Geometrical Optics Based Path Loss Model for Furnished Indoor Environment

E. M. Cheng [1], Z. Abbas [2], MohamedFareq AbdulMalek [3], K. Y. Lee [4], K. Y. You [5], S. F. Khor [6], and M. Afendi [1]

[1] School of Mechatronic Engineering
Universiti Malaysia Perlis (UniMAP), Arau, 02600, Perlis, Malaysia
emcheng@unimap.edu.my, afendirojan@unimap.edu.my

[2] Faculty of Science
Universiti Putra Malaysia (UPM), Serdang, Selangor, 43400, Malaysia
za@upm.edu.my

[3] Faculty of Engineering and Information Sciences
University of Wollongong in Dubai, Dubai Knowledge Village, Dubai, United Arab Emirates
mohamedfareqmalek@uowdubai.ac.ae

[4] Faculty of Engineering and Science
Universiti Tunku Abdul Rahman (UTAR), Petaling Jaya, 46200, Selangor, Malaysia
kylee@utar.edu.my

[5] Faculty of Electrical Engineering
Universiti Teknologi Malaysia (UTM), Skudai, 81310, Johor, Malaysia
kyyou@fke.utm.my

[6] School of Electrical System Engineering
Universiti Malaysia Perlis (UniMAP), Arau, 02600, Perlis, Malaysia
sfkhor@unimap.edu.my

Abstract **─** This paper describes the Geometrical Optics (GO) based path loss model for indoor environment path loss prediction. Both Geometrical Optics based total rays model and direct ray path loss model were developed. Optimization was then conducted to improve both models in path loss prediction for case of Line-Of-Sight (LOS) indoor environment. Both Geometrical Optics based total rays model and direct ray model were optimized with log-distance-dependent expression using least-square approach. This log-distance-dependent expression includes all effects due to multiple reflection and all uncertainties which is distance-dependent. The path loss measurement was conducted in Division of Information Technology (DITSC), Universiti Putra Malaysia. Both models were optimized with measured path loss which was collected from DITSC. The value of correction factor and coefficient in additional expression for optimized GO were developed and presented in this paper. The optimized GO based modes ware validated at five buildings in Universiti Putra Malaysia by referring to the absolute mean error for its accuracy and effectiveness in path loss prediction. The optimized direct ray model shows the best accuracy compared with optimized total rays model, direct ray model and total rays model.

Index Terms **─** Geometrical Optics, indoor propagation, optimization, path loss.

I. INTRODUCTION

If an antenna is deployed in building, a picocell is formed. Picocells are increasingly used not only in private location (i.e., office building), but also in public place, e.g., coffee shop, library, airport, railway station and etc. The rapid growth of wireless local area network (WLAN) is due to the implementation of this technology in all fields. Therefore, indoor wireless system plays a very important role in education, medical, business, entertainment and etc. Picocell propagation is also relevant to determine the case of propagating from microcellular and macrocellular into building, which could either act as a source of

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interference or due to the enhancement to the coverage [1]. There is similarity between the indoor propagation and outdoor propagation where they are dominated by the same propagation mechanism, i.e., reflection, transmission and diffraction, but conditions are much more variable. The mounted antenna is also crucial in large-scale propagation, e.g., mounted antenna at desk level received different signal vastly than those mounted on the ceiling.

In order to determine the propagation phenomenon, buildings are categorized into residential home in suburban areas, residential home in urban areas, traditional building with fixed walls (hard partitions), and the office area with movable wall panels (soft partitions), factory building, research laboratory in university, and sports arenas. Hard partition is the obstructions within the building which cannot be easily moved such as concrete wall, beam or pillars. While soft partition is the movable obstructions within the building, e.g., office furniture, electrical appliances, or the machinery, which have a height less than the ceiling height. Inside the building, propagation geometry can be classified as Line-Of-Sight (LOS) where the transmitter and receiver are visible to one another or Non-Line-Of-Sight (NLOS), where objects block a visible propagation path [2].

