Comparative Study on Indoor Path Loss Models at 28 GHz, 60 GHz, and 73.5 GHz Frequency Bands

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Abstract **─** In this paper, a comparative study between different indoor path loss prediction models is conducted. The investigated models include averaged wall loss model (AWM), single slope model (SSM), linear attenuation model (LM), two slope model (TSM), partitioned model (PM), and Motley-Keenan model (MKM). The models were tested in a simulated environment of the 3rd floor of Chesham building, the University of Bradford, a different set of frequencies were used including 28 GHz, 60 GHz, and 73.5 GHz, TSM shows the best performance, both AWM and MKM tend to have a similar performance at millimetre-frequencies, both models' prediction for corridor and LOS regions are pessimistic while TSM, SSM, and LM have better estimations in these regions.

Index Terms **─** Indoor path loss models, millimetre-wave frequencies, Motley Keenan model, ray tracing, received signal strength, single slope model, two slope model.

I. INTRODUCTION

The astonishing growth of wireless applications in our daily life urges the radio engineer designers to have optimum algorithms to have best radio wave coverage; those applications cover a variety of services including communication services, medical, industrial, and public transport usage [1]. The IEEE 802.11 WLAN became the principal WLAN technology due to its low cost, ease of disposition and flexible mobility [2]. The unlicensed available spectrum makes the use of WLAN attractive within indoor environments for different applications especially for millimetre wave band [3]. However, deploying WLAN routers requires knowledge of the propagation channel; therefore, having an accurate indoor channel modelling becomes critical [1]. Currently, massive research is being conducted to utilize millimetre wave frequencies in 5G systems [4-5], this utilization includes 28 GHz [4], 60 GHz [5], and 73 GHz [4].

The wireless channel in indoor environments is more complicated compared to outdoor environments. Multipath fading affects wireless systems performance; as a result, the wireless device and the router have to match in order to suppress multipath manifestations which demands awareness of the detailed propagation channel [6].

Many efforts have been done in order to characterise the channel's parameters; radio coverage designers use path loss prediction models to distribute the access points within the facility such that they provide the best coverage [7].

The indoor channel $h(t)$ is a time-space varying, which can be expressed mathematically based on Saleh Valenzuela model as [8]:

$$h(t,\theta) = \sum_{l=0}^{\infty}\sum_{k=0}^{\infty}\beta_{kl}e^{j\varphi_{kl}}\delta\begin{pmatrix} t \\ -T_l \\ -\tau_{kl}\end{pmatrix}\delta\begin{pmatrix} \theta \\ -\Theta_l \\ -\omega_{kl}\end{pmatrix}, \quad (1)$$

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where β_{kl} is the multipath gain, φ is the phase associated with the l^{th} cluster and k^{th} ray, l is the number of clusters, k is the number of arrival rays within the l^{th} cluster, T_l is the arrival time of the l^{th} cluster, τ_{kl} is the arrival time of the k^{th} ray within the l^{th} cluster, and ω_{kl} is the arrival angle of the k^{th} ray of the l^{th} cluster [9].

In the case of small bandwidths, multipath components fall within the bins on the delay axis which follow either Rayleigh or Rician distributions [9]; however, when using Ultra Wide-Band (UWB) systems the number of components falling within the delay bins is less; therefore, the Central Limit Theorem is no longer valid. In such a case, the 802.15.3a standard model is adopted to consider these effects [9]. Indoor systems can be considered as pico-cell arrangements, a single pico-cell arrangement together with a general MIMO scheme is proposed in [10]. The MIMO system shows the potential to improve system performance.

MIMO antennas are widely used in 5G systems to increase data rate [11], one of the major concerns regarding designing a MIMO antenna is the mutual coupling, several research papers tackled this problem and obtained a lower mutual coupling [12]. Improvements on the IEEE 802.11n indoor channel were made by [13] where more realistic channel representation for MIMO systems using uniform circular array antenna at either the transmitter or the receiver was established and studied. In their work, the spatial and temporal clustered channel model developed involving treating the reflected rays as clusters. In [14] capacity investigations on hybrid uniform linear and circular arrays were conducted, it was concluded that using multi-cluster based approach gives more accurate results compared to single cluster case which leads to better optimum design of antenna.

