Radio propagation modeling on 433 MHz

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Abstract. In wireless network design and positioning it is essential to use radio propagation models for the applied frequency and environment. There are many propagation models available for both indoor and outdoor environments; however, they are not applicable for 433 MHz ISM frequency, which is perfectly suitable for smart metering and sensor networking applications.

During our work, we gathered the most common propagation models available in scientific literature, broke them down to components and analyzed their behavior. Based on our research and measurements, a method was developed to create a propagation model for both indoor and outdoor environment optimized for 433 MHz frequency.

The possible application areas of the proposed models: smart metering, sensor networks, positioning.

Keywords: Radio propagation model, 433 MHz, smart metering, positioning

1 Introduction

We are accustomed to use various wirelessly communicating devices, which possess different transmission properties according to their application areas. There are devices operating at high bandwidth in short range, but can not percolate walls. On the contrary, other devices can penetrate all kinds of materials for long distances, but operate on lower bandwidth.

The transmission properties of these various technologies – beyond transmission power and antenna characteristics – are principally determined by the operating frequency range of the system. In addition, the operating frequency determines the amount of attenuation for the technology, caused by different media.

The ability of calculating the signal strength in a given distance from the transmitter is severely important in case of network planning, because such a model helps us to determine where to place the devices, so that the system operates properly. Another typical application area of propagation models is positioning. Having the information of visible transmitters' signal strength, the receiver can deduce its position.

For most of the widely used frequency bands there are different, usable propagation models, but these are not directly applicable for the 433 MHz ISM frequency, which has beneficial propagation properties in case of 1-2 kilometer range and low bandwidth systems, like sensor networks. This frequency can be advantageous for smart metering and environmental monitoring systems.

This article introduces radio propagation basics, then analyses available outdoor and indoor propagation models. Based on our research and measurements, a proposed propagation model is presented for 433 MHz in both outdoor and indoor conditions, applicable for scaling sensor networks, smart metering systems and for use in indoor positioning.

2 Radio Propagation

The quality and reliability of a connection depends on many parameters, among those factors the received signal strength is the most important. The packet loss and packet corruption is less likely on proper signal strength, if other destructive factors, like interference are minimal.

$$Received\ signal\ strength\ =\ Transmission\ strength\ +\ Gain\ -\ Losses$$

The transmission strength and gain values are depending on the antenna and the allowed radio regulations. The losses are site specific, but they can be predicted by models.

The types of propagation models are the following:

- Empirical models are based on measurement data at various sites. According these measurements they provide a simplified general model (only using a few parameters), but not very accurate.
- Semi-deterministic models are based on empirical models and use deterministic aspects, which are computed based on the site they are applied to.
- Deterministic models are site-specific, they require enormous number of geometric information about the site, they are complicated (use many parameters and computations), but accurate.

The most of the radio propagation models are empirical, because of the impossibility of taking every possible factor of propagation into account in case of different complex scenarios. However, simplifications can be made, but the model has to be developed based on enough amount of collected data. Radio propagation models do not describe the precise behavior of a link, rather, they predict the most likely behavior according to the scenario.

The path loss consists of propagation losses caused by the natural expansion of the radio wave front in free space (usually shaped as an ever-increasing sphere), penetration losses (also called absorption losses), diffraction losses (the wave is obstructed by an opaque obstacle), losses, caused by multipath effect (simultaneous paths arriving to the receiver), interference, and also losses caused by other phenomena.

The propagation models can also be distinguished by the type of environment they are valid.

The following propagation models are well known and used in telecommunications. The models are presented based on the research of [1]. However these models are not applicable for 433 MHz frequency, they form good base for our proposed indoor and outdoor models.

2.1 Outdoor propagation

Outdoor propagation models are mainly developed for cellular communications purposes. Mobile companies required models to help them determine where to place their base stations. The radio signal in an outdoor environment is determined by the free path loss, the station heights and the canyon effect of the streets.
The most common outdoor propagation models for urban areas are the following.

