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Indoor Empirical Path Loss Prediction Model for 2.4 GHz 802.11n Network

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Abstract—**The purpose of this study is to develop an indoor empirical path loss prediction model for IEEE 802.11n network at 2.4 GHz. As 802.11n features Multiple-Input Multiple-Output (MIMO) which is not present in any previous wireless local area network (WLAN) standards, it is considered imperative to figure out a suitable prediction model for 802.11n network. Signal predictions using empirical models such as Dual-Slope Model, Partitioned Model, Log-Normal Shadowing Model, ITU-R Recommendation P.1238-1 Model, Adjusted Motley-Keenan Model and COST 231-Multi-Wall Model were carried out at an academic building to determine the best prediction model. Analysis showed that Partitioned Model is the best signal estimation model and is chosen as the reference model for optimization. The optimization process involves modification of the Partitioned Model through three selected steps. Prediction results of the optimized model showed a further increase in signal prediction accuracy. This new model is named as Solah's Model and is recommended for predicting indoor signal loss in 802.11n WLAN, especially in assisting network deployment, migration and management in office or academic buildings.**

Keywords-802.11, MIMO, model comparisons, WLAN

I. INTRODUCTION

802.11n is the latest version in the wireless local area network (WLAN) family. 802.11n is a relatively huge performance leap from previous WLAN standards due numerous improvements, particularly with the implementation of Multiple-Input Multiple-Output (MIMO). MIMO transmits parallel data streams in more than one antenna simultaneously where each antenna will propagate its signal in different multi-paths. This maneuver is known as spatial multiplexing and allows it to gain higher signal-to-noise ratio (SNR) which in turn increases its throughput and range [1]. As MIMO is not present in any previous WLAN standards, thus, it is befitting that research is done to analyze and verify the received signal strength (RSS) performance boost brought by 802.11n.

The main objective of this research is to come out with a reliable indoor empirical path loss prediction model for 2.4 GHz IEEE 802.11n network using established path loss models as references. The expectation is that the proposed model adds accuracy in indoor signal prediction while retaining a level of consistency at the same time.

II. EMPIRICAL PROPAGATION MODELS

Empirical path loss model is an experimental mathematical formulation which predicts radio wave propagation based on limited but essential parameters such as frequency, path loss exponent, distance, physical blockings and others. Accuracy of measurements and similarity of sites under analysis are especially important to ensure signal prediction accuracy [2]. Depending on the environment under study, some models may prove to be better compared to others. To validate the accuracy of the proposed model in this research, it is vital that comparisons are made between the proposed model with other well-known empirical indoor propagation models.

III. ESTABLISHED PREDICTION MODELS

A. Dual-Slope Model

Dual-slope model, as the name itself implies, has two slopes; the first is for line of sight (LOS) and the second is for non-line of sight (NLOS) region. The path loss in dB, given by [3] is:

$$L = L_0 + \begin{cases} 10 n_1 \log_{10} d, & 1m < d \le d_{bp} \\ 10 n_1 \log_{10} d_{bp} + 10 n_2 \log_{10}\left(\dfrac{d}{d_{bp}}\right), & d > d_{bp} \end{cases} \quad (1)$$

where the path loss exponent n_1 and n_2 are determined experimentally, d is the transmitter-receiver (T-R) separation distance and L_0 is the path loss in dB obtained at 1 meter distant from the transmitter. The method to determine the breakpoint d_{bp} is different in the works of [3] compared to research conducted by [4]. Thus, in this study, site survey observation is taken into consideration to determine a suitable breakpoint between LOS and NLOS region.

B. Partitioned Model

This model consists of four different signal loss prediction formulas with pre-defined values which are separated based on different distance range. The value of path loss exponent, distance range and additional signal loss values are fixed based on previously conducted research [3]. The path loss in dB, given by [3] is:

$$PL = PL_0 + \begin{cases} 20\log_{10} d, & 1m < d \le 10m \\ 20 + 30\log_{10}\left(\frac{d}{10}\right), & 10m < d \le 20m \\ 29 + 60\log_{10}\left(\frac{d}{20}\right), & 20m < d \le 40m \\ 47 + 120\log_{10}\left(\frac{d}{40}\right), & d > 40m \end{cases} \quad (2)$$

where PL_o is the path loss in dB obtained at 1 meter distant from the transmitter and d is the T-R separation distance.

