters t_2, t_4, t_6, and the solution path will be formed by the nodes 1, 3, 11, and 16, respectively. Figure 3.9 shows some sample simulations with different number of sampling points generated by the proposed coverage algorithm. In Figure 3.9, the circles represent the sampling points (receiving points), the circles surrounded by the dotted triangles represent the optimized positions of the transmitters, and the rectangles are the objects working as obstacles. The following recursive algorithm brings out the whole wireless coverage optimization technique for a typical indoor environment. The optimization algorithm is included as follows:

(i) Suppose there are n sampling points in the indoor propagation area. Therefore, in the worst case, maximum n number of transmitters is required for the optimum wireless coverage as sampling points are being used as the transmitting positions.

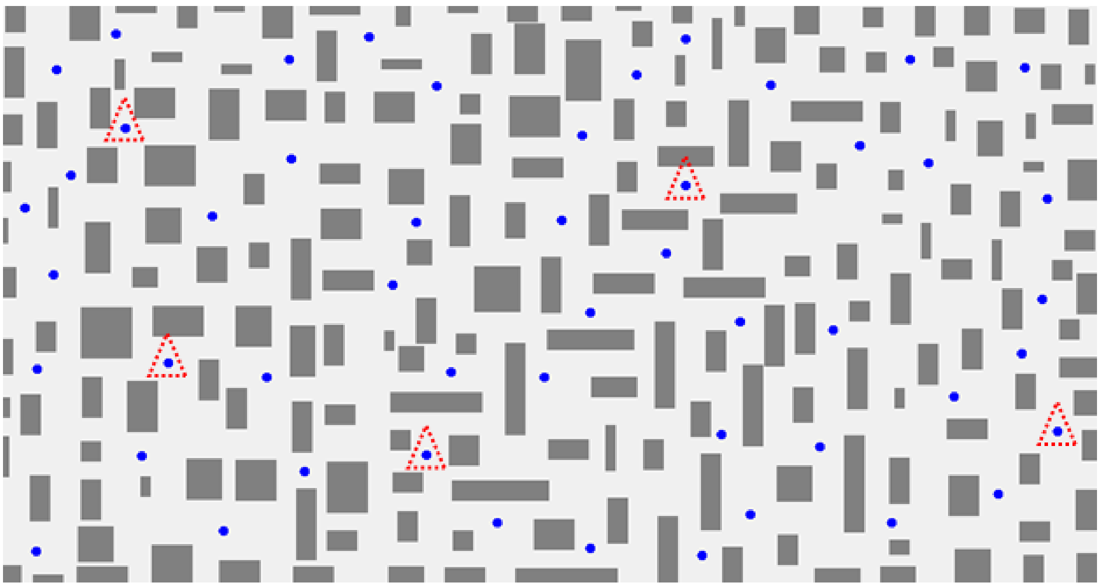
(ii) Select i^{th} sampling point as the i^{th} transmitter position and run the ray tracer as proposed in section 3.1 to calculate the received power at each sampling point and generate the coverage pattern for the i^{th} transmitter. Here, the range of i is $1 \le i \le n$.

(iii) If there is any duplicate coverage pattern, keep only one of them and skip others to handle redundancy issue. Hence, if k numbers of coverage patterns are skipped because of duplication, the number of accepted coverage pattern of the corresponding transmitters (for the generation of the solution space) will be $m = n - k$. Here, each or different combination of the m coverage patterns are possible solution candidates for the current optimization problem.

(iv) Generate the search space tree based on the BFS. While expanding any live node of the search space, apply the proposed bounding functions as mentioned before to avoid generation of unnecessary sub-tree. Also check the termination criterion as stated before to make sure the proper termination as well as obtain the optimum solution.



(a) 30 sampling points with 4 optimized transmitter positions.



(b) 50 sampling points with 5 optimized transmitter positions.

Figure 3.9: The floor plan of indoor area and the locations of sampling points where optimized transmitter positions are surrounded by dotted triangles (Δ).