The indoor wireless measurement was conducted in this study. Indoor wireless measurement is different from the outdoor measurement in two aspects - the distances covered are much smaller and the variability of the indoor environment is much greater for a much smaller range of transmitter-receiver separation distances. Propagation path characteristics for indoor communication systems are very unique compared to outdoor systems because there are obstacles that reflect, diffract, or shadow the transmitted radio waves, e.g., wall, ceiling, floor, and various type of office furniture. Reflections from obstacles and their path differences are unpredictable since the pedestrian moves horizontally. In the indoor radio channel, the distances covered of wave propagation are much smaller, and the higher variability of the environment is presented in smaller range of distance between transmitter and receiver, even though in scenario of Line-Of-Sight (LOS). The performance of indoor propagation channel is highly affected by the building material, the building type, and layout of the building, especially obstacle appears along the LOS propagation channel. On top of that, signal levels is also greatly changed due to the movement of people, mounting of the antenna, opening and closing of doors etc., inside the office. Therefore, some indoor propagation models, e.g., empirical models are not suitable to be used to characterize the propagation channels in the environment due to the aforementioned unique characteristics of propagation. In addition, direct ray model [3] or free space propagation model [4] from transmitting antenna to receiving antenna might not be able to describe the LOS propagation accurately. The multiple reflections caused infinite ray received by receiving antenna. It occurred at indoor environment due to the presence of obstacles (scatterers), ceiling and ground. This aspect is very crucial to be studied.

II. PROPAGATION MODELS

Path loss is one of the most important characteristics for the propagation environment. The path loss needs to estimate accurately to select optimum location of base station (mobile communication system) [5] or access point [6] with transmitting antenna (WLAN system).

Therefore, it required an accurate propagation model as a tool for estimation.

A propagation models is a set of mathematical expressions and algorithms used to represent the radio characteristics in a given environment. Propagation model can be presented in empirical (a.k.a statistical) [7], theoretical [8] (a.k.a deterministic), or a combination of both (a.k.a semi-empirical or semi-deterministic [9]). The empirical model is based on the measurements taken in a specific location. Meanwhile, the theoretical models deal with the fundamental principles of radio wave propagation phenomenon.

In the empirical models, all environmental influences are implicitly taken into account regardless of whether they can be separately recognized. This is the main advantage of empirical model. On the other hand, the accuracy of this model is not only relying on the accuracy of model, the similarities between the environment to be analysed and the measurement where the measurement taken are also important [10].

The deterministic models are based on the principles of physics. Therefore, it is free from the influence of dissimilarity of environment (i.e., pressure, temperature, and climate) and can maintain its accuracy. In practice, their implementation needs a rigorous computation especially when looking for the parameters (i.e., incident angle) of the model, which is sometime either impractical or impossible to obtain. For that reason, the implementation of the deterministic models is commonly restricted to smaller areas such as indoor environment. Nevertheless, if the deterministic models are implemented correctly, greater accuracy of prediction can be expected compared to empirical models.

The problem of the indoor field level prediction can be considered statistically or theoretically. While almost all statistical (empirical) models are based on the same general model, there are several distinguished theoretical models of which ray-tracing models are the most common use as propagation model for indoor environment.

The general idea of each of the presented models can be easily applied to any specific frequency band.

However, the major indoor radio systems operate today, i.e., 1.8-2 GHz frequency band is commonly used [11].

The characteristic for indoor environment is within short distance and, strongly rely on the material of obstacle especially its permittivity [12], conductivity and permeability. However, great variability of condition may affect the indoor radio propagation. For example, signal levels vary greatly depending on whether the interior doors are open or closed inside the building. In addition, the location of antenna mounted also play a significant impacts in large-scale fading. Antenna mounted at desk level exhibit the different signals variation than those mounted on the ceiling.

In this work, path loss, L [dB] can be determined by subtracting the signal strength at a specific position (Eq. 1) from the reference signal strength. The reference distance (1m) is utilized to normalize the path loss that occurs at 1m from the antenna so that only propagation effects are included in the path loss [13]. It is presented in the value of 30 dBμV/m in this paper [3].