Young. The Young model [2] was built on the data of 1952 in New York City, which is limited. The model is ideal for modeling the behaviour of cellular communications in large cities with tall structures. This model is valid in the frequency range from 150 MHz to 3700 MHz.
The mathematical formulation for Young model is:

$$L = G_B\, G_M \left(\frac{h_B\, h_M}{d^{\,2}}\right)^2 \beta$$

Where:
L = Path loss in dB,
G_B = Gain of base transmitter in dB,
G_M = Gain of mobile transmitter in dB,
h_B = Height of base station antenna in meters,
h_M = Height of mobile station antenna in meters,
d = Distance in kilometers,
β = Clutter factor.
These parameters are defaults in almost every model. If no further explanations are give, the parameters are considered to represent the default meanings as above.

Okumura. The Okumura model [3] for Urban Areas is a Radio propagation model that was built using the data collected in the city of Tokyo, Japan in 1960. The model is ideal for using in cities with many urban structures but not many tall blocking structures. The model is purely empirical and served as a base for the Hata Model.
Okumura's model prediction area is divided into terrain categories: urban, suburban and open areas. The model for urban areas was built first and used as the base for others. However, the application of all the correction factors is difficult.
The Okumura model is formally expressed as:

$$L = L_{FSPL} + A_{MU} - \mathrm{H}_M - \mathrm{H}_B - \Sigma K_{corr}$$

Where:
L = Median path loss in dB,
L_{FSPL} = Free Space Path Loss in dB, calculated as:

$$L_{FSPL} = 20 \log_{10} d + 20 \log_{10} f + 92.45$$

f = Frequency in GHz,
A_{MU} = Median attenuation in dB,
H_M = Mobile station antenna height gain factor in dB,
H_B = Base station antenna height gain factor in dB,
K_{corr} = Correction factor gain (such as type of environment, water surfaces, isolated obstacle etc.).

Hata models. The Hata Model [1] for Urban Areas, also known as the Okumura-Hata model for being a developed version of the Okumura Model, is the most widely used radio frequency propagation model for predicting the behavior of cellular transmissions in built up areas. This model also has three varieties for transmission in urban, suburban areas and open areas.
This model is suited for both point-to-point and broadcast transmissions and it is based on extensive empirical measurements taken.
Frequency is valid from 150 MHz to 1500 MHz. Mobile Station Antenna Height: between 1 m and 10 m. Base station Antenna Height: between 30 m and 200 m. Link distance: between 1 km and 20 km.
The Hata Model for urban areas is formulated as following:

$$L = 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_B - C_H + [44.9 - 6.55 \log_{10} h_B] \log_{10} d$$

For small or medium sized city,

$$C_H = 0.8 + (1.1 \log_{10} f - 0.7) h_M - 1.56 \log_{10} f$$

For large cities,

$$C_H = \begin{cases} 8.29(\log_{10} 1.54 h_M)^2 - 1.1 \text{, if } 150 \le f \le 200 \\ 3.2(\log_{10} 11.75 h_M)^2 - 4.97 \text{, if } 200 < f \le 1500 \end{cases}$$

Where:
C_H = Antenna height correction factor.
d = Distance between the base and mobile stations in kilometers.

COST 231. The COST 231 model [4] in an enhanced version of the Hata model with the 1800-1900 MHz included. This model consists of three components: the Free Space model, taking the general attenuation between Base Station (BS) and Mobile Terminal (MT) into account; one over rooftops, accounting for the multiple diffraction on the rooftops of the buildings in between the BS and the street where the MT is located; and the inside street one, considering the propagation from the rooftop to the MT, where the walls form a canyon. The second component, and this general approach, originated from the research group led by Henry Bertoni, while the third is taken from Ikegami et al., The development of the COST 231 involved the measurement campaigns, performed by several groups participating in the project, in several European cities. The model was finalized in 1991. Nowadays, the model still needs improvements [5], [6].