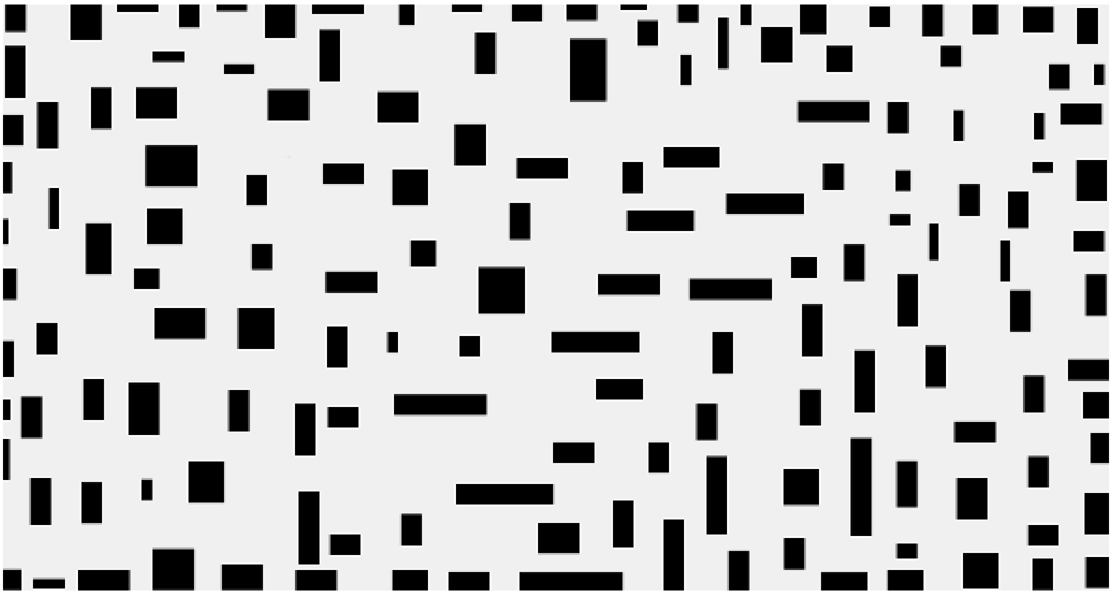
CHAPTER 4

RESULTS AND DATA ANALYSIS

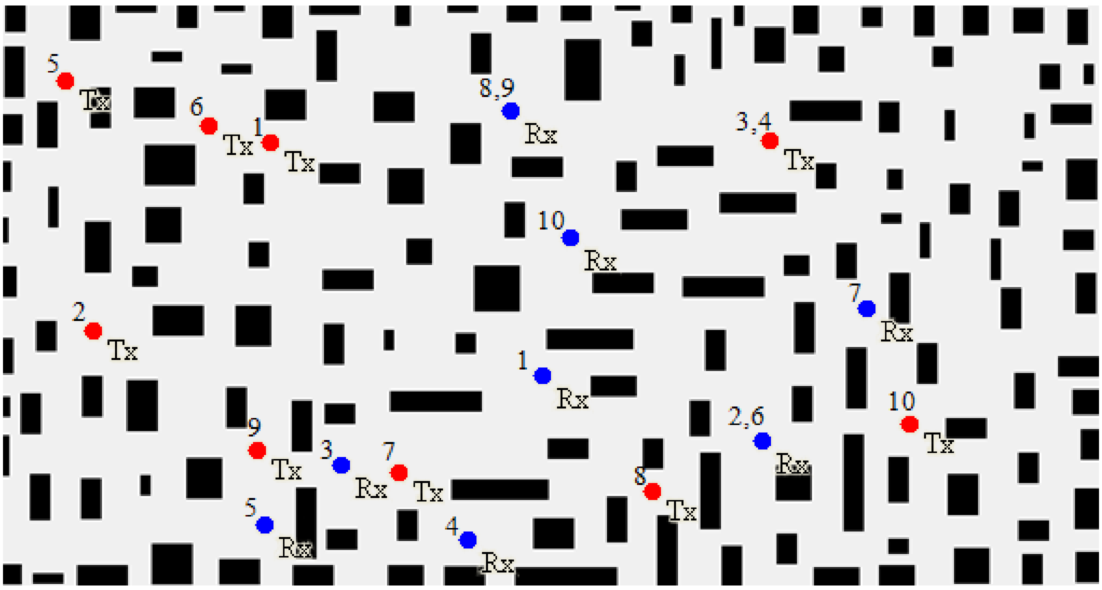
4.1 PROPOSED RAY-TRACING TECHNIQUE

The simulation results of the proposed ray-tracing technique have been generated and analyzed in this section. To do this, a typical simulation environment of Figure 4.1(a) has been used where the rectangles are represented as obstacles that are working as reflectors. Using simulation environment of Figure 4.1(a), 10 different scenarios consisting of transmitter (*Tx*) receiver (*Rx*) pairs have been created as in Figure 4.2(b). So the Figure 4.2(b) is actually representing 10 different scenarios in one picture. The simulation has been carried out between one *Tx* and one corresponding *Rx*. The numerical labels of the *Tx* and *Rx* in Figure 4.1(b) represent the number of scenarios. Each scenario consists of simulation environment of Figure 4.1(a) and one *Tx*, *Rx* pair having the same numbering. The obtained simulation results carried out for 10 different scenarios have been plotted in Figures 4.2 and 4.3, respectively.

The graph in Figure 4.2 plots the time required to execute the proposed ray tracing algorithm for each of the 10 individual scenarios. Here the execution time is recorded in milliseconds (ms). On the other hand, in Figure 4.3, the graph shows the number of significant signals traced by the proposed ray tracer for the 10 different scenarios. The proposed ray tracer starts tracing signals from the transmitter to the receiver and finds out all the significant signals that are received by the receiver and discards all the signals that are lost. Here significant signal means the signal that has been received by the corresponding receiver in the indoor environment.



(a) A sample indoor environment.



(b) 10 different scenarios.

Figure 4.1: A sample indoor environment with 10 different scenarios for performance evaluation.

