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An Empirical Study of Propagation Models for Wireless Communications in Open-pit Mines

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***Abstract*—In this paper, we investigate the suitability of the propagation models ITU-R 526, Okumura Hata, COST Hata models and Standard Propagation Model (SPM) to predict the path loss in open-pit mines. The models are evaluated by comparing the predicted data with measurements obtained in two operational iron-ore mining complexes in Brazil. Additionally, a simple deterministic model, based on the inclusion of an effective antenna height term to the ITU-R 526, is proposed and compared to the other methods. The results show that the proposed model results in root-mean-square error (RMSE) values between 5.5 dB and 9.2 dB, and it is capable of providing a close approximation of the best predictions (i.e. those with lowest RMSE) as provided by the SPM. The proposed model, however, reduces the calibration complexity considerably.**

***Index Terms*—Radio Propagation, UHF measurements, Industrial communications in mines**

I. Introduction

In the recent years, the mining industry has been pushed towards unmanned operations by the incessant need for improved safety and greater operational efficiency. However, the use of autonomous and teleoperated machinery will bring a new set of requirements to the wireless network such as the support of broadband services with very high reliability and lower latency. This is a change of paradigm in the wireless network planning in open-pit mine since in the past, only narrowband services with not so strict requirements were offered [1]. Additionally, this environment presents a challenge when compared to traditional ones: the topography of the mine changes on a daily basis due to the extraction of raw materials, which is inherent of the mining activity. Therefore, radio propagation models that can predict the path loss even with constant topography changes are very useful for network planning in this industry.

While multiple research initiatives have successfully derived models for characterizing wireless communication in underground mines [2], radio propagation in open-pit mines has been, generally, taken for granted. One of the few references proposing a radio propagation model for this challenging environment requires intensive computation, and detailed information to calculate and combine multiple reflected and diffracted fields [3]. However, in this study no empirical data was presented for verification.

In our previous contributions, [4], [5], we started to fill in this gap in the literature by analyzing the results of a measurement campaign in two iron-ore open-pit mining complexes located in Minas Gerais, Brazil. In [4] we presented an analysis of the mining scenario, and showed that the altitude differences between transmitters and receivers can go up to 500 m for Macro Cells. We also derived empirical propagation models for the 700 MHz and 2.6 GHz frequency bands, in macro and small cell deployments. Although we were able to define a single model to characterize small cell propagation, the topographic differences between the two mines impacted significantly the macro cell results, requiring one model for each mining complex. Additionally, the values of root-mean-squared-error (RMSE) between the macro cell models and the measured data were between 10.3 dB and 12.7 dB. These high values of RMSE motivated us to look into the suitability of other radio propagation models.

Therefore, the contribution of this paper is two-fold. First, we present a comparison of the efficacy of a variety of propagation models to predict the path loss in open-pit mines. We chose models widely implemented in radio planning software [6]: ITU-526 [7], Okumura-Hata, COST-Hata, the Standard Propagation Model (SPM) [8], and included a comparison with the empirical models from our previous work. Second, we derive a simple deterministic model that is able to approximate the results of SPM, while reducing the calibration complexity. The model is derived based on the observations of the efficacy of the models evaluated in this paper and the altitude difference observed in [4]. The proposed model (Vale model) is thus, an extension of the ITU-R 526, which characterizes propagation by diffraction, by the addition of an effective antenna height component, as proposed in [9].

The remainder of this paper is organized as follows. Section II briefly presents the measurement campaign and scenario. Section III presents reference propagation models and details the calculation of the Vale model. Section IV presents the results. In Section V we conclude this work.

II. Open-pit mine scenarios and measurement setup

The measurements were collected in two open-pit, iron ore mine complexes located in Brazil. Although both complexes are located in the same region, their topology vary significantly, mainly due to their stage of exploration. The first complex, Mine 1, has been in operation for 75 years, and consists of three deep mining pits, while the exploration of the second complex, Mine 2, started 11 years ago and it consists of a single pit. The shape of the mining pits in mine 1 resemble inverted pyramids, while the pit in mine 2 follows the slope of the hill where the mine is located [4].