C. Log-Normal Shadowing Model

The Log-Normal Shadowing Model is an extension of the One-Slope Model. Here, the effects of random shadowing due to varying levels of clutters are taken into account. The average path loss between a transmitter and its receiver is expressed by [5] as:

$$PL\,[\text{dB}] = PL(d_0) + 10n\log(d/d_0) + X\sigma \qquad (3)$$

where $PL(d_0)$ is the decibel path loss at close-in distance d_0 which serves as a reference distance due to free space propagation from the transmitter to a 1 m distance, n is the path loss exponent which indicates how fast path loss increases with distance, d is the distance between the transmitter and receiver and $X\sigma$ is a zero-mean Gaussian distributed random variable with standard deviation, σ [6].

D. ITU-R Recommendation P.1238-1

Recommendation P.1238 specifically caters for short-range indoor propagation prediction modeling. Recommendation P.1238-1 standard for indoor radio communication system given by [7] in dB is:

$$L_{total} = 20\log_{10}(f) + N\log_{10}(d) + Lf(n) - 28 \qquad (4)$$

where N is distance power loss coefficient, f is frequency in MHz, d is distance in meters between nodes, Lf is floor penetration loss factor in dB and n is number of floors penetrated. The coefficient of N *and* $Lf\,(n)$ are obtained empirically and specific values based on scenarios are made standard in calculations. The use of this model also assumes that both the transmitter and receiver are within the same building. The distance power loss coefficient recommended for office environment is 30. As this study focuses only on single floor, the parameters related to floor penetration in (4) would be substituted with wall penetration factor. To increase the accuracy of this model, parameter N would also be adjusted based on site measurement.

E. Adjusted Motley-Keenan Model

Reference [8] has proposed an improved Motley-Keenan model and verified it to be more accurate, which added the thickness factor of wall as given below:

$$PL(d)\,[\text{dB}] = PLr + 10n\log(d) + \sum_{i=1}^{N} k_i L_{0i}\, 2^{\log_3\left(\frac{e_i}{e_{0i}}\right)} \qquad (5)$$

In this equation, PLr is the reference loss in dB taken at 1 m distant between transmitter and receiver, n is the path loss exponent, N is the number of walls between transmitter and receiver, k_i is the number of type i walls, L_{0i} is the penetration loss in the type i reference wall, e_{0i} is the thickness of the reference wall and e_i is the thickness of the type i wall which obstructed the signal.

F. COST-231 Multi-Wall Model

COST 231 - Evolution of Land Mobile Radio (Including Personal) Communications has established reference models for path loss estimation and from here on many other improved models have been proposed such as COST 231-Hata Model and COST 231-Walfisch-Ikegami Model [9]. The principle of the COST 231-Multi-Wall Model is based on direct path between the transmitter and receiver with path losses introduced by walls and floors. The model is given by [3] in dB as:

$$L = L_o + 20\log_{10}(d) + k_f^{\left[\frac{k_f+2}{k_f+1} - b\right]} L_f + \sum_{i=1}^{k_w} k_{wi} L_{wi}, \qquad (6)$$

where L_o for 2.4 GHz Industrial, Scientific and Medical (ISM) is 40.2 dB, k_f denotes the number of penetrated floors, d is the distance between transmitter and receiver, b is used to fit empirically the non-linear effects of the number of floors on the path loss, L_f denotes the loss between adjacent floors, integer k_w is the number of wall types; k_{wi} and L_{wi} denote the number and loss for walls of *ith* type respectively.

IV. METHODOLOGY

A D-Link™ DIR-615 802.11n (draft 2.0) router which operates in 2.4 GHz serves as the transmitter or access point (AP) which enables the WLAN service. A D-Link™ Rangebooster DWA-140 802.11n (draft 2.0) USB adapter acts as the receiver, which is attached to a laptop that serves as the data collection unit. Both AP and receiver were on draft 2.0 to ensure full interoperability and compliances. The hardware arrangement assumes a 2 x 2 MIMO setup where there exist two short dipole antennas at the transmitter and two internal omni-directional antennas at the receiver. 802.11n draft 2.0 makes it mandatory for a minimum of 2 x 2 MIMO specification. Signal decibel (dB) measurements were taken using Vistumbler v9.8 software, which is installed into the laptop. The site selected for study is Universiti Teknologi MARA (UiTM) Academic Block which is located at Penang, Malaysia. The Academic Block consists of multiple adjacent blocks which contains classrooms and office rooms. The dimension of each block is 6.7 x 19.6 x 2.8 for length, width and height in meters respectively. A total of five adjacent blocks were used for data collections and ten measured data were taken in each spot. However, in determining the path loss exponent, n for LOS and NLOS, measurements were only taken in a single block. Fig. 1 shows the data collection spots, AP placement and the predicted shortest path signal propagation.