III. MEASUREMENT SITES

A. Division of Information Technology (DITSC)

Foyer in DITSC as shown in Fig. 1 is the first measurement site. A transmitting antenna is located at this site is mounted on the ceiling. The antenna is deployed in such a way, so that the antenna is in line-of-sight at all the measuring position in Site C. However, there are two obstacles that contribute to the multipath signal (apart from the wall and ceiling), i.e., the wooden round table with wooden pillar (reception) and the wooden shelf as shown in Fig. 1 and Fig. 2, respectively. The area of Site C is the widest among the rest. Therefore 11 measuring positions are chosen. The plan of Site C is shown in Fig. 3.

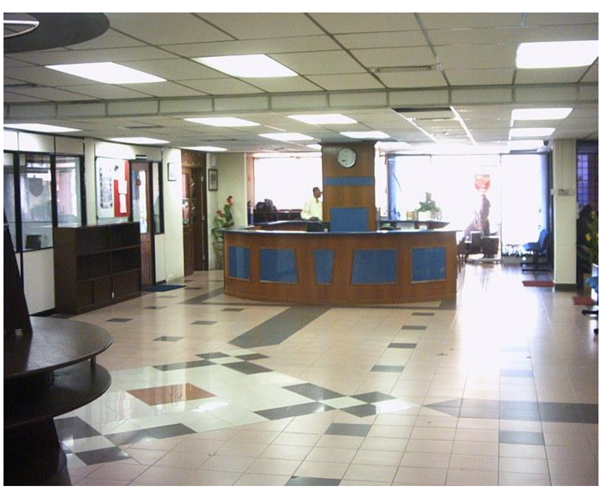

Fig. 1. Foyer of building.

Fig. 2. Foyer of building.

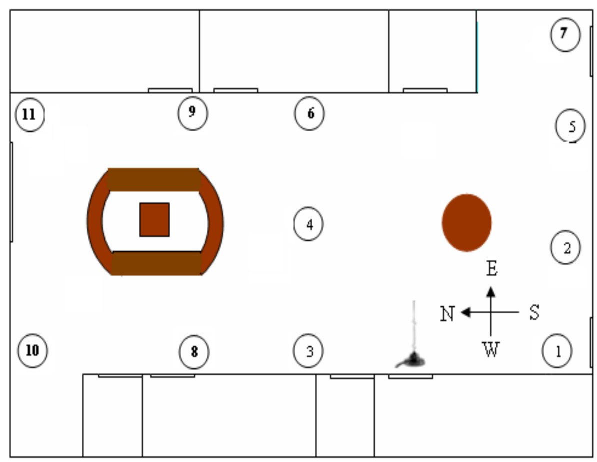

Fig. 3. Plan of Site C.

B. Validation of optimized model

After the optimization, the validity of optimized model must be proved. The effectiveness can be measured by comparing the optimized model [Eq. (3) and Eq. (4)] with its original model in terms of absolute mean error and mean relative error. Then, others location, e.g., first floor in Division Information Technology (DITFF) (Fig. 4), ground floor in Faculty Science (FSGF) (Fig. 5), second floor in Faculty Science (FSSF) (Fig. 6), third floor of Building of Mathematics (BMTF) (Fig. 7) and foyer of Building of Annex (BAF) (Fig. 8) were selected to validate the optimized model.

For validation purposes, four measurement sites, i.e., DITFF, FSGF, FSSF, BMTF and BAF were chosen to validate the optimized models. These measurement sites provide the LOS region for the measurement.

Fig. 4. First floor in Division Information Technology (DITFF).

Fig. 5. Ground floor in Faculty of Science (FSGF).

Fig. 6. Second floor in Faculty Science (FSSF).

Fig. 7. Third floor of Building of Mathematics (BMTF).

Fig. 8. Foyer in Building of Annex (BAF).

IV. GEOMETRICAL OPTICS (GO)

GO is a high-frequency method for approximating wave propagation for incident, reflected, and refracted fields. It uses the ray concept, so it is often referred to as ray optics. It was developed to analyze the propagation of light (waves) at high frequencies [14].

