# A Novel Indoor Channel Model for TVWS Communications based on Measurements

Syed Muhammad Hashir,[1] Serhat Erkucuk,[2] Tuncer Baykas[1]
[1]Department of Electrical-Electronics Engineering, Istanbul Medipol University, Istanbul, Turkey
[2]Department of Electrical-Electronics Engineering, Kadir Has University, Istanbul, Turkey
Email: msyed@st.medipol.edu.tr, serkucuk@khas.edu.tr, tbaykas@medipol.edu.tr

***Abstract*—In this paper, we present an indoor measurement campaign for TV white space bands inside a university building. The measurement results are compared with different indoor propagation models in the literature. We observed large estimation errors for the total path loss value from all existing models. Consequently, we are proposing a new indoor propagation model for TVWS frequencies, which concatenates the effects of frequency dependent path loss with penetration losses due to walls and windows. Performance comparison with existing models show that the proposed model achieves superior performance compared to existing models in terms of Root-Mean-Squared Error (RMSE).**

***Index Terms*—TV white space, TVWS, spectrum sharing systems, measurement, indoor propagation model.**

## I. Introduction

During the last decade, the increase in wireless data traffic forced the limits of communication systems in terms of reliability and throughput [1]. One of the solutions is allocating more RF spectrum for data communication purposes in higher frequency bands such as 60 GHz [2] and THz [3] bands. Utilizing such bands results in complex systems due to relatively high path losses and shorter communication ranges. Another solution is utilizing spectrum sharing techniques to increase the efficiency in lower frequency bands [4], which are allocated to other services such as broadcasting. Among these bands, the so called television white space (TVWS) bands have attracted much attention in the last decade. Although it depends on the local regulations, most of the available TVWS bands are between 470 and 700 MHz.

In TVWS bands, regulatory organizations have enabled spectrum sharing [5], where the systems are categorized as primary and secondary systems [6]. Primary systems are the licensed systems. Secondary systems are allowed to operate given that they do not cause harmful interference to the primary users. The efficient and reliable performance of secondary systems becomes more challenging since the available channels for them are limited.

There are multiple standards developed for TVWS bands including IEEE 802.15.4m, 802.11af, 802.22 and 802.19.1 standards, which cover the implementation of systems in these bands for personal, local and regional area networks as well as for the coexistence of these systems. In [7] and [8], different standards for TVWS are presented. Among them, the standards IEEE 802.11af and IEEE 802.15.4m have use cases for indoor applications. For example, IEEE 802.11af systems can support a local area network, which requires data rates in tens of Mb/s and communication range up to 100 meters. On the other hand, the potential applications of IEEE 802.15.4m standard are low power wireless systems like smart utility networks (SUNs). SUN systems require low data rate (few hundreds of kb/s) and coverage both indoors and outdoors. Thus, detailed indoor channel models are required for network deployments. There are many propagation models in the literature for TV bands [9], [10]. Most of these models are for outdoor scenarios and for long range systems. On the other hand the literature for indoor scenarios and short range systems in TV bands is limited. Most important channel models for indoor use are the log-distance model [11], Linear Attenuation Model (LAM) [12], ITU-R P.1238 [13] and Multi Wall and Floor Model (MWF) [14]. However, these models are not specifically intended for the TVWS band operation. Therefore, a more accurate indoor channel model is needed for TVWS bands.

Considering these issues, in this paper initially the propagation characteristics in TVWS band in a real indoor scenario is considered by evaluating path loss measurements. Based on these results, an indoor propagation model for TVWS bands is proposed and compared with existing indoor channel models.

The rest of the paper is organized as follows: Section II discusses the measurement setup and the measurement results. Section III presents the details of indoor propagation models in the literature and compares the measurement results with the existing models. Section IV presents the proposed propagation model. Section V compares the accuracy of the proposed model and the existing models based on the measurement results. Section VI concludes the paper.

## II. Measurement Setup and Environment

For the measurement campaign, a software defined radio based system is used. We have used Ettus Research's USRP B210 with a Tri-band antenna and a laptop computer having a high speed USB 3.0 port, National Instrument's LabView Software and an updated USRP Hardware Driver (UHD) for both transmitter (Tx) and receiver (Rx). Measurement setup is shown in Figure 1.