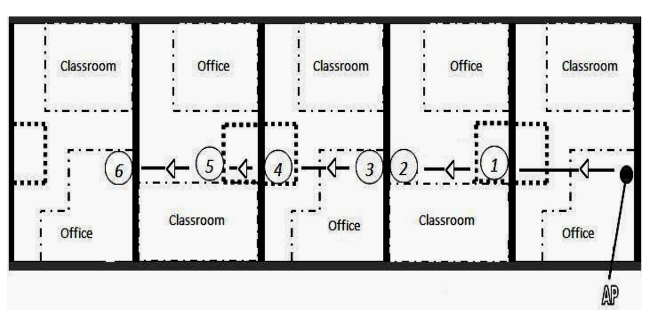

Figure 1. Visualization of data collection spots and the shortest path signal propagation through all five blocks.

Actual measurement data were collected at 6.7 m, 11.4 m, 13.4 m, 18.1 m, 20.1 m and 26.8 m as assigned in points from 1 until 6 respectively as shown in Fig. 1. RSS readings were not collected beyond the fifth block as connection could no longer be established between the AP and receiver.

V. RESULTS AND DISCUSSION

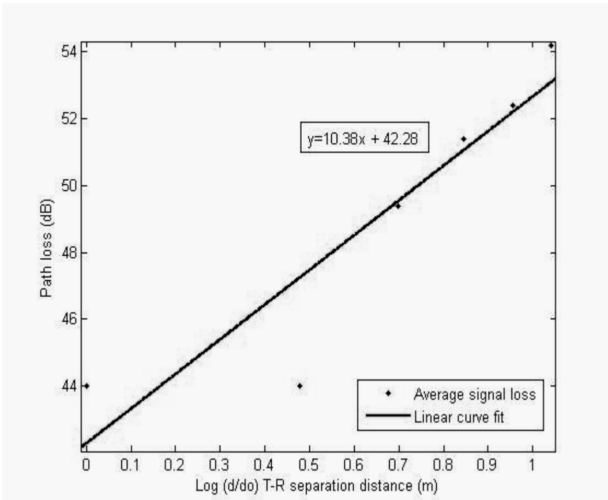

Figure 2. Linear curve fit for LOS received signal strength.

MATLAB curve fitting tool and the least square method is used to plot the graph to calculate curve fitting. Data for LOS measurements are plotted as shown in Fig. 2 and the inclination of the graph is 10.38. This indicates that the path loss exponent *n* for LOS scenario is 1.038, as *n* is equals to the slope divided by 10. In this study, the value of *n* for indoor LOS is rounded up to 1.04 with a standard deviation of 4.34 dB.

Similarly, the regression fitting method is used to figure out the path loss exponent, *n* for NLOS indoors. This *n* would be subjected to obstructed LOS, which is still a case of NLOS, where signal penetration of walls are not present but a direct LOS is still not attained. The slope of the curve in Fig. 3 is 25.16. Thus, the value of *n* in a typically shadowed office room is 2.52 with a standard deviation of 5.75 dB. This value of *n* will be assigned for NLOS signal estimation for the rest of the analysis and modeling in this research.

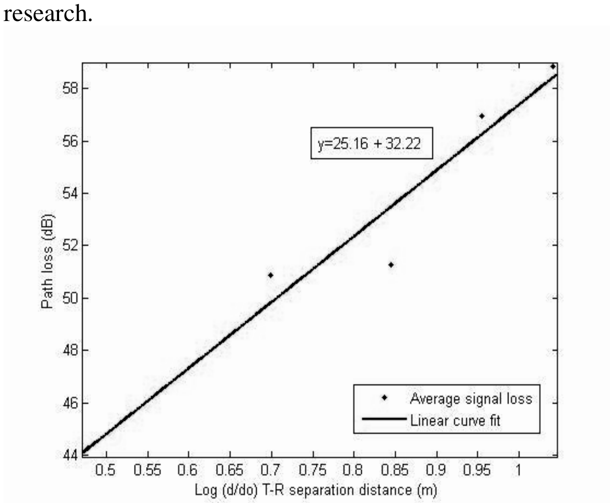

Figure 3: Regression fitting method for NLOS received signal strength.