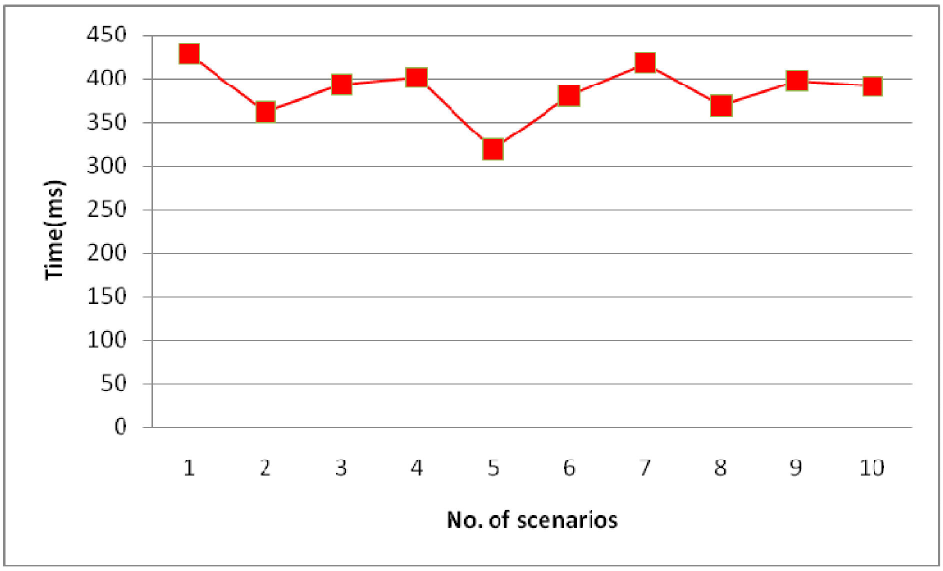


Figure 4.2: Simulation result in terms of computation time considering 10 different scenarios.

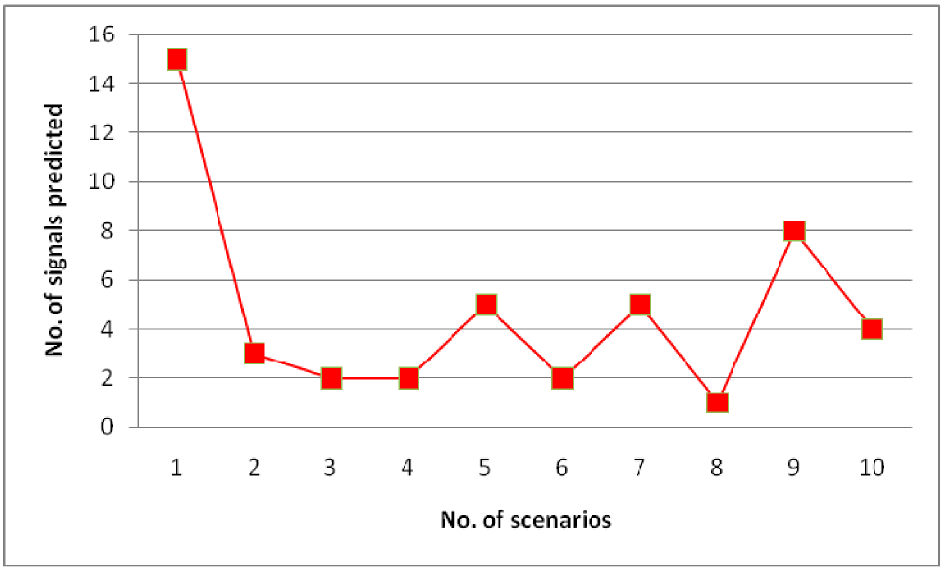


Figure 4.3: Simulation result in terms of accuracy of signal prediction considering 10 different scenarios.

The proposed ray tracing algorithm is capable of identifying invalid region that consists of the propagation paths of two consecutive signals and these two propagation paths experience the same obstacle in the same sequence. The invalid region indicates that all other signals that supposed to be launched from the transmitter within this region will be lost. So, the proposed algorithm discards the redundant processing for those signals that are within the invalid region. The concept of this invalid region is helpful to skip the processing of the unnecessary signals. The capability of identifying a bunch of unnecessary signals reduces the computation time of the proposed ray tracer. As the proposed ray tracing algorithm skips only those signals that fall within the range of the invalid regions, there is no possibility of missing any significant signals. So, the proposed algorithm makes sure of good accuracy in terms of signal prediction from the transmitter to the receiver. Thus it can be said that the proposed algorithm has been developed to increase the performance with respect to both time and accuracy. Therefore, the capability of skipping the processing of the unnecessary signals based on the invalid region makes the algorithm faster as well as more accurate in terms of signal prediction.

In summary, the proposed ray tracing algorithm can identify the region of insignificant rays and ignore the processing of those signals to reduce the computation time. However, following the trajectory of the ray until it passes away the propagation area is a complex and time consuming operation.

4.2 PROPOSED COVERAGE ALGORITHM

The proposed algorithm is developed to optimize the wireless coverage as well as maximize the overall performance for a typical indoor radio propagation modeling. In this section, both space and time complexities of the proposed coverage algorithm have been deduced. As the proposed coverage algorithm is the accelerated version of the existing algorithm as reported in (Yun et al., 2008), it is important to derive the complexities of the algorithm of (Yun et al., 2008) before proceeding to the derivation of the proposed algorithm. The method discussed in (Yun et al., 2008) is developed to optimize the wireless coverage in a typical indoor environment. Here, ray-tracing algorithm is exploited to calculate the received power at each sampling point due to one or more transmitting antennas. Moreover, GA is used to determine the minimum number of transmitters as well as their corresponding positions. In each generation, for any generated chromosome, the algorithm reruns the ray tracer to calculate the field distribution to every sampling point from the location of the transmitter(s) as provided by the corresponding chromosome(s). At the beginning, the position of the transmitter is optimized using only one transmitter. If there is any bad sampling point for the obtained position of the transmitter, another GA optimization is applied with two transmitters to reduce the number of bad sampling points. The algorithm continues running GA optimization considering more transmitters until the optimum wireless coverage is achieved. According to this algorithm, a preorder (method to visit each node before its children) based search space tree for a typical indoor environment having 6 sampling points can be generated as illustrated in Figure 4.4. Here, the labeling of the edge refers to the corresponding transmitter. For example, i refers to the i^{th} transmitter.