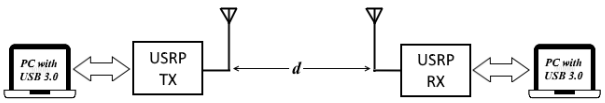


Figure 1: Measurement setup

The transmitter and receiver setups are detailed in Figures 2 and 3. BPSK modulated PN sequence is obtained using LabView software and transmitted through a USRP at three different frequencies separately, which are within the TVWS band. These frequency bands were not occupied by any primary and/or secondary systems during the measurement campaign. The transmitted signal is received via another USRP. After the signal reception, two operations are performed simultaneously. In parallel, the received signal strength (RSS) values are recorded and plotted, and the signal is demodulated for constellation plot and PN sequence detection. Measurement setup parameters are given in Table 1.

Table I: Measurement setup parameters

| | |
|---|---|
| Center frequency | 480, 580, 630 MHz |
| Tx Power | 16.60 dBm |
| Antenna polarization | Horizontal |
| Antenna radiation pattern | Omni-directional |
| Antenna heights (Tx and Rx) | 1.5 m |
| Transmitted signal | PN sequence |
| Modulation | BPSK |
| Sampling rate | 300 kHz |

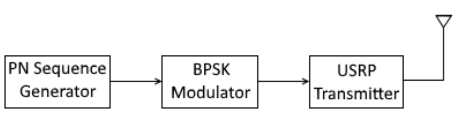


Figure 2: Transmitter setup

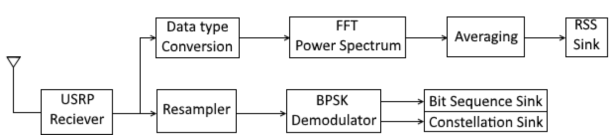


Figure 3: Receiver setup

To maximize the measurement area, the transmitter power was set to 16.60 dBm. Receiver antenna height was adjusted to 1.5 meter to model average holding height for a cellular phone. The IQ sampling rate of the receiver was 300 kHz to reduce complexity. Antenna polarization and radiation pattern were selected based on the indoor environment.

Measurements were taken on the 2nd floor of a university building, during non-working hours, to reduce interference from human body as much as possible. Figure 4 shows the layout of the floor. All indoor walls on the floor map are wooden material with certain insulation. Some doors are made up of glass and some are wooden, whereas all of the windows of the classrooms, labs and other office area are made of glass. Tx location is marked with black star (cf. south side of the floor plan), whereas Rx positions are marked with red stars (in total, 88 of them) in Figure 4. Both Tx and Rx antenna heights were kept constant at 1.5 meter during the measurements. Rx system was placed on a small trolley and RSS values were recorded in a still position at all marked points between Points A and B.


Figure 4: Floor plan (Size: 74.1 x 35.75 meters)

There have been multiple line-of-sight (LOS) and non-LOS (NLOS) paths between Tx and Rx in the measurement setup, which makes it suitable for verifying different models effectively. There were 88 measurements taken in total with a separation of approximately 1 meter. In order to mitigate fast fading effects, an average of 10 readings were taken for each location.

Radiation patterns of both Tx and Rx antennas were omni-directional in horizontal axis. The antenna orientation was horizontal for Tx. For the Rx, we measured RSS for three different antenna orientations, i.e., up (vertical), left (horizontal) and right (horizontal). It was found that all three antenna orientations have similar propagation characteristics. Thus, the rest of the measurements were taken for the vertical antenna orientation.

## III. Channel Models in TVWS Band

In the literature, there are few channel models for indoor environments, where the effect of direct path distance is incorporated into the path loss. We consider 4 path loss channel models from the literature in this work. These are the log-distance model [11], Linear Attenuation Model (LAM) [12], ITU-R P.1238 [13] and Multi Wall and Floor Model (MWF) [14]. Among them, ITU-R P.1238 and MWF models integrate the effect of floors. In addition, the MWF model incorporates the effect of attenuation due to walls. These models are defined as follows:

$$\mathbf{Log-distance}: PL = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) \quad (1)$$

where,
$PL$ = path loss in dB
$PL(d_0)$ = path loss at distance $d_0$
$n$ = power decay parameter
$d_0$ = reference distance between Tx and Rx
$d$ = direct path distance between Tx and Rx.