Mutual coupling reduction has been studied extensively in the literature using meta-material [15, 16], periodic multi-layered EM bandgap structures [17], and orthogonal structure [18].

The small-scale effect is undesired and has to be removed; there are two methods to remove small scale effect, the first method takes the power sum of all multipath rays, known as "*power sum prediction, (PS)*" [29]:

$$\langle P_{PS}\rangle = \sum_M P_M, \tag{2}$$

where $\langle P_{PS}\rangle$, M, and P_M are the averaged power using the PS method, number of multipath rays and power of each individual ray respectively.

The second method takes the average of the squared sum of all-electric fields (amplitudes and phases): this is known as "*vector sum prediction (VS)*" [29]:

$$\langle P_{VS}\rangle = \left|\sum_M \sqrt{P_M}\, e^{-j\varphi_M}\right|^2, \tag{3}$$

where $\langle P_{VS}\rangle$ is the averaged power using the VS method and φ_M is the Mth ray phase in radians.

Wireless InSite supports both methods, it is up to the user to select the operating method from the settings. Practically, it's difficult to use the PS averaging method, especially at higher frequencies therefore, VS averaging method is used instead.

In [30] a comprehensive study on estimating local mean signal strength in indoor environments using VS averaging method was conducted using a different number of samples, different arrangement sizes and different arrangement configurations. In this paper, different indoor path loss prediction parameters are investigated for different sets of frequencies. The organisation of this paper is as follows: Section II presents the methodology adopted in the conducted study and describes the simulation setup and the procedure followed to evaluate each model. Section III investigates the collected results; a comparative study between the investigated models is conducted, and finally, conclusions and recommendations are presented.

II. PROBLEM DEFINITION AND METHODOLOGY

The main target of this paper is to understand, the performance of some popular indoor path loss models at millimetre wave frequencies. Many indoor path loss models have been studied in literature, some models consider free-space loss along with losses due to walls and floors like Motley Keenan Model (MKM) [19], averaged wall loss model (AWM) [7], ITU-R P.1238 model [20], COST231 indoor model [21], and enhanced COST231 [22]. Another set of models use free space propagation model with different values for the path loss exponents (PLE) like single slope model (SSM) [23], two slope model (TSM) [24], and partitioned model (PM) [25].

Some models consider the effect of free space propagation in addition to attenuation factors which depend on the nature of the tested environment and the operating frequency like linear attenuation model (LM) [26].

Since simulations are conducted for a single floor, propagation through floors will not be investigated since COST231 model will turn into Motley-Keenan model. Similarly, the ITU-R P.1238 model will be reduced to a single slope model. The examined models include Motley-Keenan model, single slope model, two slope model, linear attenuation model, averaged wall loss model and partitioned model. The multi-floor propagation environment will be discussed in another paper.

A. Single Slope Model (SSM)

The received power at any distance is given by [23]:

$$P_r(dB) = P_0(dB) - 10n\log_{10}(d), \tag{4}$$

where P_0 is the reference power measured at a 1 m from the transmitter, n is the path loss exponent and d is the distance from transmitter (Goldsmith, 2005).

B. Two Slope Model (TSM)

In [24] two-path loss exponents were used to have a better fitting for the signal strength variation, the first PLE n_1 is applied for the "*near transmitter propagation*" where no obstruction in the 1st Fresnel zone, while the second PLE n_2 is applied for the "*breakpoint propagation*" when furniture and other obstacles fall in the 1st Fresnel zone and PLE is larger than free-space path loss,

$$P_r = P_0 - 10\begin{Bmatrix} n_1 \log_{10}(d) & d < d_{bp} \\ n_1 \log_{10}(d_{bp}) + n_2 \log_{10}\left(\frac{d}{d_{bp}}\right) & d > d_{bp} \end{Bmatrix}, \quad (5)$$

where d_{bp} is the breakpoint distance.