The properties of the tree organization of Figure 4.4 can be described in Table 4.1, where *l* and *Tx* refer to the levels and transmitters, respectively. The node 1 at level 0 is not being highlighted in Table 4.1 for the simplicity of analysis. The node 1 refers only the root node of the tree but it doesn't refer to any transmitter. So, node 1 can be considered as a dummy node. It indicates only the root of the overall search space tree. Table 4.1 also highlights how many times a transmitter is being considered in each level of search space.

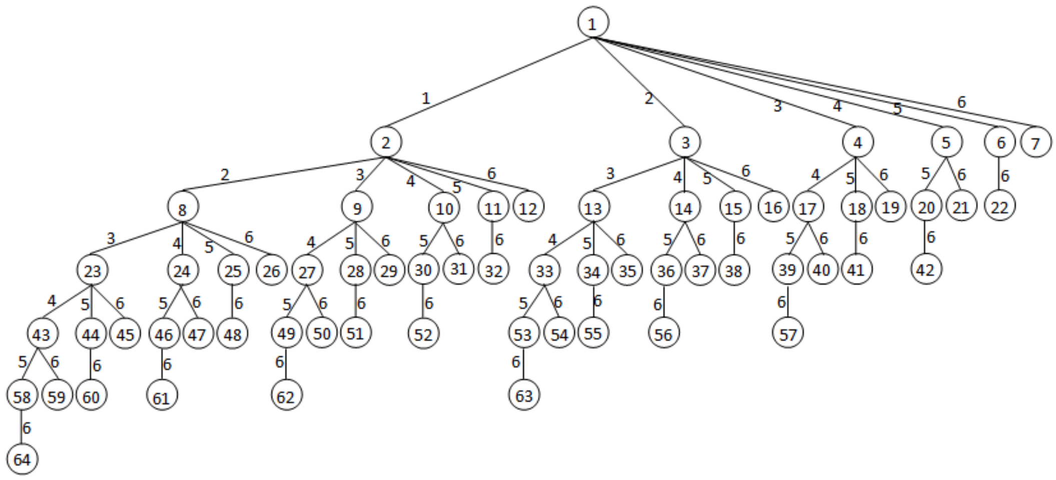


Figure 4.4: Tree organization for the existing coverage algorithm.

Table 4.1: Tabular format of the search tree of Figure 4.4.

Tx \ *l*	1	2	3	4	5	6
1	1					
2	1	1				
3	1	2	1			
4	1	3	3	1		
5	1	4	6	4	1	
6	1	5	10	10	5	1

A careful study of Table 4.1 reveals the criteria of Pascal's triangle, where any number is made up of the sum of the number above it and the one to the left. It can be expressed as the following symbol:

$$\binom{r}{k} = \binom{r-1}{k} + \binom{r-1}{k-1} \qquad (4.1)$$

where r is the number of row and k is the number of column. The value of each cell can also be calculated using the combination formula ${}^{r-1}C_{k-1}$, where the values of r and k start from 1. Thus, in general, the total number of nodes generated by the tree can be calculated as the following level-wise formula:

$$1 + \sum_{1 \le r \le n} {}^{r-1}C_0 + \sum_{2 \le r \le n} {}^{r-1}C_1 + \ldots + \sum_{n-1 \le r \le n} {}^{r-1}C_{n-2} + \sum_{r=n} {}^{r-1}C_{n-1} \qquad (4.2)$$

$$= 1 + \left(\sum_{1 \le l \le d} \sum_{l \le r \le n} {}^{r-1}C_{l-1} \right) \qquad (4.3)$$

$$= 2^n \qquad (4.4)$$

where d is the maximum depth of the tree and n is the number of sampling points in the indoor environment. Here the value of d equals to n in the worst case that means the number of sampling points equals to the number of transmitters. The Equation (4.4) represents the time complexity of the algorithm as in the worst case; all the nodes are generated until the required solution is found. As all the generated nodes stay in memory, therefore, the space complexity is also same as the time complexity. So, the space complexity of the proposed algorithm in the worst case is as follows:

$$2^n \tag{4.5}$$

Now both of the Equations (4.4 & 4.5) can be modified based on the proposed bounding functions as stated in previous chapter. Suppose there are *n* numbers of sampling points in the indoor environment. The ray tracing program is run for the *n* numbers of positions and generates *n* number of coverage patterns. Suppose among *n* number of coverage patterns, *m* numbers of them have been discarded because of duplication. And while exploring the search space tree, *k* numbers of nodes have been unexplored because of the proposed bounding functions as stated in Chapter 3. As the time complexity depends on the number of nodes generated or expanded until the required solution has been found; the average time complexity of the proposed algorithm can be expressed as follows by modifying the Equation (4.4):

$$2^{n-m} - k \tag{4.6}$$

Again, as the space complexity refers to the number of nodes generated until the deepest level; the average space complexity of the proposed algorithm can be expressed as follows by modifying the Equation (4.5):

$$2^{n-m} - k \tag{4.7}$$

From Equations (4.6 & 4.7), it is seen that both time and space complexities of the proposed algorithm are similar. The time complexity of the proposed algorithm has been highlighted in Figure 4.5 by considering arbitrary values of *m* and *k* as 1 and 2 respectively in Equation (4.6) and the number of sampling points in the environment are considered to be increasing. From Figure 4.5 it is observed that the time complexity of the proposed coverage algorithm increases exponentially with the increase of the number of the sampling points in the indoor environment.