The final form of the GO equation is:

$$E(s) = E_0(0)e^{j\varphi_0(0)}\sqrt{\frac{\rho_1\rho_2}{(\rho_1+s)(\rho_2+s)}}\, e^{-j\beta s}, \qquad (1)$$

where $\varphi_0(0)$ = field phase at reference point (s = 0), and the parameters ρ_1, ρ_2, and s are as illustrated in Fig. 9. The spreading factor $\sqrt{\frac{\rho_1\rho_2}{(\rho_1+s)(\rho_2+s)}}$, can be reduced to $\sqrt{\frac{1}{s}}$, as expressed in [4].

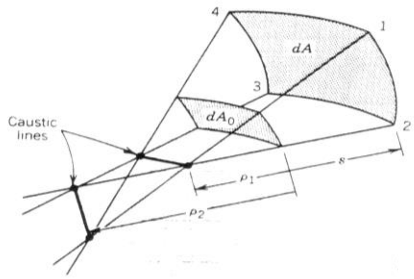

Fig. 9. Astigmatic tube of rays [14].

The GO field is a very useful description of the incident field, reflected field, and refracted field. However, such a description leads to incorrect predictions when considering fields in the shadow region behind an obstruction, since it predicts that no fields exist in the shadow region. This suggested that there is an infinitely sharp transition from the shadow region to the illuminated region. In practice, the transition from the illuminated region to the shadow region is never completely sharp, because some energy propagates into the shadow region.

V. MODEL OPTIMIZATION

The least-squares approach [15] is applied to Geometrical Optics model, in order to produce the best-fitting line through the measured data points for Site C in DITSC by associated it with the multiple reflections.

An improved (optimized) geometrical optic (IGO) model is proposed based on the geometrical optics model (GO) [Eq. (1)] by introducing an additional term, $A\log_{10}(d+x)+B$:

$$L_{IGO}(d,h_r,h_t,\varepsilon_r)[dB] = L(d,h_r,h_t,\varepsilon_r)[dB] + A\log_{10}(d+x)+B \quad , \quad (2)$$

where L [dB] is predicted path loss from Eq. (1) and $L_{IGO}[dB]$ is improved path loss due to optimization. In addition, h_r is the height of receiving antenna; h_t is the height of transmitting antenna; ε_r is relative permittivity of propagation medium and x is corrective constant for distance, d. A and B is coefficient and constant of correction factor, respectively. The additional expression that described in logarithm of distance is derived from the concept of log-distance model where both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance in indoor environment. In addition, this model also considers the fact that the surrounding environmental clutter may have vast difference at the same separation or distance between the transmitter antenna and receiving antenna due to the obstacles [4].

The additional term were also found by minimizing the differences between measurement data with improved model from Eq. (1) using the objective function:

$$F = \sum_{i=1}^{n}(L_{measured} - L_{IGO})^2 , \quad (3)$$

where $L_{measured}$ and L_{IGO} represent the measured and IGO path loss, respectively. n is the number of measured data points. The additional term was figured out by using the least-square technique through Eq. (3).

From least-square technique, the correction factor and coefficient of additional expression for direct ray is listed in Table 1. Single ray (direct ray model) and total rays model are considered in this work. The total rays model included the multiple reflected ray until the third order [16]. These optimized models and original models are compared for its accuracy in predicting path loss.

The optimizations of models are based on the measurement data that acquire from DITSC. The generated parameters after the optimization are listed in Table 1. Therefore, the additional expression is:

$$-7.4\ \log_{10}(d+3.3)+9.2 , \quad (4)$$

for fitting of direct ray model while,

$$-9.0\ \log_{10}(d-0.01)+10.5 , \quad (5)$$

for fitting of total ray model in DITSC with coefficients and constants are as given in Table 1. These additional expression are included in direct ray model and total rays model, respectively to compensate the non-inclusion of infinity ray, loss due to mismatch of impedance on the connector, dissipation of energy due to the heat, and the deviation due to random error where it's assumed distance-dependent.

In this background of development, it is definitely constrained and limited by all the climatic, and environmental factors during the measurement. Since all the measurements were conducted at non-busy hour, the effect due to moving object or population density were not taken into account. In addition, the optimized model is not applicable for outdoor propagation and operating frequency out from ISM band.