C. Linear Attenuation Model (LAM)

Instead of using the path loss exponent, a loss factor a was proposed to be added to the free space loss [26],

$$P_r(dB) = P_0(dB) - 20\log_{10}(d) - a \cdot d, \quad (6)$$

where d represents distance in metre.

D. Partitioned Model (PM)

Predetermined values of n are used depending on the transmitter-receiver separation [25]:

$$P_r = P_0 - \begin{cases} 20\log_{10} d, & 1m < d \le 10m \\ 20 + 30\log_{10}\frac{d}{10}, & 10m < d \le 20m \\ 29 + 60\log_{10}\frac{d}{20}, & 20m < d \le 40m \\ 47 + 120\log_{10}\frac{d}{40}, & d > 40m \end{cases}. \quad (7)$$

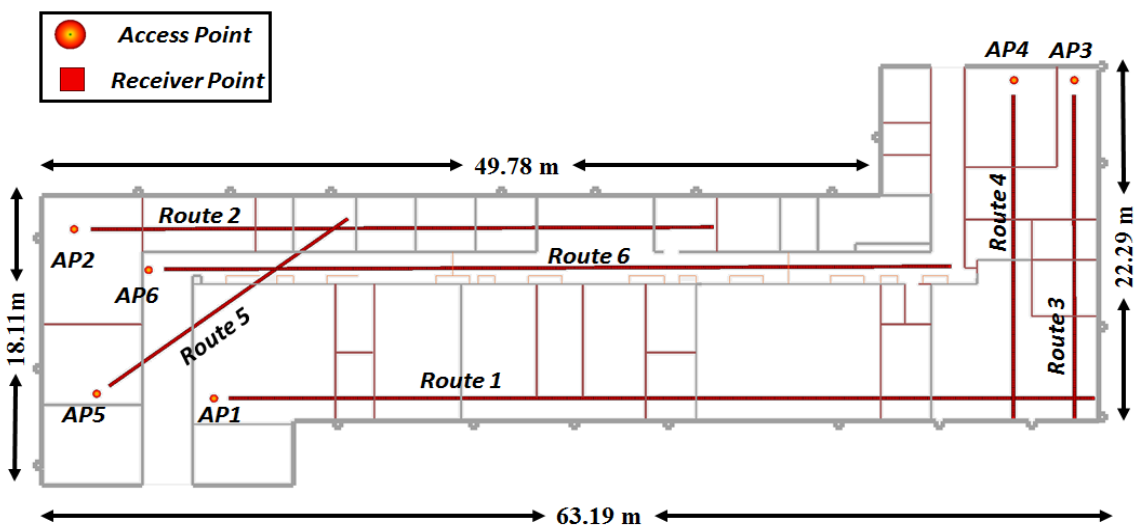


Fig. 1. Simulated experiment in the 3rd floor Chesham building, University of Bradford.

E. Motley-Keenan Model (MKM)

In Motley-Keenan Model, losses are estimated by considering the free space propagation loss in addition to the effect of walls and floors [19],

$$L = L_{FS} + L_C + \sum_{i=1}^{I} N_{wi}L_{wi} + \sum_{j=1}^{J} N_{fj}L_{fj}, \quad (8)$$

where L_{FS}, L_C, N_w, N_f, L_w, L_f, i, and j are the free space loss, a constant term (loss at a reference distance $d_0 = 1\ m$), number of walls, number of floors, wall loss factor, floor loss factor, type of wall and type of floor respectively.

F. Average Wall Model (AWM)

This model is similar to MKM; however, due to multipath and waveguiding effects, losses from walls are considered as correction factors, in other words, wall losses W_{AML} can be positive or negative whatever makes the best fit for the measurements, the received signal strength after the Lth wall is given by [7]:

$$P_r(d) = P_0 - 20\log_{10}(d) - W_{AWM} \cdot L. \quad (9)$$

Upon applying the above equations, there is a set of unknown parameters to be estimated, these parameters include PLE for SSM (i.e., n), PLE for TSM (i.e., n_1, n_2), attenuation factor (AF) for LM (i.e., a), wall losses for MKM (L_{wi}), and averaged wall losses for AWM (W_{AWM}). The estimation of these parameters is explained in the next section.