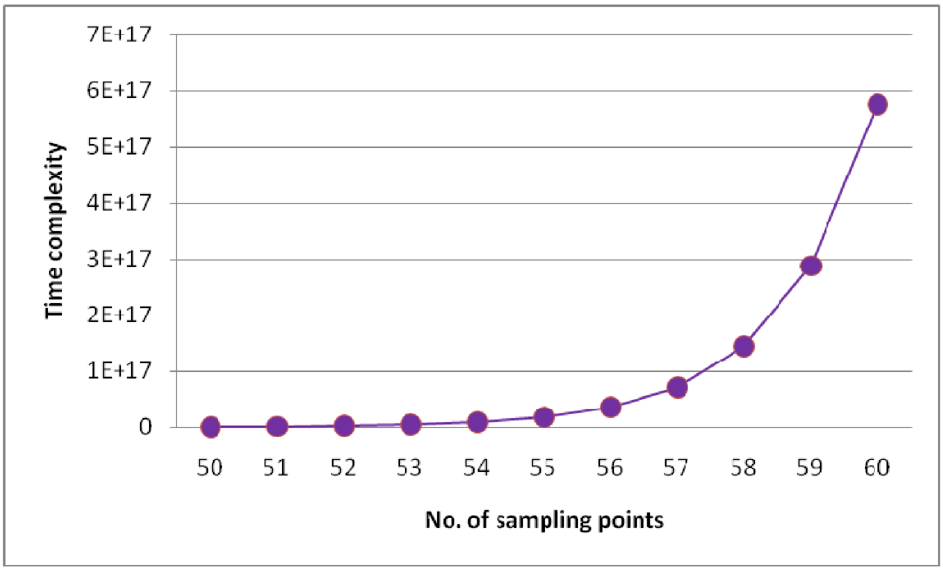


Figure 4.5: Time complexity graph of the proposed coverage algorithm.

Figure 4.6 highlights the space complexity of the proposed coverage algorithm. The values of m and k are also considered arbitrarily as 1 and 2 respectively for the Equation (4.7). Similar to Figure 4.5, it is also observed from Figure 4.6 that the space complexity of the proposed coverage algorithm increases exponentially as the number of the sampling points in the indoor environment increases.

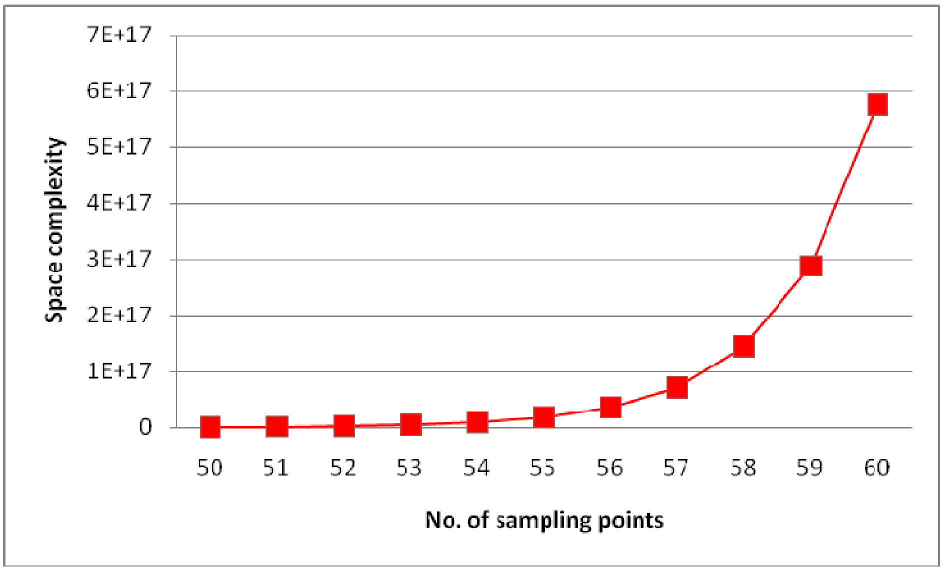


Figure 4.6: Space complexity graph of the proposed coverage algorithm.

The execution time of the proposed coverage algorithm has been calculated for 10 different typical indoor environments having different numbers of sampling points. The graph based on execution time has been plotted in Figure 4.7. From the graph of the Figure 4.7, it is noticed that the graph is a linear graph. That is the computation time of the proposed coverage algorithm is proportional to the number of sampling points in the indoor propagation area.

In summary, the proposed coverage algorithm runs the ray tracer once for a transmitting position and keeps the coverage information of a transmitter as a binary coverage pattern. This binary coverage pattern is reused in next iteration (if required) instead of rerunning the ray tracer like other existing algorithm. This concept also reduces the computation time significantly.