The COST-Hata-Model is formulated as:

$$L = 46.3 + 33.9\log_{10} f - 13.82\log_{10} h_B \\ - C_H + [44.9 - 6.55\log_{10} h_B]\log_{10} d + \mathrm{C}$$

$$C = \begin{cases} 0\ dB\ for\ medium\ cities\ and\ suburban\ areas \\ \qquad 3\ dB\ for\ metropolitan\ areas \end{cases}$$

Where:
L = Median path loss in dB,
f = Frequency of Transmission in MHz (valid from 1500 to 2000 MHz),
C_H = Mobile station Antenna height correction factor as described in the Hata Model for Urban Areas.

Analysis of outdoor propagation models. For further analysis, the Young and Okumura model was omitted. The Young model was used with a clutter factor of 100 and failed to provide accurate values for distances smaller than one kilometer. The Okumura model was omitted, as the Hata model is its extended version.

The Hata Urban and the COST 231 models were calculated at f=433 MHz, and with h_B and h_M = 1 meter. This setting modifies the models' ability to take canyon effects into account. However, 433 MHz frequency is not suitable for cellular-like applications (being an ISM band). Possible applications, like positioning or smart metering use the sensors in near to the ground (height is less than 5 meters). The Hata Urban CH parameter is set according to large cities to 1.113.

The COST 231 model's C correction factor was set to zero, as the measurement was not at a metropolitan area.

The Hata Suburban and Open models are derived from the original Hata Urban model and provide no further accuracy in this case.

The previously described models were applied to our measurement site, which took place in a suburban area in Hungary, at (46°44'5.47"N, 17°32'10.54"E). One of the sensors was placed next to the electricity meter (marked as meter), the other is placed at the marked positions. The signal was lost at the distance of 354 meters at marker M. The map of the measurement scenario is presented on Figure 1. Our measurement was conducted with Texas Instruments CC1101 radio module [7] on 10 mW power, at the height of 1 meter, and with no additional amplification on the standard λ/4 antenna. All the path loss values of the models are subtracted from the original CC1101 signal strength, which is calculated as 14.3 dB to get the result of signal strength. The results are calculated by 5 measurement values as the following:

omit the lowest and highest values and the mean of the remaining 3 values is the result. The measured and the calculated signal strengths are summarized in Table 1. The Hata and COST 231 models are not significantly different in their structure. Both consider the same parameters only some constants are modified. The comparison diagram of the models for the suburban area is presented on Figure 2. The results show that the summed square errors are around 300 for both the Hata and the COST 231 model, the latter is slightly less. Our proposed outdoor propagation model, which is presented in the next section had about half the error than these models. Also the error mean is significantly less. The minimal and maximal errors however are roughly the same. The maximal error occurs for all models at marker F, which means, that there might be a considerable obstacle.

Marker	***Distance (km)***	***Hata Urban (dB)***	***Diff***	***Cost 231 (dB)***	***Diff***	***Proposed (dB)***	***Diff***	***Measured (dB)***
A	0.192	-93.178	8.178	-90.342	5.342	-90.50	5.502	-85
B	0.149	-88.234	5.234	-85.397	2.397	-86.62	3.624	-83
C	0.077	-75.361	2.361	-72.525	0.475	-76.52	3.525	-73
D	0.019	-48.074	5.926	-45.237	8.763	-55.12	1.118	-54
E	0.079	-75.861	2.139	-73.025	4.975	-76.92	1.083	-78
F	0.107	-81.777	9.223	-78.941	12.059	-81.56	9.442	-91
G	0.195	-93.480	0.520	-90.644	3.356	-90.74	3.261	-94
H	0.266	-99.535	1.535	-96.699	1.301	-95.49	2.551	-98
I	0.305	-102.203	5.203	-99.366	2.366	-97.58	0.582	-97
J	0.336	-104.090	4.090	-101.254	1.254	-99.06	0.937	-100
K	0.289	-101.152	5.152	-98.316	2.316	-96.76	0.758	-96
L	0.316	-102.894	6.894	-100.057	4.057	-98.12	2.124	-96
Σsquared error and error mean		345.1	4.705	323.42	4.055	170.64	2.872	0