III. SIMULATION SETUP

Figure 1 shows the examined scenarios in the simulated environment; these routes are chosen in a representative way for the indoor environments, route 1 and 4 represent propagation in lab offices, which have both concrete and drywalls. Route 2 represents propagation in lecturers' offices which mainly have concrete walls, route 3 represents propagation in lab offices with drywalls only. Route 5 represents propagation in the environment with concrete walls only while route 6 represents propagation in corridors. MIMO antenna systems are widely integrated into the mm-wave applications, therefore in our simulation a 16×16 MIMO circularly polarised antenna system was used with a λ/2 spacing between elements. Access points transmit power is 20 dBm, receiver sensitivity was set to -120 dBm.

In this paper, simulations were conducted using Wireless InSite ray-tracing software for high-frequency ranges namely, 28 GHz, 60 GHz, and 73.5 GHz, their corresponding bandwidths are 0.8 GHz [4], 2.15 GHz [27], and 2 GHz [28] respectively. The Wireless InSite scenarios settings are presented in Table 1.

Table 1: Wireless InSite settings for the investigated scenarios

Property	Setting
Number of reflections	6
Number of transmissions	4
Number of diffractions	1
Number of reflections before the first diffraction	3
Number of reflections after the last diffraction	3
Number of reflections between diffractions	1
Number of transmissions before the first diffraction	2
Number of transmissions after the last diffraction	2
Number of transmissions between diffractions	1
Ray tracing method	SBR
Propagation model	Full 3D

As shown in Fig. 2, the simulation environment considers concrete walls, drywall, glass, wooden doors and tables, metal cabinets and indoor foliage which makes the environment more representative. The model also considered the effect of the interaction between building materials and operating frequencies as shown in Table 2 according to the ITU-R P.2040 recommendations [31]. The purpose of this study is to evaluate the behaviour of each model with high frequencies, these frequencies are proposed for use in the 5G systems. Simulations took place in a simulated environment of B3-wing, Chesham Building, University of Bradford.

In Wireless InSite, received signal strength (RSS) data were collected over routes shown in Fig. 1, since path loss models are used to predict the signal strength along a route, we took samples from the simulated data and then models' parameters were generated using a Matlab routine such that they make the best fit to the samples. After that, those parameters are passed to a Matlab routine to predict the RSS for each model for the investigated routes. Root means Square Error (RMSE) between the Wireless InSite data and the generated path loss models data is used as a performance metric, the smaller the RMSE, the better the model.

Table 2: Material properties with frequency

Frequency (GHz)		28	60	75.3
Concrete	ε_r	5.31	5.31	5.31
	σ	0.48	0.90	1.06
Glass	ε_r	6.27	6.27	6.27
	σ	0.23	0.57	0.72
Wood	ε_r	1.99	1.99	1.99
	σ	0.17	0.38	0.47
Drywall	ε_r	2.94	2.94	2.94
	σ	0.12	0.21	0.24