$$\mathbf{LAM}: L = L_{FS} + \alpha d \quad (2)$$

where,
$L$ = total propagation loss
$L_{FS}$ = free space loss
$\alpha$ = attenuation coefficient

$$\mathbf{ITU-RP.1238}:$$
$$L = 20\log_{10}(f) + N\log_{10}(d) + L_f(n) - 28 \quad (3)$$

where,
$f$ = transmission frequency (MHz)
$N$ = distance power loss coefficient
$n$ = total number of floors in between
$L_f$ = attenuation due to floor penetration (dB)

$$\mathbf{MWF}:$$
$$L_{MWF} = L_0 + 10\beta\log(d) + \sum_{i=1}^{I}\sum_{k=1}^{K_{wi}} L_{wik} + \sum_{j=1}^{J}\sum_{k=1}^{K_{fj}} L_{fjk} \quad (4)$$

where,
$L_0$ = path loss at 1m distance
$\beta$ = power delay index
$I$ = number of wall types
$J$ = number of floor types
$K_{wi}$ = number of traversed walls of type $i$
$K_{fj}$ = number of traversed floors of type $j$
$L_{wik}$ = attenuation due to wall of type $i$ and *k-th* traversed wall
$L_{fjk}$ = attenuation due to floor of type $j$ and *k-th* traversed floor

To assess how the measurements are compared with the models above, initially curve fitting is used to determine the parameters based on the measurements at three different frequencies.

At 480 MHz, parameters after calculations are found to be $n$ = 3.805 for log-distance, $\alpha$ = 1.45 for LAM, $N$ = 39.2 for ITU-R P.1238 and $\beta$ = 1.91 for MWF. It is to be noted that wooden doors were considered as walls, glass doors were neglected in our calculations and floor penetration loss were not considered in the work. The results can be seen in Figures 5 and 6.

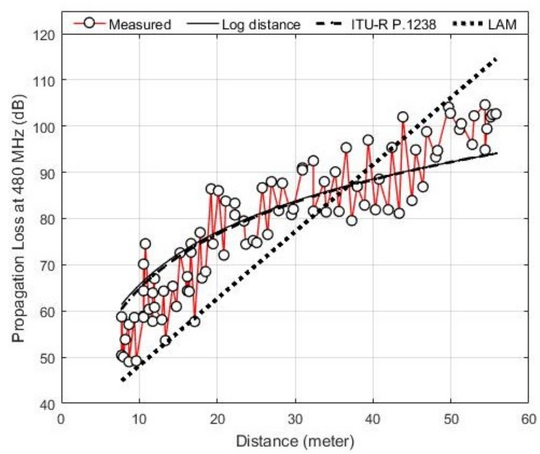


Figure 5: Measurement results compared with estimation results at 480 MHz (log-distance, ITU-R P.1238, LAM)

At 580 MHz, parameters after calculations are found to be $n$ = 3.558 for log-distance, $\alpha$ = 1.322 for LAM, $N$ = 36.25 for ITU-R P.1238 and $\beta$ = 1.663 for MWF. The results can be seen in Figures 7 and 8.

At 630 MHz, parameters after calculations are found to be $n$ = 3.403 for log-distance, $\alpha$ = 1.255 for LAM, $N$ = 34.63 for ITU-R P.1238 and $\beta$ = 1.507 for MWF. The results can be seen in Figures 9 and 10.

From Figures 5-10, it can be seen that log-distance and ITU-R P.1238 models have approximately the same results. LAM can only model in a small patch of distance, otherwise, it does not fit the measurement results well. MWF model can represent the measurement results better compared to other three models, as it shows less estimation error throughout the measurement range. This

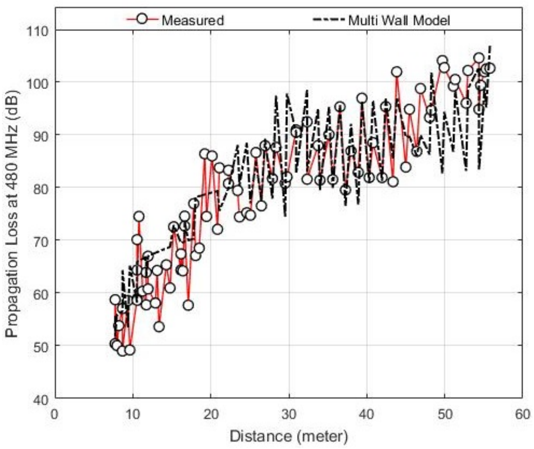


Figure 6: Measurement results compared with estimation results at 480 MHz (MWF)