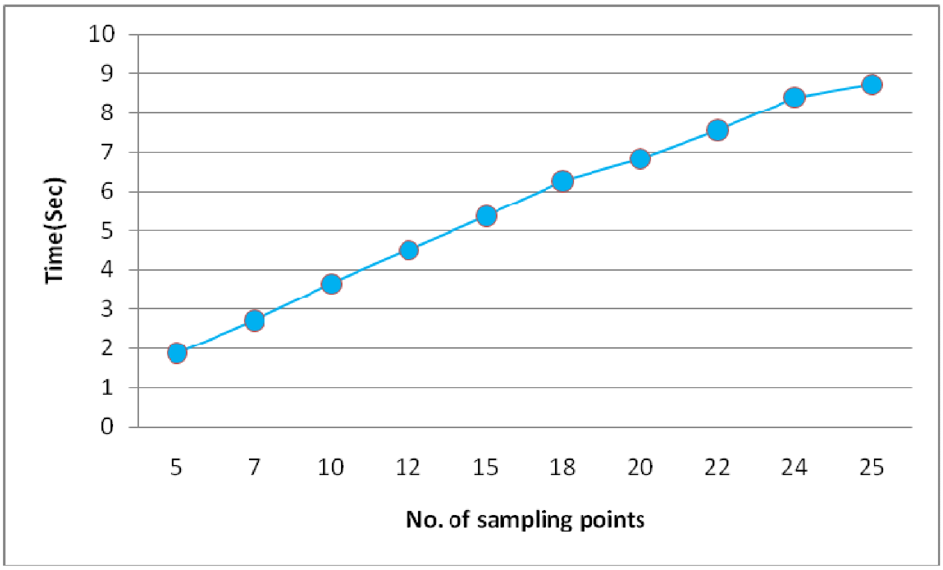


Figure 4.7: Computation time of the proposed coverage algorithm for different number of sampling points.

Moreover, the proposed coverage algorithm runs the ray tracer only once for one transmitting position and generates a coverage pattern that is used for further iterations if necessary. Therefore, if there is *n* number of sampling points in the indoor environment, the proposed coverage algorithm runs the ray tracer maximum of *n* times that refer to the remarkable reduction of the computation time as the ray tracer can be a costly service for a complex indoor environment. Furthermore, as the proposed coverage algorithm is capable of ignoring the generation of unnecessary nodes, it can find out the optimum solution using less number of iterations that indicates the capability of the faster processing of the proposed algorithm.

CHAPTER 5

DISCUSSION

This chapter discusses about the proposed ray tracing and coverage algorithms and shows a comparative study with other existing systems. The proposed system has been proved superior while comparing with the existing relevant algorithms.

5.1 PROPOSED RAY-TRACING TECHNIQUE

The proposed ray-tracing algorithm based on the Binary Angle Division has been compared with the conventional ray-tracing algorithm reported in (Iskander & Yun, 2002; Ling et al., 1989; Wang et al., 2008; Dikmen et al., 2010; Saeidi et al., 2009; Tao et al., 2010; Buddendick & Eibert, 2009; Mohtashami & Shishegar, 2010; Kipp, 2010; Amornthipparat et al., 2007; Geng et al., 2008; Gao, 2010) and also with the ray-launching algorithm defined in (Hoppe et al., 1999; Raida et al., 2008; Lawton & McGeehan, 1994) as reported earlier. To perform a fair comparison with the existing techniques, a simulation environment shown in Figure 5.1 has been selected and all experimental settings have been kept analogous. Here, the filled rectangles are represented as obstacles that are working as reflectors and the circles having titles *Tx* and *Rx* are representing transmitting and receiving antennas respectively. The numerical labels of the circles in Figure 5.1 represent the number of scenarios. Each scenario has one *Tx* and one corresponding *Rx* that have the same numbering. The comparative simulations have been done for 10 scenarios and plotted in Figures 5.2 and 5.3, respectively. The obtained results confirm the precedence of the proposed algorithm. Basically, the conventional ray-tracing technique considers all the rays emanated from the transmitter, which takes more computation time and keeps the accuracy better. On the other hand, the existing ray-launching technique is faster and less accurate. It launches the rays from the transmitter with a constant angle increment. Hence, there is huge possibility of neglecting a wall or other obstacles which are very small and located in the middle of the trajectories of two signals. Thus, it can be said that, the conventional ray-tracing technique has lack of time efficiency while ray-launching technique is suffering from accuracy in terms of signal prediction.

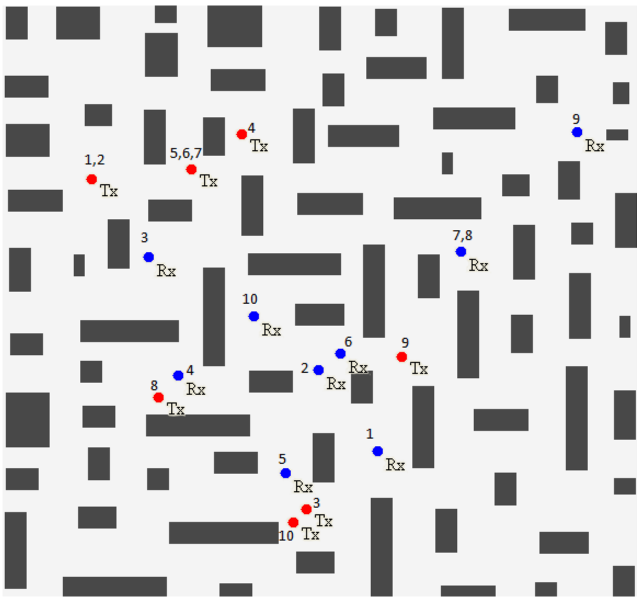


Figure 5.1: A sample indoor environment for performance evaluation.

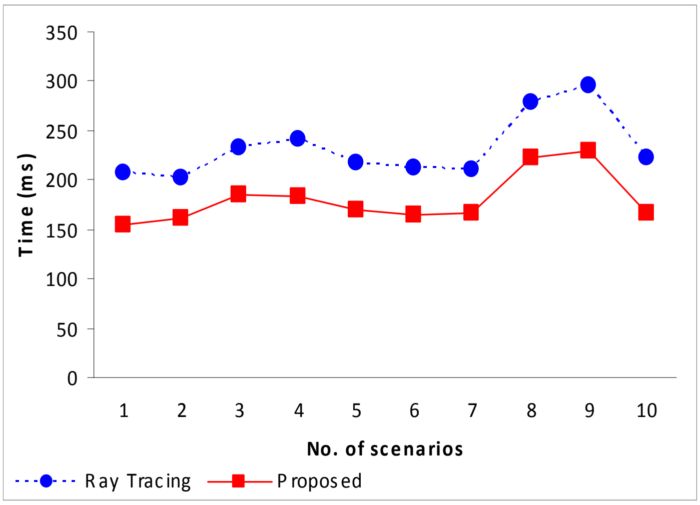


Figure 5.2: Comparison between conventional ray-tracing and the proposed algorithm in terms of computation time.