Table 1: Optimized parameter (based on measurement data in DITSC) with its correction factor as well as coefficient and constant in additional term for total rays model and direct ray model

Models	Parameter	Fitted Parameter
Direct ray	A	-7.4491
	B	9.1925
	x	3.2896
Total ray	A	-9.0175
	B	10.4744
	x	-0.0129

A. Effectiveness of optimized models

The effectiveness of optimized model with its correction factors and coefficients are illustrated in Fig. 10.

The information shown in Table 2 and Table 3 implied that optimized direct model has better agreement with measured path loss. Therefore, the objectives to introduce optimized direct ray model in comparison is achieved. The original model is proved to be improved via optimization. The improved model is more realistic to be used.

For the case in DITSC, the optimization was conducted on total rays model too, apart from direct ray model. The optimized total rays model in DITSC shows better improvement than the original total rays model if compared with the optimized direct ray model from original direct ray model through Table 2. The idea of optimization of total rays model is inclusion higher order of multiple reflected rays in total rays model. Therefore, it is more practical if compared with direct ray model.

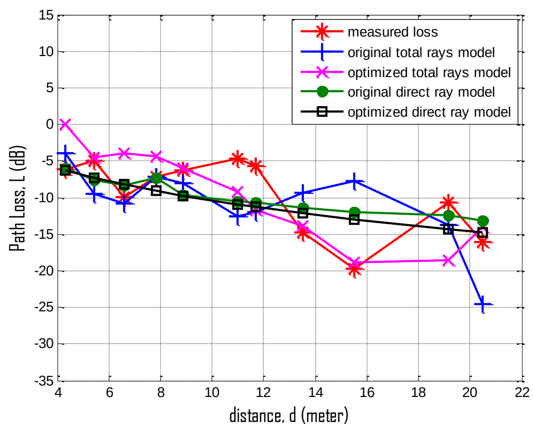

Fig. 10. Comparison of optimized models and original models with measurement data in DITSC.

The insignificant improvement that exhibited by optimized direct ray model in DITSC as listed in Table 2 if compared with optimized total rays model (direct ray + multiple reflected ray) explained that the inclusion of first, second and third order of multiple reflected rays and additional term [Eq. (5)] indeed give major contribution in predicting path loss at DITSC. Besides, the multiple reflected rays in total rays model are improved too via the corrected distance. Hence, it seems that the optimized total ray model became the main contributor in DITSC (Fig. 10).

The direct ray model and optimized direct ray model in DITFF (Fig. 11) give the least of mean relative error among the theoretical model and its optimized model, i.e., 8.23% and 7.43%, respectively. It can be noticed that there is an improvement of about 0.8% for mean relative error while 0.06 dB for absolute mean error. It can be explained easily by comparing the environment where the same height between the floor and ceiling and with the same antenna used can be noticed as in DITSC.

Total rays model in DITFF, however shows satisfactory results even though the mean relative error increases about 0.7% after it has been optimized. The conditions in DITFF are similar to the case in DITSC. The characteristic of vertical polarization possessed by the antenna is tally matches with the multiple reflected rays that occur in vertical plane (between the ceiling and floor).

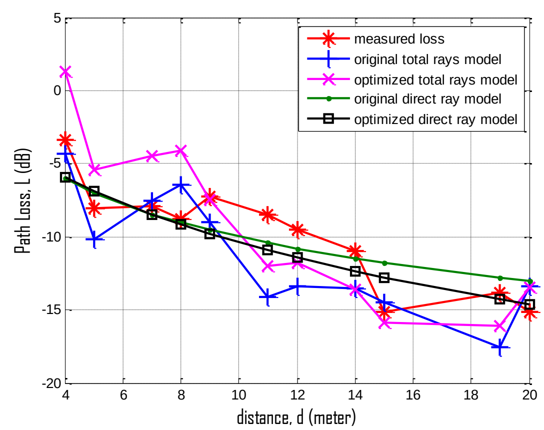

Fig. 11. Comparison of optimized models and original models with measurement data in DITFF.