RSS readings were taken before and after a particular wall and the difference are the signal penetration loss caused by the wall. The wall penetration loss is shown in Table I.

Table I. Signal loss incurred by each type of wall.

Type of wall	Width	Symbol	Signal loss
Brick wall A	24.5 cm	▬▬▬	0.4 dB
Brick wall B	12.9 cm	………	0.2 dB
Soft partition	7.5 cm	._._._	0 dB

The data collected for path loss exponent for LOS, NLOS and wall penetration factor are used to calculate signal prediction for all the reference models. The comparison between the numerical predictions and the actual measurement is shown in Fig. 4.

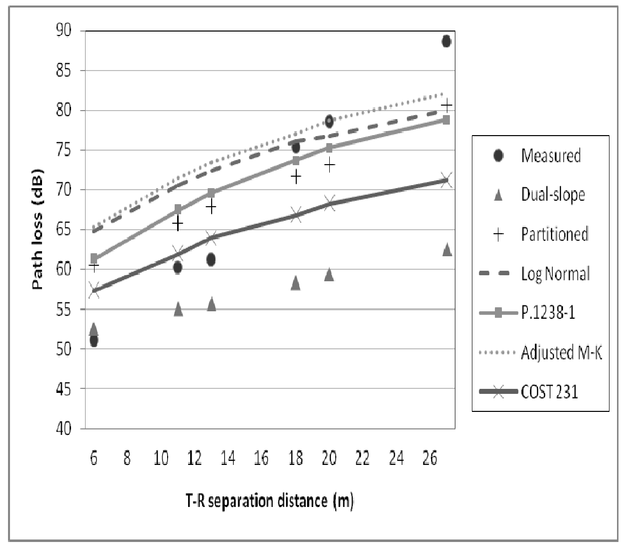

Figure 4. Actual measurements and numerical results for Dual-Slope, Partitioned, Log-Normal Shadowing, P.1238-1, Adjusted Motley-Keenan and COST 231-Multi-Wall models.

From Fig. 4, it can be clearly seen that none of the models satisfy the actual measurement pattern. Partitioned Model and P.1238-1 Model perform slightly well in signal prediction compared to any other models. Both Log-Normal Shadowing and Adjusted Motley-Keenan model predict signal losses rather accurately between 18 m to 22 m T-R separation range but signal estimations are way off in other distances. Both Dual-slope and COST 231-Multi-wall models are also able to predict signal loss with tolerable precision in limited region but results are very appalling in other distances. A more detailed analysis is shown in Table II where the mean error and standard deviation between the actual measurement and estimation are calculated.

Table II. Mean errors and standard deviations between of prediction models.

Model	Mean error (dB)	Standard deviation (dB)
Dual-Slope	12.38	9.68
Partitioned	6.46	2.10
Log-Normal Shadowing	7.74	5.34
P.1238-1	6.79	3.54
Adjusted Motley-Keenan	7.70	5.86
COST-231 Multi-wall	7.87	6.16

Partitioned model proves to be the best model in estimating signal loss with a mean error of 6.46 dB and a standard deviation of 2.10 dB. This is closely followed by P.1238-1 Model which has a slightly higher mean error compared to Partitioned Model. The average errors and standard deviations of Log-Normal Shadowing, Adjusted Motley-Keenan and COST-231 models do not differ much between each other. Dual-slope Model is proven not to be a good model for 802.11n signal estimation due to high mean error and standard deviation.

The most obvious problem seen from the data trend in Fig. 4 is that none of the reference models, with the exception of Dual-Slope model, were able to accurately predict the signal when the T-R separation distance is low, specifically below the range of 10 m. The assumption is that MIMO performed well and greatly assists signal propagation when there exist less clutters and wall penetration in near T-R separation distance. However, as the T-R distance widens, the MIMO mechanism weakens and therefore would no longer contribute a lot in signal propagation.