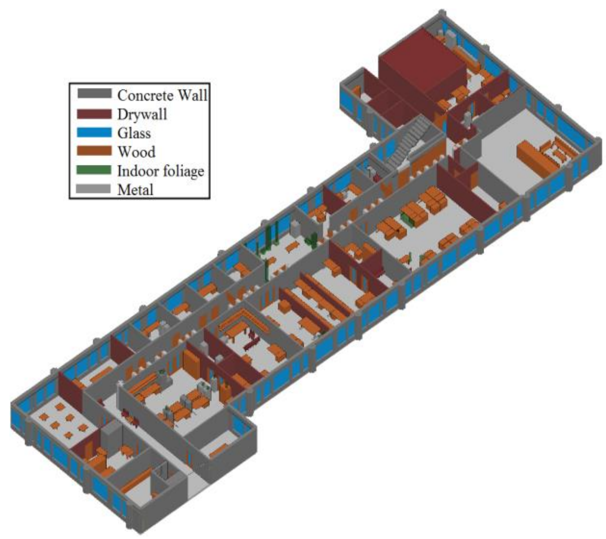
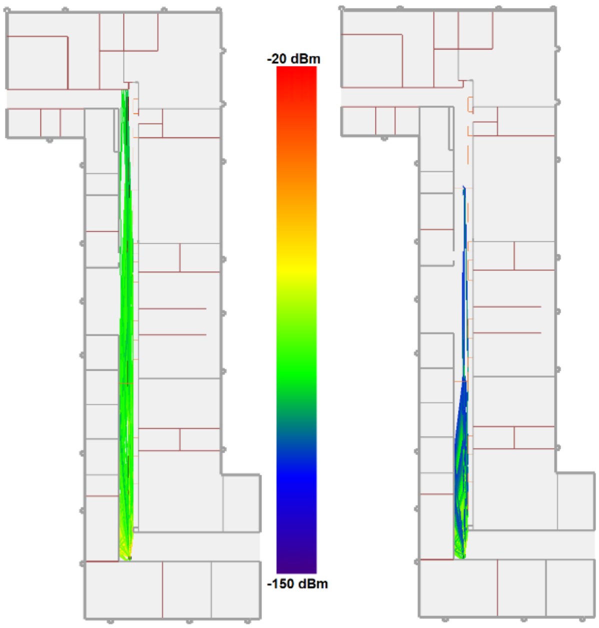


Fig. 2. 3D view of the simulated environment for B3-wing, Chesham Building, University of Bradford.

IV. RESULTS AND DISCUSSIONS

Figure 3 shows propagation through the corridor at (a) 28 and (b) 73.5 GHz. As seen in the figure, there is a remarkable path loss difference between the two frequencies; at 73.5 GHz most of the RSS values fall down -100 dBm after 20 m, while at 28 GHz, all RSS readings are above -90 dBm for the entire route. Since the operating frequencies are at millimetre wave, walls tend to act as reflectors. In the following discussion, we refer to each simulation run through one of these propagation cases as a scenario.

Propagation through drywalls (Route #3 in Fig. 1) at 60 GHz is presented in Fig. 4. At low frequencies waves penetrate drywalls with small losses; as frequency increases, drywall losses will increase as its electrical properties will change. The RMSE for AWM, SSM, LM, PM, MKM and TSM models in dB are 8.61, 15.6, 13.6, 19.14, 9.1, and 10.12 respectively. Wall losses-based prediction models (MKM and AWM) show good performance while SSM, and PM which use PLEs have poor performance, the same observation was recorded with LM which uses AF. TSM, on the other hand, shows better performance as it uses two PLEs instead of one.



(a) (b)

Fig. 3. Propagation paths through a corridor at: (a) 28 GHz, and (b) 73.5 GHz.

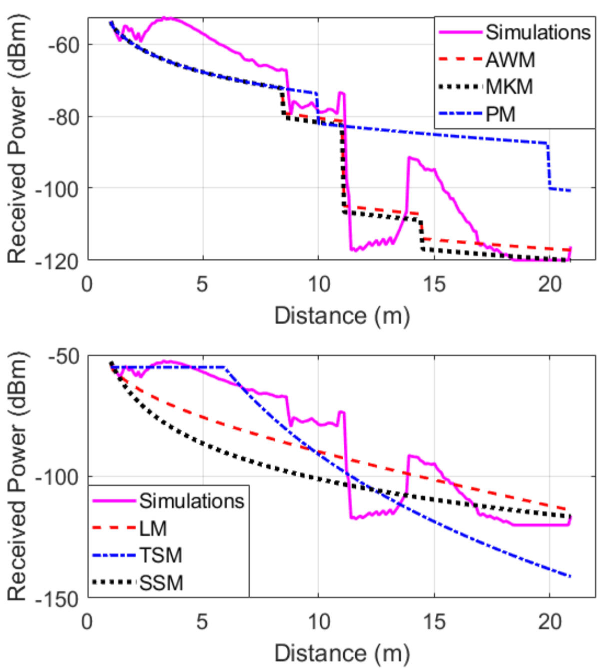


Fig. 4. Propagation through Drywalls at 60 GHz.