Table 1 – Outdoor measurement and calculations

Figure 1 – Outdoor measurement map

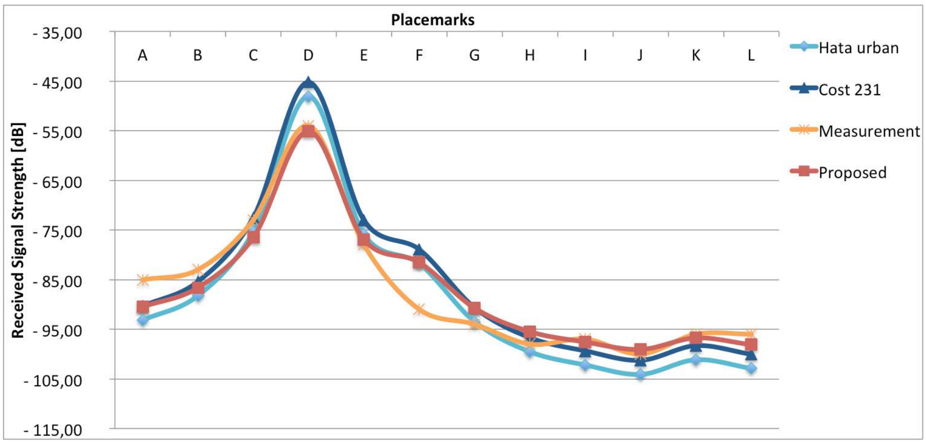

Figure 2 – Outdoor measurement and model comparison diagram

Proposed outdoor propagation model

Our measurements did not show significant difference between the Hata and COST 231 models (the latter is based on the Hata model). We decided to take the COST 231 as the base for our outdoor model, because it performed a little better.

For the possible application areas of 433 MHz ISM band (smart metering and positioning), the height of the nodes is usually less, than 5 meters. Our calculations confirmed, that when using the models at 5 meter base height, they tend to underestimate path loss. The models were the most precise at the height of 1 meter. *Remark*: The height of the mobile station only altered the mobile station gain factor component.

Both Hata and COST 231 models consider the heights logarithmically, which means, that if the height is 1 meter, then the logarithmic expression is 0. This enables to simplify the COST 231 model by omitting the use of the height factor and the calculated expressions with it. At 1 meter, this does not modify the results, we get the same. After stripping the model of the base station height factor, the path loss is calculated as:

$$L = 46.3 + 33.9 \log_{10} 433.92 - C_H + 44.9 \log_{10} d$$

The abstracted version of this formula is:

$$L = \alpha_0 + \beta \log_{10} f - C_H + \gamma \log_{10} d$$

The C_H value contains the mobile station height, which in case of 1 meter is -1.1. This can be contracted with the α_0 parameter.

$$L = \alpha + \beta \log_{10} f + \gamma \log_{10} d$$

This model has the following parts: $\beta \log_{10} f$ is the frequency dependent part, $\gamma \log_{10} d$ is the distance dependent part and the α parameter is the clutter factor for the site.

To determine the exact value of the α, β, γ parameters, the methods of Nonlinear Programming [8] were employed. The objective function was to minimize the summed square error by the measurement. Formally expressed, as:

$$\min \Big(\sum_{all\ measurement\ points} (model\ result\ - measured\ value)^2$$

The α, β, γ parameters were constrained to be positive.

The GRG Nonlinear algorithm [9] provided the following results for the parameters: α =46.614, β =31.635, γ =35.224

As a result, the proposed formula is:

$$L = 46.614 + 31.635 \log_{10} f + 35.224 \log_{10} d$$

Remark: The first two components can be summed, if the frequency is fixed.

This formula scored 170.64 of summed square error calculated by our measurements, which is about half of the Hata and the original COST 231 model. Although this result is optimal for this particular measurement site. To create a general empirical outdoor model, more measurements are needed and the proposed method can be applied to fine-tune the parameters.

2.2 Indoor Propagation

Radio propagation in an indoor environment is different from outdoor propagation, because multipath fading is much more present and line of sight propagation is limited. In addition, in indoor environment the range is less because of the various obstacles. In this case, signal consists of reflected, diffracted and scattered waves.