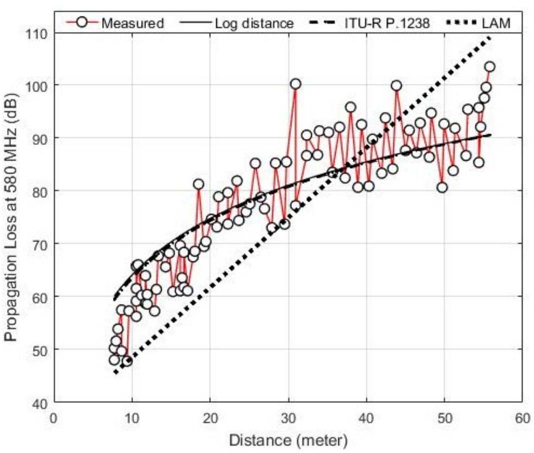


Figure 7: Measurement results compared with estimation results at 580 MHz (log-distance, ITU-R P.1238, LAM)

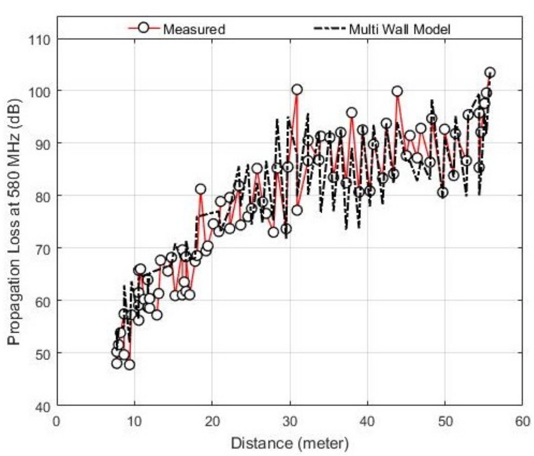


Figure 8: Measurement results compared with estimation results at 580 MHz (MWF)

is due to the additional term of propagation loss due to walls in the definition of MWF model. Accordingly, the

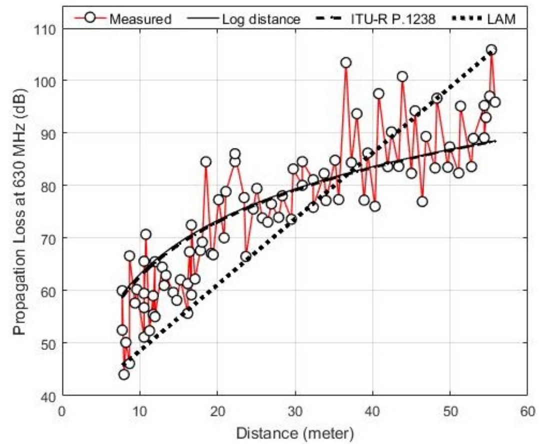


Figure 9: Measurement results compared with estimation results at 630 MHz (log-distance, ITU-R P.1238, LAM)

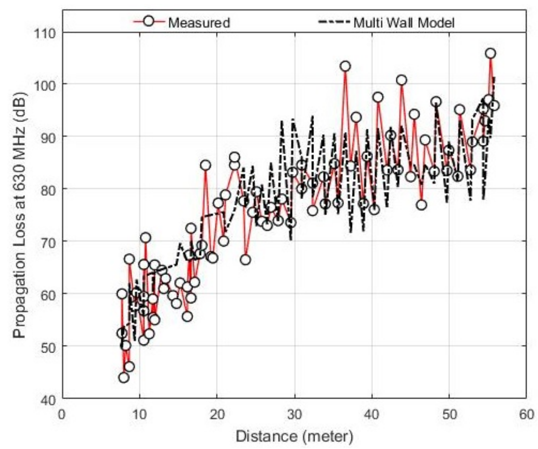


Figure 10: Measurement results compared with estimation results at 630 MHz (MWF)

MWF model seems to be the most suitable model for TVWS frequency bands.