Propagation through concrete walls (Route #5 in Fig. 1) at 73.5 GHz is presented in Fig. 5. The average signal loss for a wave propagates through the concrete wall is in the range of (20 - 30) dBm. Unlike wall losses-based model, PLE-based models and LM were unable to represent the sharp changes in RSS level, PM underestimates the losses through concrete walls; since it uses fixed values for PLEs. The RMSE for AWM, SSM, LM, PM, MKM and TSM models in dB are 8.56, 10.44, 17.6, 28, 10.43, and 12.1 respectively.

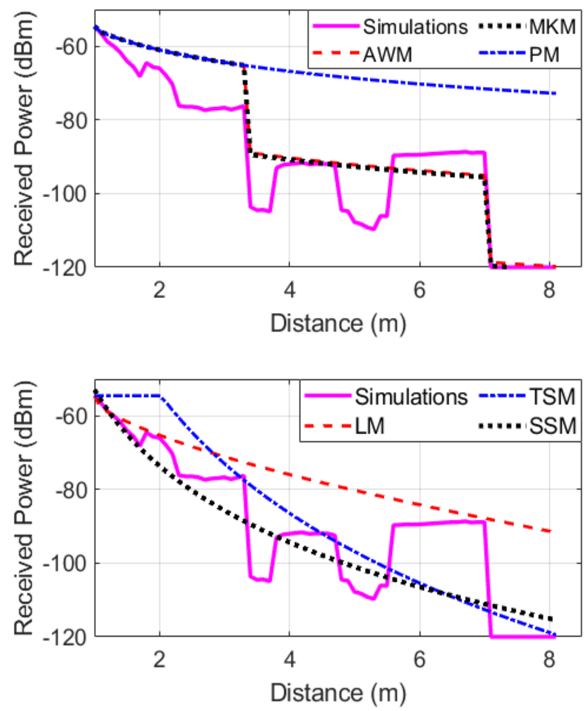


Fig. 5. Propagation through concrete walls at 73.5 GHz.

Figure 6 shows propagation through the corridor in the simulated environment (Route #6 in Fig. 1) at 28 GHz; propagation paths are shown in Fig. 3 (a). The RMSE of the AWM, SSM, LM, PM, MKM and TSM models in dB are 10.05, 4.03, 3.87, 18.04, 10.05, and 2.98 respectively. Waveguiding effect has a great impact on the propagation through corridors, therefore models that have parameters that only counts for losses (like AWM, MKM, and PM) will be insufficient to predict the signal behaviour. On the other hand, models that use the PLEs and AF tend to have better performance as they can predict the signal strength more accurately. TSM model shows the best performance, where (n_1, n_2) found to be 1.56 and 3.41 respectively. LM shows the second-best performance, where $a = 0.3$ adjusts the path loss values to consider the effect of waveguiding propagation. SSM shows third-best performance where γ is found to be 2.88 which can be regarded to the effect of waveguiding.

In this particular scenario, both AWM and MKM performances are not accurate as the models use the simple Friis formula (γ=2) due to the absence of walls. However, propagation in the indoor environment including corridors does not generally follow Friis formula. PM shows the worst result as it does not consider the waveguiding effect.