Table 2: Comparison between the original and optimized total rays model

Measurement Site	Total Rays Model		Optimized Total Rays Model	
	Absolute Mean Error (dB)	Relative Mean Error (%)	Absolute Mean Error (dB)	Relative Mean Error (%)
DITSC	4.78	29.57	3.44	16.61
DITFF	2.35	12.00	2.61	12.70
FSGF	3.72	25.39	3.67	23.00
FSSF	12.85	754.49	14.15	730.50
BMTF	11.50	270.00	13.01	305.00
BAF	11.32	143.33	14.09	164.14

Table 3: Comparison between the original and optimized direct ray model

Measurement Site	Direct Ray Model		Optimized Direct Ray Model	
	Absolute Mean Error (dB)	Relative Mean Error (%)	Absolute Mean Error (dB)	Relative Mean Error (%)
DITSC	3.14	18.64	3.25	18.17
DITFF	1.56	8.23	1.50	7.43
FSGF	7.47	45.53	2.23	13.17
FSSF	1.91	55.04	0.69	14.38
BMTF	1.55	34.25	0.90	11.02
BAF	2.23	25.12	0.76	10.06

The effectiveness of optimized direct ray model in validation for FSGF (Fig. 12) is shown in Table 2. The optimized direct ray model improved the mean relative error from 45.53% to 13.17% as well as the absolute mean error from 7.47 dB to 2.23 dB. Unexpectedly, the relative mean error for total rays model of about 25.39%, while optimized total rays model of about 23.00% in FSGF is relatively high even though it shows improvement of about 2.39%. The case of total rays model and optimized total rays model in FSSF (Fig. 13) is worse than other measurement site because it indicates extremely high percentage in mean relative error (754.49% and 730.50%, respectively) and absolute mean error for both model (12.15 dB and 15.15 dB, respectively). On the contrary, the optimized direct ray model gives better agreement with measurement data if compared with direct ray model because it gives 14.38% of mean relative error. It also improves the mean relative error (40.66%) and the absolute mean error (1.22 dB) for direct ray model.

The cases in BMTF (Fig. 14) and BAF (Fig. 15) however show similar condition as in FSSF where both of the measurement sites gave abnormal figure of absolute mean error and mean relative error for total rays model and optimized total rays model as illustrated in Table 2. The mean relative error in BMTF (305%) implies the failure of optimization in this case because the mean relative error has not been improved. Similarly, for the case in BAF, optimized total rays give relatively higher mean relative error (164.14%) than total rays model (143.33%).

However, the optimized direct ray model shows better agreement with measurement data in BMTF and BAF. In BMTF, the mean relative error improved from 34.25% to 11.02% and 1.55 dB to 0.90 dB for absolute mean error. Meanwhile, the mean relative error and absolute mean error in BAF reduces from 25.12% to 10.06% and 2.23 dB to 0.76 dB, respectively

From Table 2, it can be noticed that most of the case in optimized total rays model shows no improvement. However, all the cases in optimized direct ray model show positive improvement. It can be observed in Table 3. The total rays model comprise of first, second, third order of reflected ray model and direct ray model. Therefore, the total rays model consists of many parameters and it's a very complex model. All the uncertainties in total rays model may be amplified after the optimization (optimized total rays model). No tendency of improvement but even worse is observed.

As a matter of fact, actual field strength is governed the inverse square law. Nevertheless, the field strength is distorted and hence deviates from inverse square law due to the presence of the obstruction and interference. It can be noticed at Fig. 10 to Fig. 15.

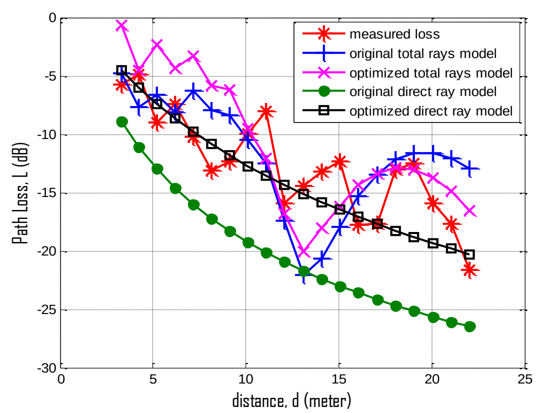

Fig. 12. Comparison of optimized models and original models with measurement data in FSGF.