In this measurement campaign, two continuous-wave (CW) signals, one at the 700 MHz band and the other at the 2.6 GHz band, were generated, combined, and transmitted by a single dual-band antenna. Details about the equivalent isotropically radiated powers (EIRP), calibration and location of the transmitters can be found in [4], [5].

The measurements are collected of with a sampling rate of 150 samples/second. These samples are then spatially averaged considering a window of 40λ, where λ represents the 700 MHz wavelength [10]. From the averaged received power, P_{RX}, in dBm, the path loss per link (L) can be estimated by:

$$L = P_{TX} + G_{TX}(\theta) + G_{RX} - P_{RX} - L_{\mathrm{c}} \tag{1}$$

where P_{TX} represents the transmitted power, in dBm, L_{c} represents the combined cable losses at the transmitter, Tx, and the receiver, Rx; $G_{TX}(\theta)$ is the Tx antenna gain considering the vertical angle, θ, between Tx and Rx, in order to compensate for the elevation pattern. It is important to highlight that the use of the vertical antenna pattern is crucial in an open-pit mine scenario where the altitude difference between Tx and Rx can be in the order of hundreds of meters [4]. We also ensured that the considered measurements were concentrated in the vertical half-power beamwidth. Both Tx and Rx antennas are assumed to be omni-directional.

III. Propagation models

In this Section we present an overview of the models to be compared. The models that consider a diffraction component (ITU-526, SPM and Vale model) assume the availability of a digital terrain map (DTM) of the interest area. The results to be presented in Section IV considered a DTM of each mining complex with 1 m resolution.

A. Reference models

The models presented in this subsection were evaluated based on their implementations in Atoll [6], and after calibration with measured data. Here, it is important to mention that other models such as Longley Rice and Ecerg were also tested. However, they will not be presented here due to their poor fitting to the measurement data.

ITU-526 [7]: This recommendation defines a generic propagation model, with no limits to distances between transmitters and receivers, or frequency ranges. It is based on free space loss, $FSPL(f)$ and a diffraction component, L_D as in:

$$PL_{ITU_{526}} = FSPL(f) + L_D \tag{2}$$

where free space loss is given by:

$$FSPL(f) = 20\log_{10}(d) + 20\log_{10}(f) - 27.55 \tag{3}$$

where d is the 3 dimensional distance, in meters, between the transmitter and the receiver and f is the frequency in MHz. In the model specification, many methods to calculate L_D are given, according to the type of obstacle [7].

Okumura Hata (OH): this empirical model describes the path loss as a function of d, f, the Tx height, h_{tx} and considering the Rx height, $h_{rx} = 1.5$ m. The path loss is calculated as:

$$\begin{aligned} PL_{OH_{urban}} = A_1 + A_2\log_{10}(f) + A_3(\log_{10}(h_{tx})) +\\ (B_1 + B_2\log_{10}(h_{tx}) + B_3 h_{tx}) \cdot \log_{10}(d) \end{aligned} \tag{4}$$

The Okumura-Hata model implemented in Atoll considers $A_1 = 69.55$, $A_2 = 26.16$, $A_3 = -13.82$, $B_1 = 44.9$, $B_2 = -6.55$ and $B_3 = 0$. The **COST Hata** model considers $A_1 = 49.3$, $A_2 = 33.9$, A_3, B_1, B_2 and B_3 remain unchanged.