In general, walls, furniture, doors, etc. may be in the direct path distance between Tx and Rx, and cause their own propagation loss. Therefore, it is important to model the loss of these effects to minimize the overall estimation error. On the other hand, the modeling of all these obstacles is not trivial due to their respective positions in an indoor environment. In [15], authors assume that these obstacles are uniformly distributed in the indoor environment and propose another model based on this assumption, which is a variation of the existing LAM model (we have named it extended LAM in this paper). The model is given as:

$$L = L_{FS} + \gamma d + n_w L_w + n_f L_f + C \tag{5}$$

In the above equation, $\gamma$ is the attenuation coefficient, $n_w$ is the number of penetrating walls, $n_f$ is the number of penetrating floors, $L_w$ is the loss of each wall, $L_f$ is the loss of each floor and $C$ is the attenuation constant. Floor penetration loss is assumed to be 0dB. We have also performed estimations using this model and compared with measurement results. The comparison at 580 MHz is plotted in Figure 11.

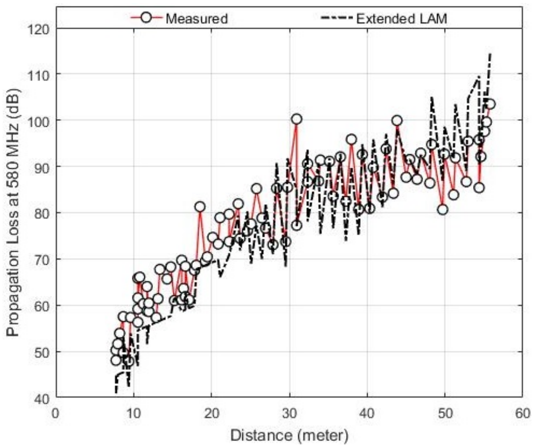


Figure 11: Measurement results compared with estimation results at 580 MHz (extended LAM)

In Figure 11, the estimated value of $\gamma$ is 0.767. The extended LAM model can model the measurement results similar to the MWF model and better than the LAM model. Numerical values for comparison will be provided in Section V.

## IV. Proposed Indoor Propagation Channel Model for TVWS Band

None of the channel models in the previous section considered the loss due to glass windows and doors. In the literature, it is assumed that glass has slight penetration loss. This assumption can be accepted to some extent, but in cases where there are many glass objects, the effect of glass can be incorporated to minimize the modeling error. Here, we should mention some points on our floor map with dotted rectangles (c.f. Figure 4), where the actual propagation loss is more than the estimated values, calculated from MWF and extended LAM models. Incorporation of loss due to wall does not reduce estimation error at these points. This is because there are less number of walls than the glass windows and glass doors in the direct path. Here, the effects of glass windows and glass doors cannot be neglected on the path loss. Although some of the errors are due to furniture and other obstacles, these objects are harder to model compared to windows and doors. With the addition of these effects, the following equation has been proposed:

$$L = L_{d_0} + 10\zeta \log\left(\frac{d}{d_0}\right) + n_{wl}L_{wl} + n_{wd}L_{wd} + n_dL_d \quad (6)$$

where, $L_{d_0}$ is the path loss at distance $d_0$, $n_{wl}$ is the number of walls, $n_{wd}$ is the number of windows, $n_d$ is the number of doors, $L_{wl}$ is the loss of each wall, $L_{wd}$ is the loss of each window and $L_d$ is the loss of each door. This model does not incorporate the effect of floor penetration loss. The estimated results at three different frequencies are plotted in Figures 12, 13 and 14.

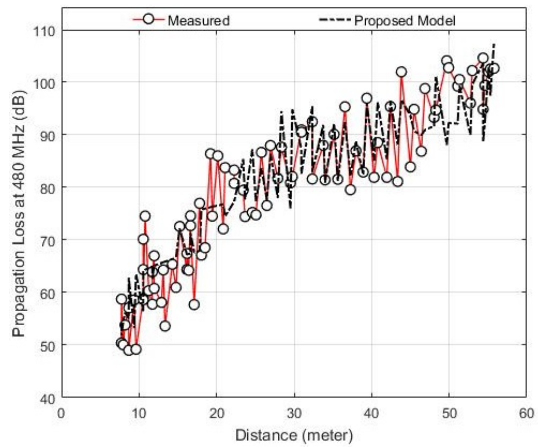


Figure 12: Measurement results compared with estimation results at 480 MHz (proposed model)