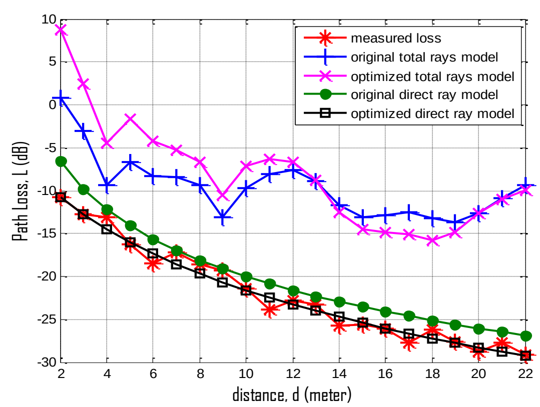

Fig. 13. Comparison of optimized models and original models with measurement data in FSSF.

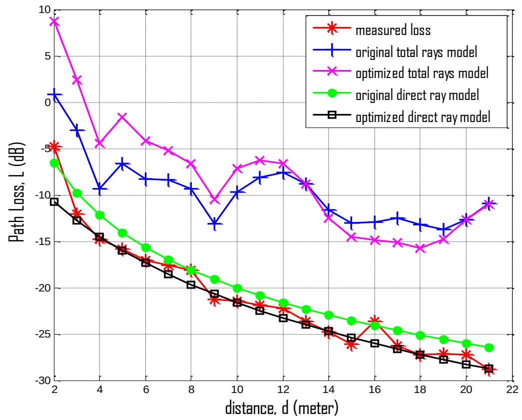

Fig. 14. Comparison of optimized models and original models with measurement data in BMTF.

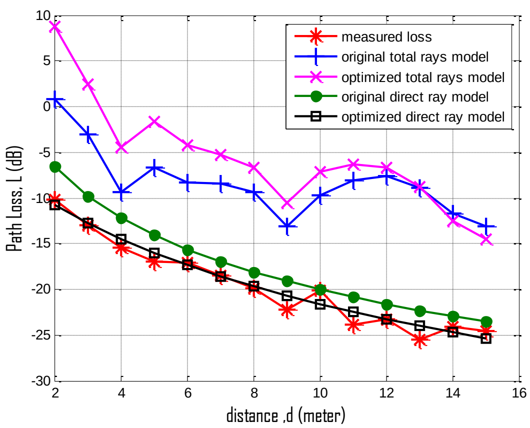

Fig. 15. Comparison of optimized models and original models with measurement data in BAF.

VI. CONCLUSION

In this project, we successfully optimized the direct ray model which is GO based through measurement at DITSC that can predict path losses in furnished indoor environments with obstacles. This study highlights the improvement of accuracy of optimized GO (direct ray model) in predicting path loss in furnished indoor environment. The direct and total ray models are optimized with addition of log-distance expression. These optimized models were validated by comparing the measured path loss at DITFF, FSGF, FSSF, BMTF and BAF. After the comparison, it can be noticed that the total rays model has the absolute and relative mean error of 2.35 dB and 12.00%, respectively at DITFF when compared with measured path loss. The optimized total ray model meets the failure in improving the accuracy as some of the measurement sites have even greater error after the optimization. Its absolute and relative mean error is increased to 2.61 dB and 12.70%. Absolute and relative mean errors for the other measurement sites were even worse than DITFF.

On the other hand, the direct ray model performs considerable good by exhibiting good agreement with measured path loss for all measurement sites especially DITFF if comparing with total ray model and optimized total ray model. The absolute and relative mean error shows considerably low, i.e., 1.56 dB and 8.23%, respectively for DITFF. After the direct ray model has been optimized, the absolute and relative mean error show decrement in term of absolute and relative mean error. The comparisons among the direct and total ray model as well as optimized direct and total ray model were came to learn that the optimized direct ray model exhibit the best accuracy in predicting path loss at all measurement sites. Meanwhile, the error in total rays model has been amplified aster optimization and it is inconvenient to be used as prediction tool in this work.