Considering an open rural-area environment[1], there is a correction for the path loss value in Eq. (4) and it is calculated as:

$$\begin{aligned} PL_{OH} = PL_{OH_{urban}} - a(h_{rx}) - 4.78(\log_{10}(f))^2 -\\ 18.33\log_{10}(f) - 40.94 \end{aligned} \tag{5}$$

in which $a(h_{rx})$ is a correction for $h_{rx} \neq 1.5$ m:

$$a(h_{rx}) = 3.2(\log_{10}(11.75 h_{rx}))^2 - 4.97 \tag{6}$$

Standard Propagation Model: this model is a empirical propagation model also based on the Hata formulas, and it is valid for distances between 1-20 km and frequencies in the range of 150-3500 MHz. The path loss is calculated as:

$$\begin{aligned} PL_{SPM} = k_1 + k_2 \cdot \log_{10}(d) + k_3 \cdot \log_{10}(H_{eff_{tx}}) + k_4 \cdot L_D\\ + k_5 \cdot \log_{10}(d) \cdot \log_{10}(H_{eff_{tx}}) + k_6 \cdot (H_{eff_{rx}}) + k_7 \cdot\\ \log_{10}(H_{eff_{rx}}) + k_{clutter} \cdot f_{clutter} + k_{hill_{LOS}} \end{aligned} \tag{7}$$

where k_1 to k_7 are tunable weights: k_1 is a constant offset, k_2 is a multiplying factor for $\log_{10}(d)$, k_3 is a multiplying factor for the logarithm of the effective transmitter antenna height, k_4 is a multiplying factor for the diffraction loss, k_5 is a multiplying factor for $\log_{10}(d) \cdot \log_{10}(H_{eff_{tx}})$, k_6 is a multiplying factor for the effective receiver antenna height, $H_{eff_{rx}}$, k_7 is a multiplying factor for $\log_{10}(H_{eff_{rx}})$, $f_{clutter}$ is the average weight losses for the clutter with $k_{clutter}$ as it's multiplying factor, and $k_{hill_{LOS}}$ is the correction constant for hilly regions in LOS. The authors used the calibration tool available in Atoll to determine the multiplying factors from the measurements.

B. Alpha-beta Model

The alpha-beta model is a general model, that was fitted to the measurement data collected in the mines described in Section II. This is an empirical-based model that estimates the path loss, $PL_{\alpha\beta}$, based on the linear regression of the path loss estimates given by Eq. (1):

$$PL_{\alpha\beta} = 10\alpha \cdot \log_{10}(d) + \beta \tag{8}$$

The path loss exponent, α, and the intercept, β, are obtained by means of a least squares linear regression of the L samples.

[1]Other environments were also tested, but the rural-area had the best fit.

The fitting procedure is detailed in [5]. For convenience, the values of α and β for each case are repeated in Table I. It is important to note that the Macro Cell models do not differentiate between LOS and NLOS samples.

TABLE I: Summary of Large-scale propagation parameters

	Macro Cell				**Small Cell**	
	Mine 1		**Mine 2**		**All**	
f [GHz]	0.7	2.6	0.7	2.6	0.7	2.6
α_{LOS}	2.2	2	3.3	3.2	2.3	2.3
α_{NLOS}					4.1	3.6
β_{LOS}	39	63	1.4	19.2	30	41
β_{NLOS}					-8.5	24

C. Vale Model

The Vale model consists in extending the concept of the ITU-526, that combines free space path loss with a diffraction component, by including a term to compensate for the effective antenna height. The motivation for the inclusion of this term will be discussed later in this paper. The model is given by:

$$PL_{vale} = FSPL(f) + L_D + k \cdot \log_{10}(H_{eff}) \tag{9}$$

where L_D is the diffraction loss, k is a calibration constant and H_{eff} is the effective antenna height.

There are multiple methods to calculate L_D, such as the Epstein-Peterson, Deygout and Millington [6], [7], and any can be used to estimate it in Eq. (9). The results shown in this paper estimate the diffraction losses by a single knife-edge diffraction [7], [11]. First, the h parameter is computed based on the distance, in meters, between the Tx and the most relevant obstacle, d_1, the distance from this obstacle to the receiver, d_2, the altitude of the obstacle, h_{obs}, the altitude of Tx and Rx, h_1 and h_2, as in Figure 1.