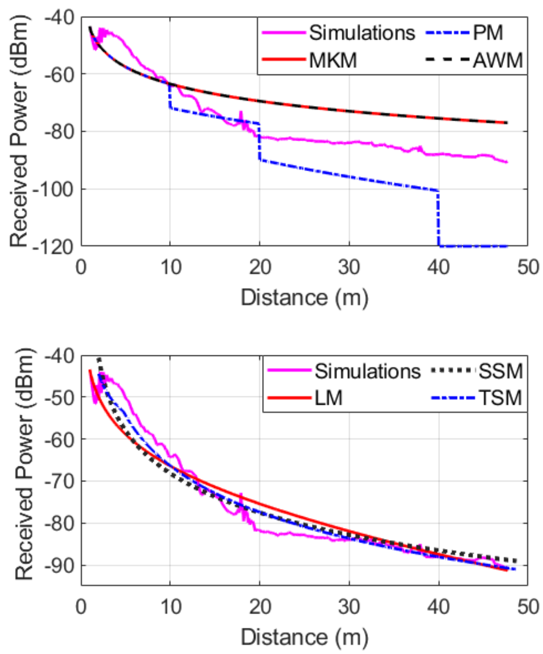


Fig. 6. RSS through the corridor at 28 GHz.

It's observed for high frequencies, that AWM does not provide a significant improvement over MKM; this may be regarded as the fact that AWM uses a similar concept of MKM. However, losses due to walls may be positive (i.e., add gain rather than loss). This may be possible for UHF or WLAN frequencies. At higher frequencies like millimetre wave frequencies, wall penetration losses become higher and it's unlikely to have a stronger signal level even if the wall is thin or made from a material that has very low conductivity. Table 3 shows how wall losses for AWM and MKM are close. As a result, the behaviour is almost the same as seen in Fig. 7, therefore, there is no great distinction between the two models at high frequencies. Metrics comparison for the investigated frequencies are presented in Tables 4, 5, and 6 which show similar performance for the two models.

Table 3: Estimated wall losses for AWM and MKM in dB

Frequency (GHz)	Concrete		Drywall	
	MKM	AWM	MKM	AWM
28	27	27	7	6.82
60	24	23.5	8	8.02
73.5	24	23.5	9	9.23

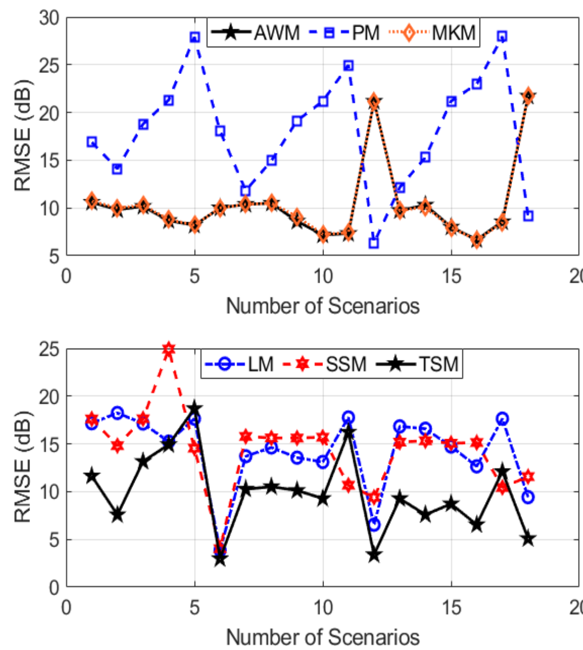


Fig. 7. Performance comparison between all investigated models.

The PM shows poor results as the mean RMSE for all scenarios and frequencies exceeds 20 dB; this is because the model has fixed PLEs which do not necessarily fit any geometry at any frequency. The result is consistent with the metrics presented in Tables 4, 5, and 6 where the PM has the worst performance statistics.

Using two PLEs gives the TSM more flexibility and advantage over SSM as seen in Fig. 7 where TSM outperforms SSM for more than 83% of the tested scenarios. This also is confirmed by metrics statistics. In some scenarios, the dataset used for generating PLEs for TSM may not be adequate, therefore, SSM may have similar or better performance as shown in the figure.

Both LM and SSM have similar performance as shown in Fig. 7, this demonstrates the similarity between α and γ. LM has better results at 28 GHz and at 60 GHz since the performance is more stable as depicted in Tables 4 and 6. At 60 GHz, SSM outperforms the LM and shows more stable performance as shown in Table 5.