ITU indoor model. The ITU indoor model [10] is a modified power law that uses empirical building data to predict the path loss. The ITU model also provides a model for the impulse response of the indoor channel to account for delay spread, again using empirical data.

The ITU indoor path loss model is formally expressed as:

$$L = 20 \log_{10} f + N \log_{10} d + P_f(\mathrm{n}) - 27.54$$

Where:

f = Frequency of transmission in MHz (in the range from 900 MHz to 5.2 GHz),

N = Empirical distance power loss coefficient for residential, office and commercial areas,

n = Number of floors between the transmitter and receiver,

$P_f(n)$ = Empirical floor loss penetration factor, dependent on the number of floors the waves need to penetrate (ranging from 1 to 3) for residential, office and commercial areas.

Log-distance path-loss. The Log-distance path loss model [11] is another site-general model with a modified power law with a lognormal variability, similar to lognormal shadowing. The Log-distance path loss model is frequency independent, and it is based on an initial measurement, which is not always available. In that case, the theoretical free-space path loss is calculated to set the model curve to the proper gradient.

$$L = L_{REF} + N \log_{10} \frac{d}{d_0} + X_s$$

Where:
L_{REF} is the path loss at the reference distance, usually taken as (theoretical) free-space loss at 1 m,
N/10 is the empirical path loss distance exponent,
X_s is a Gaussian random variable with zero mean and standard deviation of σ in dB.

There are also foliage, terrain, and sky-wave propagation models, but they are not relevant in the case of positioning.

Analysis of indoor propagation models. For the calculation of the ITU indoor model the *N* parameter (empirical power loss coefficient) was set to 33 according to [11] Table 2. The *n* (floor indicator) parameter was set to zero (A, B), 9 (C, D) and 19 (E, F) according to floor distance.
For the calculation of the Log-distance path loss model, the L_{REF} parameter is set to 14 dB according to our measurement at point A as the reference path loss. The N parameter is set to 30 and X_s is set to 11.5 (calculated from the σ of 7) according to Table 4.6 from [10].
Remark. If the parameter N was set to 40, the results were much better, reaching a final summed square error of 370.
The previously described models were applied to our indoor measurement site. The measurement took place at the I building of BUTE in Hungary (47°28'21.69"N, 19°3'35.97"E). The measurement scenario is presented on Figure 3. This measurement was also conducted with Texas Instruments CC1101 radio module on 10 mW power with no additional amplification.
This example calculation for this particular measurement scenario showed, that the empirical values used in each model are not optimal (generalized parameters are usually sub-optimal). Both models had the summed square error around 700. Our proposed model produced only 7.929 for the summed square error. Also the error mean by the measurements and the maximum error (marked with red) is significantly less. The comparison between the models is presented on Table 2. The models are compared on a diagram on Figure 4. Our proposed indoor propagation model is presented in the next section.

Mar-ker	***Dis-tance (m)***	***ITU indoor (dB)***	***Diff***	***Log-dist. (dB)***	***Diff***	***Proposed (dB)***	***Diff***	***Measure-ment (dB)***
A	1	-10.908	3.092	-25.500	11.500	-12.729	1.271	-14
B	25	-52.846	10.960	-67.438	0.562	-69.271	1.271	-68
C	30	-64.222	17.347	-69.813	16.186	-84.223	1.777	-86
D	3	-34.222	6.347	-39.813	2.186	-43.777	1.777	-42
E	6	-53.253	14.413	-48.844	21.155	-70.000	0	-70
F	40	-77.970		-73.561		-103.324		No signal
Σsquared error & error mean		678.599	10.432	714.648	10.318	7.929	1.219	0