$$h = h_{obs} - \frac{d_1(h_2 - h_1)}{d_1 + d_2} - h_1 \tag{10}$$

Then, we compute the Fresnel-Kirchoff diffraction parameter, ν, to quantify the phase difference caused by obstructions in Fresnel zones [11]:

$$\nu = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \tag{11}$$

where λ is the wavelength in meters. A fairly good approximation for the diffraction loss, $L_D = 20\log_{10}|F(\nu)|$ is [10]:

$$|F(\nu)| = \begin{cases} 1 & \nu \leq -1 \\ 0.5 - 0.62\nu & -1 < \nu \leq 0 \\ 0.5exp(-0.95\nu) & 0 < \nu \leq 1 \\ 0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2} & 1 < \nu \leq 2.4 \\ \frac{0.225}{\nu} & \nu > 2.4 \end{cases} \tag{12}$$

The last term in Eq. 9 is the effective antenna height, H_{eff}. It is calculated by the method presented in [9], [12], that proposes modifications to the H_{eff} calculation in the recommendation ITU-1546, which was known for having

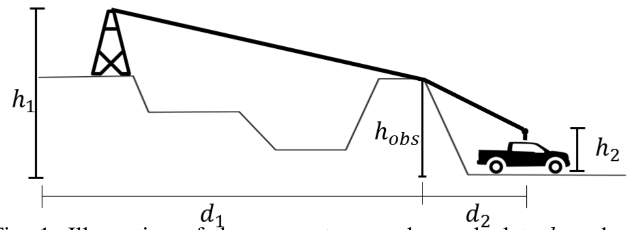


Fig. 1: Illustration of the parameters used to calculate h and ν in Eq. 10 and Eq. 11.

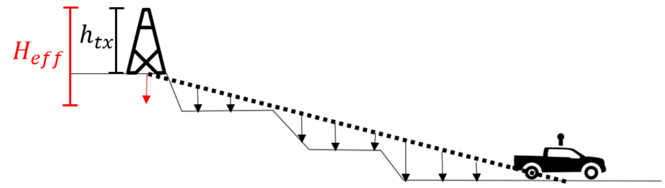


Fig. 2: Example of the calculation of H_{eff} as proposed in [9]. The red arrow represents the average difference between the dashed line connecting the ground levels of Tx and Rx in respect to the terrain profile, which is subtracted from h_{tx}.

problems with negative values and reciprocity. H_{eff} is thus defined as the average difference of the terrain height, relative to a line connecting the ground levels at Tx and Rx antennas subtracted from the Tx antenna height, as in Figure 2.

IV. Results

Table II shows the RMSE between the measured data and the path loss predictions considering the models defined in Section III. It also contains the number of samples collected in each case, after the spatial average mentioned in Section II.

A. Reference Models and Alpha-Beta Model

The first model to be evaluated is the *ITU-526*, with the Deygout method to calculate L_D. In this case, RMSE values varied from 6.2 dB to 15.4 dB, and the median value is 10.8 dB. This simple model, based only on free space path loss and diffraction, was capable of a fairly good prediction in some of the cases, indicating that diffraction is an important phenomenon in this environment. For example, considering Small cell number 4, the RMSE was 8.8 dB for the 700 MHz band, and 9.9 dB for the 2.6 GHz band. However, when we compare these results with the results in Macro Cell 1, which were respectively 13 dB, and 15.4 dB, the prediction of the model is not so good. Macro Cell number 1 is the one with the highest altitude difference between transmitter and receiver, as detailed in [4]. In this case, 90% of the receiver locations were at least 150 m below the transmitter, and 50% were at least 350 m below the transmitter. Furthermore, most of the collected data in Macro Cells drive tests were collected in LOS conditions. In model ITU-526, these locations are characterized only with the FSPL model, since the diffraction losses are equal to zero. Therefore, it is important to investigate the role of the effective antenna height in the prediction of path loss values.