VI. OPTIMIZED EMPIRICAL PATH LOSS MODEL

From the previous section, Partitioned Model is verified to be the best model to predict signal loss in 802.11n networks. However, improvement on the Partitioned Model can still be done to further increase the accuracy of the prediction. The optimization process is performed by modifying the Partitioned Model where methods from other reference models are added and applied into the Partitioned Model. First, the wall penetration factor from COST 231-Multi-Wall Model is added. Second, all the pre-determined parameter values are substituted with variables. Third, only two boundaries are formed; one for LOS and the other for NLOS region. This would make the proposed model more dynamic in signal estimation. The new optimized model, named as Solah's Model, is given in dB as:

$$PL = PL_0 + \begin{cases} 10n_1 \log_{10} d_1 + \sum_{i=1}^{kw} k_{wi}\, PL_{wi} & 1m < d_1 \le d_{bp} \\ 10n_2 \log_{10} d_2 + \sum_{i=1}^{kw} k_{wi}\, PL_{wi} & d_2 \le d_{bp} \end{cases} \tag{7}$$

where PL_0 is the path loss in dB obtained at 1 meter distant from the transmitter, n_1 is the path loss exponent for LOS, n_2 is the path loss exponent for obstructed LOS, d_{bp} is the breakpoint distance between LOS and NLOS pattern region, integer k_w is the number of wall types; k_{wi} and PL_{wi} denote the number and signal loss for walls of *ith* type respectively. Determination of d_{bp} is purely based on site observation to indicate LOS and NLOS region.

A graph has been plotted as in Fig. 5 to show the RSS comparison between Partitioned Model and Solah's Model with the actual measured path loss. Analysis on the standard deviation, maximum and mean errors are shown in Table III to give a better view on the improvement presented by the optimized model. Solah's Model further reduces the mean error to 3.27 dB with a standard deviation of 2.22 dB.

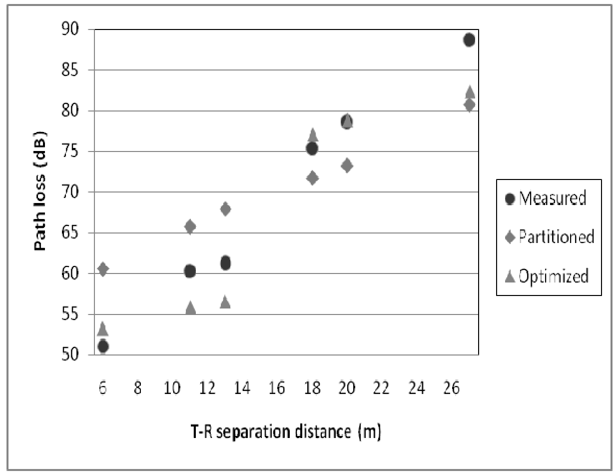

Figure 5: Actual measurements versus Partitioned Model and the optimized model.

Table III: Prediction errors for Partitioned Model and Solah's Model.

Model	Maximum error (dB)	Mean error (dB)	Standard deviation (dB)
Solah's	6.31	3.27	2.22
Partitioned	9.52	6.46	2.10

VII. VALIDATION

The proposed model is applied in another office building to verify the accuracy, consistency and suitability of Solah's path loss prediction model. UiTM's Primary Block, situated in another district in Penang, Malaysia, was selected to validate Solah's model. The layout of the floor under study along with the measurement spots are shown in Fig. 6. All the rooms in the floor are office rooms and separated from each other by soft partition walls which incurred 0.1 dB signal loss. The size of each room is approximately 5.31 x 3.23 x 2.46 for length, width and height in meters respectively.

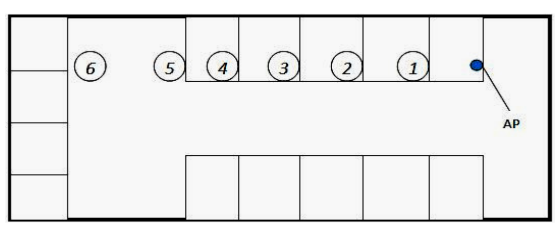

Figure 6: Floor layout of UiTM's Primary Block

As each of the office rooms are heavily cluttered, the breakpoint distance for Dual-Slope Model and Solah's Model is assigned to 3.23 m, which is the width of a single office room. The measured RSS is then compared with Solah's Model and all other prediction models.