Table 2 – Indoor measurement and model comparison

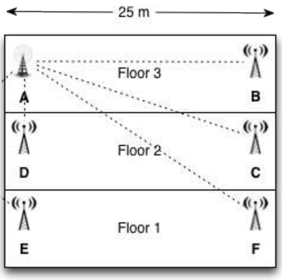

Figure 3 – Indoor measurement scenario

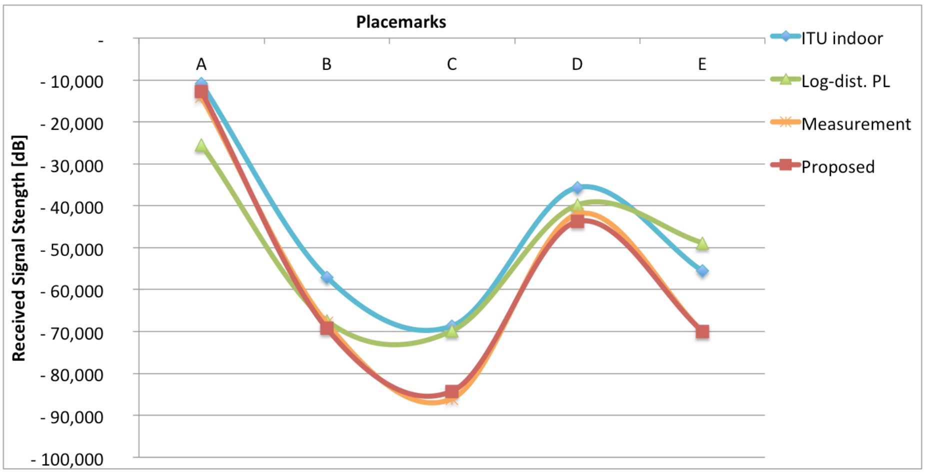

Figure 4 – Indoor measurement and model comparison diagram

Proposed indoor propagation model. For our indoor propagation model, we chose the ITU indoor model as a base model, which performed slightly better, than the Log-distance path loss model compared to our measurements. The ITU indoor model consists of a frequency dependent, a distance and clutter dependent, a floor/wall dependent and a constant part. Our model contracts the frequency dependent and the constant part into a single parameter, for fixed 433.92 MHz (center) frequency. The proposed model can be formally expressed as:

$$L = \alpha \log_{10} d + \beta + \gamma$$

Where, α is the distance dependent scale factor, β is the general clutter factor, and γ is the floor/wall parameter. The γ constant is depending on the number of walls or floors the signal has to penetrate. In this model, 30 cm ferro-concrete walls are considered as one unit. Walls and floors are treated equally, because the antenna loses signal strength in vertical dimension quickly. According to Figure 3, the number of walls in case A and B is 0. In case C and D, the obstacle class is 1, in E and F it is 2, as there are two walls between the nodes.

The constant values of α, β and γ were determined by NLP GRG algorithms: α = 40.447, β = 27.029. The values of γ are depending on obstacle classification and summarized on Table 3.

Obstacle class	*γ parameter*	*Marker on Figure 3*
0	0	A, B
1	11.749	C, D
2	25.797	E, F

Table 3 – Obstacle classification

Our model scored 7.929 in summed square error, which means it fits our measurement curve (Figure 4) visibly well. This score is two orders of magnitude better, than the original ITU indoor and Log-distance path loss models. Similarly, as in the outdoor model, in this indoor case, more measurements are needed to fine tune the parameters and create a general indoor propagation model for 433 MHz based on the proposed methods. Moreover, our model is specially developed for 433 MHz, while other models are supporting a wide range of frequencies, which makes them less precise for a particular frequency.

3 Conclusions

During our research we collected the factors and their properties that affects radio propagation, then analyzed the functioning of indoor and outdoor models, especially the Cost 231 and ITU indoor models. Afterwards based on the models and our measurements we developed an indoor and outdoor propagation model optimized for 433 MHz and compared the error with other models. The proposed model performed significantly better than others in the inspected environment. The exact values can be studied on Table 1 and 2.

Future work has to be done for refining our model, by many measurements in various environments. Using the proposed method of this article the model will be usable more generally. The presented models of this article can be applied for scaling sensor networks and smart metering systems, or for indoor positioning.

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