The second set of models contains the empirical models *Okumura Hata*, *COST Hata* and *SPM*. Due to the similarities between the first two models results, they are evaluated

TABLE II: RMSE values for distinct path loss models

	RMSE [dB]															
	Mine 1 Macro Cell 1		Mine 1 Macro Cell 2		Mine 2 Macro Cell 3		Mine 2 Macro Cell 4		Mine 1 Small Cell 1		Mine 2 Small Cell 2		Mine 2 Small Cell 3		Mine 2 Small Cell 4	
f [MHz]	700	2600	700	2600	700	2600	700	2600	700	2600	700	2600	700	2600	700	2600
ITU-526	13	15.4	8.9	11.1	8.7	10.2	6.2	10.5	11.8	12.1	11.2	13.7	8.8	12.1	8.8	9.9
OH	13.8	9.4	22.6	19.2	9	9.5	19.9	13	11.6	14.8	8.6	8.7	13.7	10.6	10.4	9
COST	13.2	9.4	16.8	19.2	8.8	9.1	19.2	15.4	14	17	8.2	8.9	13.1	12.4	9.8	10
SPM	5.7	6.3	4.9	4.8	6.8	6.8	4.9	5.8	7.6	5.9	4.9	3.9	4.8	5.2	5	4.8
SPM All	6.3	7	5.6	5.3	10.3	8.6	6.7	6.5	9.2	10	6.9	7.1	5.7	5.7	6.7	5.8
AB	9.8	12.7	10.4	13.8	12	13.3	11.3	13.4	7.7	9.4	12.6	13	7.9	10	10.8	10
Vale All	8.1	8	7	6.7	8.9	7.9	7.6	7.1	8.2	9.6	9.8	9.1	6	6.1	7.2	7.3
Vale	7.1	7.7	6.4	6.2	8	7.8	6.7	6.9	7.8	9.2	9.2	7.9	5.9	5.5	6.8	7.3
Optimal k	3	3	3	3	3	3	3	3	3	3	7	7	7	7	7	7
Samples	13945	11837	8324	5526	3217	3237	5760	5776	3098	2034	4243	2543	3398	2250	2160	1550

together here. In general, the suitability of these models to the measured data is worse than the ITU-526 model, and the median RMSE value is 11.1 dB for the Okumura Hata model, and 12.7 dB for the COST Hata. The RMSE varied from 8.2 dB in the best case to 22.6 dB in the worst case. This is expected because, although these empirical models have corrections for other terrain types, the adjustment of these parameters did not consider a mine scenario, which is singular when compared to urban, suburban or rural scenarios.

The *SPM* model, on the other hand, permits the adjustment of a group of calibration factors as discussed in Section III-A, which are shown in Table III. The results are shown considering two distinct types of calibration: one considering the individual calibration (row SPM in Table II), and another considering the data from all transmitters for calibration (row SPM All in Table II). Considering this specific scenario, the calibration or not, of k_6, k_7, $k_{clutter}$ and $k_{hill_{LOS}}$ did not change the results, so we did not include them here. The values k_1 and k_2 were calibrated considering LOS and NLOS cases separately.

TABLE III: SPM Calibration

Tx	f GHz	k_1 *los*	k_2 *los*	k_1 *nlos*	k_2 *nlos*	k_3	k_4	k_5
Macro Cell 1	0.7	40.2	22.9	52.6	20	-9.7	0.6	-0.9
	2.6	8.9	32.7	25.9	28.2	19.1	0.7	-7.3
Macro Cell 2	0.7	26.7	36.7	59.9	26.5	-1.7	0.8	-2.8
	2.6	55	28.8	80.5	21.7	-5.4	0.8	0
Macro Cell 3	0.7	27.4	36	30.1	35.4	7.4	0.6	-5.8
	2.6	69.6	28.9	73.4	28.4	-4.7	0.8	-3.2
Macro Cell 4	0.7	41.3	27.3	54.9	23.1	-4.7	0.7	-0.1
	2.6	77.1	20.3	84.2	20	-5.4	0.8	0
Small Cell 1	0.7	53.5	23.9	35.2	30.8	-5.6	0.3	-0.8
	2.6	78.3	20	15.3	45	20	0.4	-12
Small Cell 2	0.7	27	31.2	39.1	26.6	20	0.6	-5.7
	2.6	80.1	20.8	81.6	20	-20	0.4	-2.2
Small Cell 3	0.7	36.6	28	44.7	25.6	20	0.5	-7.4
	2.6	47.5	30	48.3	30.3	20	0.6	-7.9
Small Cell 4	0.7	53.5	23.9	35.2	30.8	-5.6	0.3	-0.8
	2.6	67.7	24.2	59.6	27.7	-9.5	0.2	0
All Cells	0.7	31.8	27.6	57	20	20	0.8	-5.2
	2.6	60.7	22.7	56.1	24.6	6	0.8	-1.1