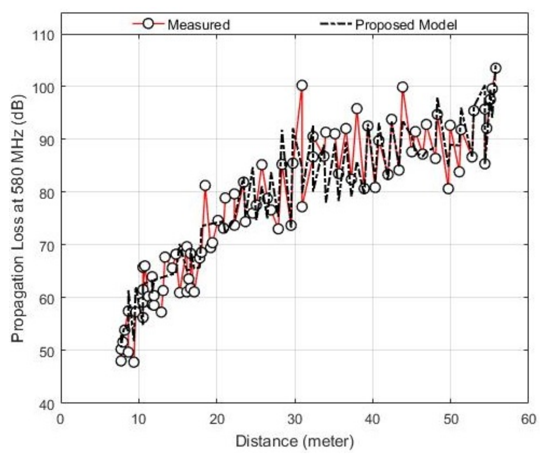


Figure 13: Measurement results compared with estimation results at 580 MHz (proposed model)

In our case, windows and most of the sliding doors are made up of glass, where only some of the doors are wooden. Glass doors and windows, wooden doors and walls have approximately same penetration loss which are 1.493 and 3.878 dB respectively. After calculations $\zeta$ was found to be 1.637 at 480 MHz, 1.39 at 580 MHz and 1.234 at 630 MHz.

As seen in Figures 12, 13 and 14 the difference in measured and estimated path loss values are reduced as compared to Figures 6, 8 and 10 (MWF model), since we add the additional loss due to glass windows and doors in the proposed model. In the floor map, total number

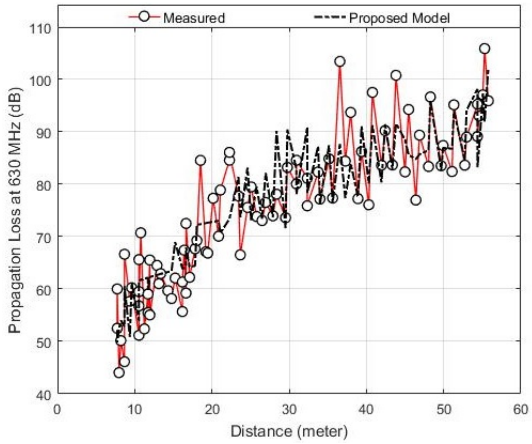


Figure 14: Measurement results compared with estimation results at 630 MHz (proposed model)

of wooden doors/walls and glass doors/windows in the direct path ranges from 0 to 10 and 0 to 9, respectively.

## V. Performance Comparison

In this section we compare the accuracy of the proposed model with other models at three different transmission frequencies. The results are given in Table II.

Table II: Comparison of propagation models

| Frequency | Parameter | LAM | Log-distance | ITU-R P.1238 | Extended LAM | MWF | Proposed Model |
|---|---|---|---|---|---|---|---|
| 480 MHz | RMSE (dB) | 9.75 | 6.38 | 6.19 | 6.90 | 5.78 | 4.96 |
| | STD (dB) | 11.22 | 7.39 | 7.16 | 8.60 | 7.22 | 6.15 |
| 580 MHz | RMSE (dB) | 9.25 | 5.66 | 5.49 | 5.83 | 4.57 | 3.72 |
| | STD (dB) | 10.53 | 6.73 | 6.58 | 7.02 | 5.56 | 4.74 |
| 630 MHz | RMSE (dB) | 8.62 | 6.13 | 6.03 | 6.10 | 5.79 | 4.90 |
| | STD (dB) | 10.45 | 7.57 | 7.46 | 7.69 | 6.83 | 6.04 |

The proposed model shows the best performance in terms of root mean squared error and the standard deviation of estimation error as compared to other models at all the frequencies. Incorporation of the effect of walls, windows and doors has reduced the estimation error significantly.

## VI. Conclusion

In this paper, indoor channel characteristics have been studied based on a measurement campaign in an indoor environment. Several existing models have been analyzed and their modeling accuracy is assessed by comparing with measurement results. Considering that the effect of glass windows and doors is neglected in previous models, a new model is proposed that not only models the effect of distance and walls on propagation loss but also models the effect of doors and windows in the environment. Results indicate that the proposed model has better estimation accuracy in terms of RMSE and standard deviation of estimation error compared to previous models.

Future work will focus on extending the proposed model for multiple floors in an indoor environment, validation of model in various types of building/environment, comparison of ray tracing simulations with real measurements and the application of different techniques to improve the model. The proposed model can be used to estimate link budget of indoor TVWS communication systems.

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