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Ee Meng Cheng was born in 1980. He obtained his B.Sc (Honours) - Instrumentation Science in Universiti Putra Malaysia in 2004. He pursued his M.Sc. in Wave Propagation at the Institute for Mathematical Research on 2005 in Universiti Putra Malaysia and his Ph.D. in Microwave at the Faculty of Science in 2007 in Universiti Putra Malaysia. Recently, he is a Senior Lecturer in School of Mechatronic Engineering, Universiti Malaysia Perlis. His main personnel research interest is in the computational electromagnetic modeling, microwave dielectric spectroscopy, wave propagation in RF & microwave and microwave sensors development for food and agricultural applications.

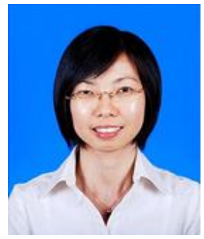
Zulkifly Abbas was born in Alor Setar, Malaysia, in 1962. He received the B.Sc. degree with honors in Physics from the University of Malaysia, Kuala Lumpur, in 1986, the M.Sc. degree in Microwave Instrumentation from The Universiti Putra Malaysia (UPM), Serdang, in 1994, and the Ph.D. degree in Electronic and Electrical Engineering from the University of Leeds, Leeds, U.K., in 2000. He is currently an Associate Professor with the Department of Physics, UPM, where he has been a Faculty Member since 1987. His main personnel research interest is in the theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave sensors for agricultural applications.

Mohd Fareq bin Abdul Malek obtained his B.Eng. (Honours) - Electronic and Communication Engineering in The University of Birmingham, United Kingdom in 1994. He pursued his M.Sc. (Eng.) in Microelectronic Systems and Telecommunications at The University of Liverpool, United Kingdom in 2003 and Ph.D. in Electrical Engineering (Radio Frequency and Microwave) on 2005 in The University of Liverpool, United Kingdom. Recently, he is an Associate Professor in Faculty of Engineering and Information

Sciences, University of Wollongong in Dubai. His main personal research interest is in electron maser, antenna design, embedded computing and microwave absorber development.

Kim Yee Lee was born in Muar, Johor, Malaysia. He received his B.Sc. Physics, M.Sc. Microwaves, and Ph.D. Microwaves, all from the Universiti Putra Malaysia in year 2002, 2004, and 2008 respectively. In December 2007, he joined Universiti Tunku Abdul Rahman as a Lecturer in Department of Electronics and Electrical Engineering. His areas of research include microwave measurement technique, microwave circuit and instrumentation, control and automation, material properties measurement, and instrumentation calibration.

Kok Yeow You was born in 1977. He obtained his B.Sc. Physics (Honours) degree in Universiti Kebangsaan Malaysia in 2001. He pursued his M.Sc. in Microwave at the Faculty of Science in 2003 and his Ph.D. in Wave Propagation at the Institute for Mathematical Research in 2006 in Universiti Putra Malaysia. Recently, he is a Senior Lecturer at Radio Communication Engineering Department, Universiti Teknologi Malaysia. His main personnel research interest is in the theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave sensors for agricultural applications.



Shing Fhan Khor was born in 1982. She obtained her B.Sc. with Edu. (Honours)-Physics in Universiti Putra Malaysia in 2007. She pursued her Ph.D. in Materials Science at the Faculty of Science in 2011 in Universiti Putra Malaysia. Recently, she is a Senior Lecturer at School of Electrical Systems Engineering, Universiti Malaysia Perlis (UniMAP). Her main personnel research interest is in the glass science and focusing on dielectric, optical, mechanical and thermal properties.

Mohd Afendi bin Rojan was born in 1981. He is a Ph.D. holder from University of Tsukuba in Engineering Mechanics & Energy. He is currently a Senior Lecturer at School of Mechatronic Engineering, Universiti Malaysia Perlis (UniMAP). His main research interests include fracture mechanics, finite element analysis, and adhesive bonding.