Table 4: Metrics statistics for examined models at 28 GHz (in dB)

	Max. RMSE	Min. RMSE	STD	Average RMSE
AWM	10.60	8.2	0.93	9.58
SSM	24.93	4.03	6.79	15.60
LM	18.24	3.87	5.49	14.88
PM	27.90	14.11	4.74	19.51
MKM	10.72	8.20	0.96	9.67
TSM	18.70	3.01	5.55	11.50

Table 5: Metrics statistics for examined models at 60 GHz (in dB)

	Max. RMSE	Min. RMSE	STD	Average RMSE
AWM	21.18	7.18	5.25	10.86
SSM	15.78	9.40	2.94	13.80
LM	17.77	6.54	3.68	13.22
PM	24.97	6.34	6.75	16.40
MKM	21.18	7.28	5.19	10.97
TSM	16.23	3.39	4.08	9.97

Table 6: Metrics statistics for examined models at 73.5 GHz (in dB)

	Max. RMSE	Min. RMSE	STD	Average RMSE
AWM	21.71	6.67	5.48	10.83
SSM	15.31	10.44	2.19	13.79
LM	17.64	9.42	3.13	14.64
PM	27.95	9.17	7.12	18.12
MKM	21.71	6.62	5.51	10.77
TSM	12.11	5.09	2.43	8.22

The averaged estimated values for PLEs and AF parameters are presented in Table 7. As seen in the table, α, γ, and n_2 tend to increase linearly as frequency increases from 60 to 73.5. These increments point to losses increments as frequency increases. Since propagation at 28 GHz covers a larger range, it is expected to have larger values for the investigated metrics. In corridors, γ found to be 2.87, 4.03, and 4.1506 at 28, 60, and 73.5 GHz respectively. While α tends to be 0.3, 0.9, and 1.2 for the same set of frequencies.

Table 7: Averaged estimated parameters for LM, SSM and TSM

Frequency (GHz)	$\boldsymbol{\alpha}$ (dB/m)	$\boldsymbol{\gamma}$	$\boldsymbol{n_1}$	$\boldsymbol{n_2}$
28	2.38	5.18	0.58	25.88
60	1.62	5	0.4	16.3
73.5	2.34	5.03	1.19	24.52

In Table 8 performance comparison between all models at all frequencies and scenarios is presented, TSM shows the best performance as it has lowest RMSE for 44.44% for all tested scenarios, PM shows the worst performance for all examined frequencies. The descending order of the Models' performance is TSM then AWM/MKM, LM, SSM, and PM.

The propagation area is larger at 28 GHz; therefore, the signal can reach further distances and more walls are included, in this case, both MKM and AWM will have better performance compared to the TSM which will have difficulty to represent this large area with only two PLE's.

Table 8: Overall performance for all models at all frequencies (dB)

Model	Min. RMSE	Max. RMSE	STD	Average RMSE
AWM	6.67	21.71	4.19	10.42
SSM	4.03	24.93	4.27	14.39
LM	3.87	18.24	4.03	14.24
PM	6.34	27.95	6.05	18.00
MKM	6.62	21.71	4.17	10.46
TSM	3.01	18.70	4.19	9.89

V. CONCLUSIONS

A comparative study between different indoor path loss prediction models has been presented, based on models generated using Matlab and compared to Wireless InSite ray-tracing software simulations. It was found that MKM and AWM have similar performance for high frequencies. Also, it was found that both models show good performance for path loss predictions through walls while their predictions for LOS propagation regions and corridors are pessimistic; on the other hand, models based on path loss exponents and attenuation factors show good performance at these regions and have poor performance for path loss predictions through walls. TSM tends to have the best performance while AWM/MKM show the best performance. LM and SSM have close performance and their corresponding parameters tend to increase as frequency increases. For all frequencies, PM had the worst results as it uses fixed values for path loss exponents.

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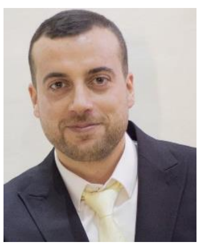

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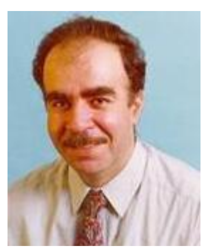

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