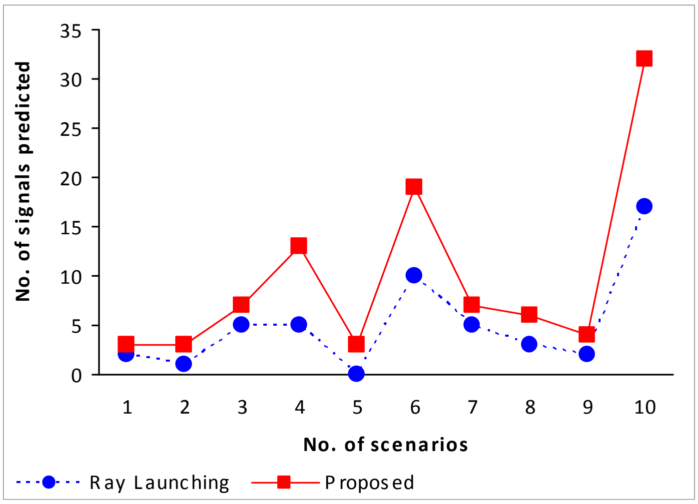


Figure 5.3: Comparison between ray-launching and the proposed algorithm in terms of accuracy.

The proposed ray tracing algorithm has been developed to increase the performance with respect to both time and accuracy to make up the drawbacks of the previous algorithms. It can ignore the processing of the unnecessary signals based on the invalid region as stated in Chapter 3 that makes the algorithm faster as well as more accurate in terms of signal prediction. As the accuracy of the proposed ray tracing algorithm is identical with the conventional ray-tracing, Figure 5.2 shows a comparison with the conventional ray-tracing technique, which is only based on the computation time that considers 10 different scenarios as presented in Figure 5.1. The time is recorded in milliseconds (ms). It can be observed that the proposed algorithm gives higher computational efficiency of about 22.17% in average. Furthermore, the proposed algorithm has also been compared with the ray-launching algorithm in terms of signal prediction as shown in Figure 5.3. Here, 2 degree angular increment has been considered for the ray-launching technique. Hence, it is found that the average accuracy of the proposed algorithm is 94% better than the ray-launching algorithm for 10 different scenarios of Figure 5.1. However the calculation of measuring accuracy is as follows:

Suppose

M = No. of signals predicted by first algorithm.

N = No. of signals predicted by second algorithm.

If N>M, then the efficiency of the second algorithm in terms of accuracy can be calculated by the formula $\left(\frac{N*100}{M}-100\right)$.

The average no. of signals predicted by the existing ray tracing algorithm is M = 5

The average no. of signals predicted by the proposed ray tracing algorithm is N = 9.7

Then, the efficiency of the proposed ray tracing algorithm over the existing one in terms of accuracy is

$$\left(\frac{N*100}{M}-100\right)=\frac{9.7*100}{5}-100$$
$$=194-100$$
$$=94\%$$

Therefore, it can be summarized that the proposed ray-tracing technique is better in terms of both computational time and accuracy while comparing with the conventional ray-tracing and ray launching algorithms.

5.2 PROPOSED COVERAGE ALGORITHM

In this section, the proposed coverage algorithm for indoor environment has been compared with the existing algorithm as reported in (Yun et al., 2008) in terms of space complexity, time complexity, computation time and number of iterations. The space and time complexities of (Yun et al., 2008) and the proposed coverage algorithm derived from the section 4.2 have been shown in Table 5.2.

Table 5.1: Complexities of (Yun et al., 2008) and proposed algorithm.

Complexity	(Yun et al., 2008)	Proposed
Space	2^n	$2^{n-m}-k$
Time	2^n	$2^{n-m}-k$

From Table 5.2, it is seen that both time and space complexities of the algorithm as reported by (Yun et al., 2008) are similar. It is computationally more expensive due to the exponential complexity that may lead to combinatorial explosion. According to the algorithm of (Yun et al., 2008), each node in the solution space is represented by a chromosome and for each generated chromosome; the algorithm reruns the ray-tracing program to calculate the field distribution at every sampling point from the given position of the transmitter. Hence, the algorithm of (Yun et al., 2008) runs the ray tracer maximum $2^n - 1$ times.

In case of the proposed coverage algorithm, both time and space complexities are also identical. So, the result obtained from the comparison based on space complexity is equivalent as the time complexity. Let, the time or space complexity of the algorithm of (Yun et al., 2008) is $C_1 = 2^n$ and the proposed algorithm is $C_2 = 2^{n-m} - k$.