Results in Fig 7 and Table IV showed that Solah's Model still gave good prediction accuracy. The mean error is still in the region of 3 dB with a standard deviation around 2 dB. This is very similar to the prediction results in the PERDA Academic Block. On the other hand, P.1238-1 produces the best signal prediction at the Primary Block. However, apart from Solah's model, no other models could retain consistency at both buildings under study. According to [2], indoor signal level is hard to predict and fluctuates more due to the indoors electric field affected by multiple components. Nevertheless, Solah's Model remains consistent, reliable and applicable in estimating signal loss in different office and academic building layout.

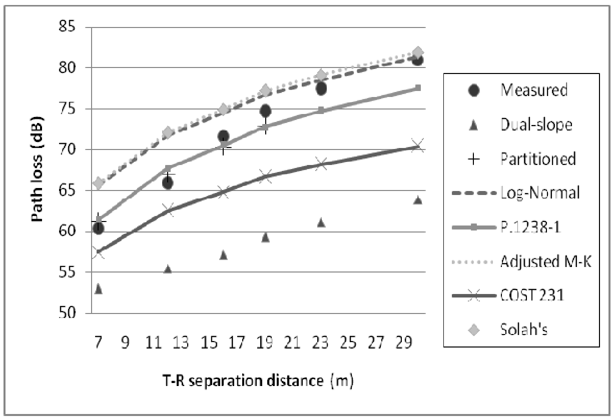

Figure 7: Actual measurements and numerical results for Dual-Slope, Partitioned, Log-Normal Shadowing, P.1238-1, Adjusted Motley-Keenan, COST 231-Multi-Wall and Solah's models.

Table IV. Mean error and standard deviation of signal path loss prediction models at UiTM Primary Block

Model	Mean error (dB)	Standard deviation (dB)
Solah's	3.38	2.12
Dual-Slope	13.49	3.82
Partitioned	7.26	9.36
Log-Normal Shadowing	2.95	2.27
P.1238-1	2.00	0.95
Adjusted Motley-Keenan	3.38	2.12
COST-231 Multi-wall	6.77	3.16

VIII. CONCLUSION

Investigation on the performance of 802.11n has been carried at an academic and office building. The path loss exponent *n* for LOS is 1.04 with a standard deviation 4.34 dB. This means that 802.11n performs extremely well in direct LOS signal propagation. The path loss exponent *n* for NLOS is 2.52 with a standard deviation of 5.75 dB.

Comparisons between six indoor empirical path loss models and the actual measurement taken at PERDA Academic Block have been performed to find out which model is most suitable for signal prediction. Partitioned model has been proven to be the best model for signal estimation for 802.11n with a mean error of 6.46 dB and a standard deviation of 2.10 dB.

An optimized empirical path loss prediction model has been proposed by adjusting the Partitioned Model to improve accuracy in signal estimation. The optimized model is named as Solah's Model, which adds wall penetration factor into the original Partitioned Model and limiting the estimation region into two; one for LOS and the other for NLOS. By doing this, the maximum error, mean error and standard deviation has been reduced to 6.31 dB, 3.27 dB and 2.22 dB respectively. Selection of the breakpoint distance depends entirely on site observation to determine the boundary between LOS and NLOS.

Validation of the newly proposed model is carried out in another office block. Solah's Model still consistently produced good signal prediction with a mean error of 3.38 dB and a standard deviation of 2.12 dB. Apart from Solah's Model, no other models could produce good and consistent predictions in different site surveys. Thus, this verifies that the newly proposed model is suitable and recommended for predicting indoor signal loss in 802.11n networks.

IX. CONTRIBUTION

Solah's Model adds even more accuracy in signal prediction in the first site survey and also producing good results and consistency at the second site survey. The optimized model presented in this research is applicable in planning network establishment and migration to 802.11n networks, typically for office and academic buildings. By performing simple site survey and analysis, the model can greatly hasten network installation and therefore reduce the cost associated with deployment. As 802.11n is also the next apparent upgrade from 802.11g standard, Solah's model is a viable signal prediction solution for 802.11n WLAN set up and performance analysis.

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