Now, $C_1 - C_2$

$= 2^n - 2^{n-m} + k$

$= 2^m.2^{n-m} - 2^{n-m} + k$

$= 2^{n-m}(2^m - 1) + k$

≥ 0

Thus, it can be written that $C_1 \geq C_2$. Therefore, both time and space complexities of the proposed coverage algorithm are better than that of the existing algorithm as reported in (Yun et al., 2008) that can also be highlighted in Figure 5.5, where the values of *m* and *k* are assigned to 1 and 2, respectively. That is, it has been considered arbitrarily that the number of rejected duplicate pattern is *m*=1 and the number of unexplored node is *k*=2 for the provided indoor environment having different number of sampling points to be covered. From the graph of Figure 5.5 it is seen that if the values of *m* and *k* are increased, the complexity difference will be much larger which indicates the better performance of the proposed coverage algorithm in terms of both space and time complexities.

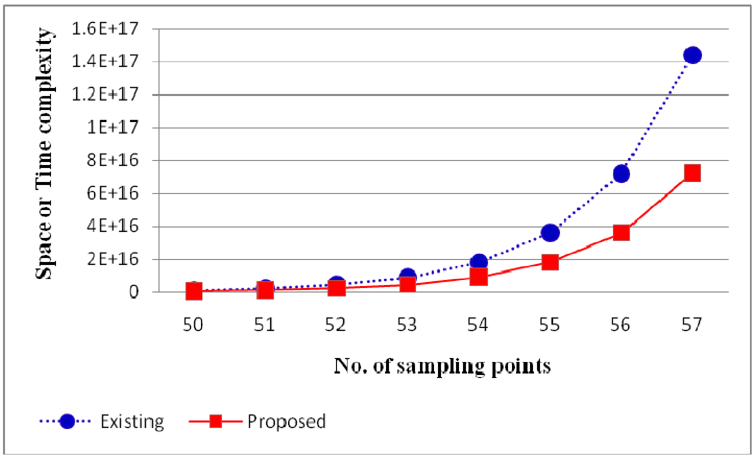


Figure 5.4: Comparison between the existing (Yun et al., 2008) and the proposed algorithm in terms of space or time complexity.

The comparison based on computation time between existing (Yun et al., 2008) and the proposed coverage algorithm has been shown in Table 5.3. Here 10 different scenarios with different number of sampling points have been considered. From the Table 5.3, it is observed that the computation time difference is becoming larger as the number of sampling points is increasing. Thus from Table 5.3 it can be decided that 99% reduction of the computation time is possible by the proposed coverage algorithm.

Table 5.2: Comparison between the existing (Yun et al., 2008) and the proposed coverage algorithm in terms of computation time.

No. of sampling points	**No. of Transmitter**	**Time for existing algorithm** (Yun et al., 2008) **in seconds**	**Time for the proposed coverage algorithm in seconds**	**Reduction (%)**
5	2	2.63	1.87	28.9
7	3	14.33	2.71	81.09
10	3	25.01	3.64	85.45
12	4	118.79	4.5	96.21
15	3	89.24	5.36	93.99
18	4	386.56	6.26	98.38
20	4	584.2	6.84	98.83
22	4	719.86	7.56	98.95
24	4	928.14	8.4	99.09
25	4	1134.19	8.72	99.23

Moreover, for each generated chromosome (node), the existing algorithm (Yun et al., 2008) reruns the ray tracing method each time. On the other hand, the proposed algorithm runs the ray tracer only once for one transmitting position and generates coverage pattern for that transmitting position that can be reused for further iterations if it is required. Therefore, if there is *n* number of sampling points in the indoor environment, the proposed algorithm will run the ray tracer maximum of *n* times that refer to the remarkable reduction of the computation time as the ray tracer can be a costly service with the increment of the complexity of the corresponding indoor environment. Moreover the proposed algorithm is capable of ignoring the generation of unnecessary nodes. So, it can also find out the optimum solution using less number of iterations than that of algorithm proposed by (Yun et al., 2008).

CHAPTER 6

CONCLUSION

6.1 OVERALL CONCLUSION

In this study, a novel model for indoor radio propagation prediction and coverage optimization has been proposed and developed. Under this model a sophisticated ray-tracing technique based on Binary Angle Division has been developed and applied for indoor radio signal prediction. This study also presents a comparative study with other ray-tracing and ray-launching techniques of indoor radio signal prediction. It is observed that the proposed method takes lower average execution time of 180.4 ms for 10 different scenarios while the conventional ray-tracing is taking 231.8. Again, in terms of accuracy, the proposed method can obtain higher number of predicted signals that is 9.7 (in average), whereas it is only 5 with the ray-launching technique for 10 different scenarios as presented in Chapter 5. Thus, the obtained results confirm that the proposed ray tracing system achieves better performance in terms of higher computational efficiency of about 22.17% and superior average accuracy of 94% in case of signal prediction compared to other existing techniques. On the other hand, a novel algorithm for wireless indoor coverage has been presented that has less time and space complexities. The complexity difference between the existing and the proposed coverage algorithms would be even larger, if the number of sampling points (receiving points) in the propagation area increases. It is also revealed that the proposed coverage algorithm is capable of reducing the computation time as high as 99% because of strong bounding functions as well as the concept of magnificent coverage pattern. Therefore, it can be summarized that the propose coverage algorithm outperforms the existing algorithm in terms of space or time complexities and computation time. Last of all, it can be concluded that the outcome of the study will facilitate the wireless radio networks and personal communication services inside buildings.

6.2 FUTURE WORK

The proposed ray tracing algorithm presented in this study is based on 2D space. But the idea can be modified for three-dimensional simulations in future. Although this study describes the coverage optimization technique based on indoor environment, it is actually a generalized algorithm that can also be applied for outdoor wireless coverage in future. However, in that case, the prerequisite is to develop a suitable radio signal prediction algorithm.

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