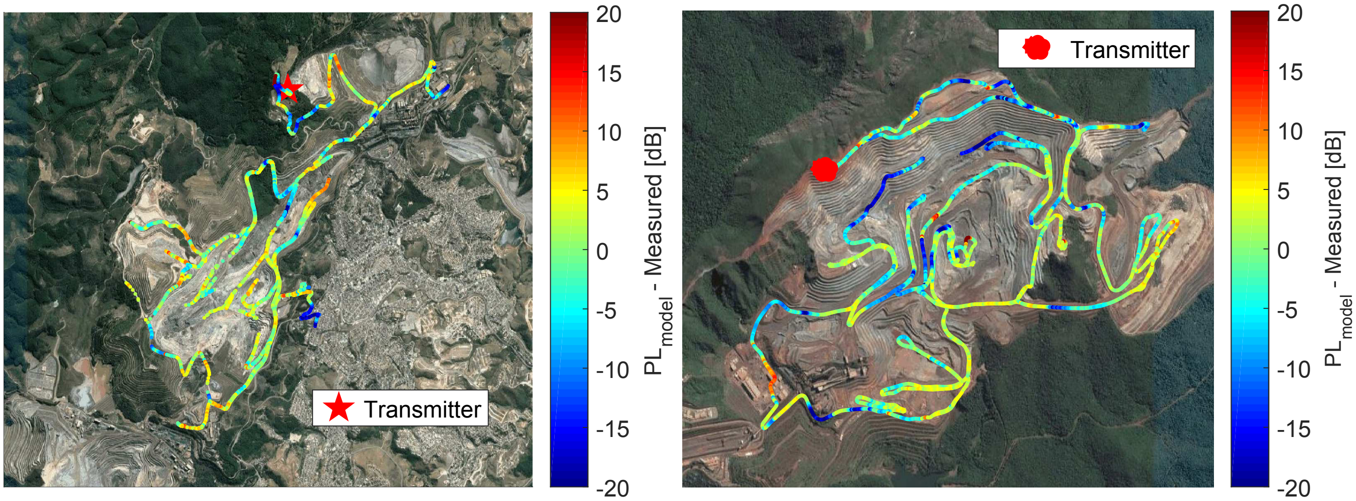
The RMSE values obtained with the SPM model calibrated individually are the best ones when compared with the other models, and fall between between the range of 3.9 dB and 7.6 dB. This is expected, considering the flexibility of the model, given by the number of terms that need to be adjusted. Although it is out of the scope of this paper, the calibration of this model is complex and many methods can be applied to enhance the curve fitting [8], [13]. This curve fitting exercise, however, makes it harder to understand the final choices of parametrization, and consequently, the physical meaning of the model. For example, considering Small Cell 2 calibration, the values of k_3 may assume the value of 20, in 700 MHz, or -20, in 2.6 GHz. The same occurs with the weight given for the diffraction component, k_4, which varies from 0.2 to 0.9. Under these circumstances, the extension of this calibration to other cases, or other topography conditions in the same mine, may be weakened.

Therefore, in order to evaluate the model general applicability to the mining scenario, we also calibrated it considering all the data from the 8 transmitters. In this case, the RMSE values varied from 5.3 dB and 10.3 dB, and the median RMSE value is 6.7 dB. Still, it is better than the other models evaluated so far.

The empirical (*AB*) models had an intermediary fit between the ITU-526, Okumura Hata and Cost models, and the median RMSE value was 11.1 dB. The RMSE values considering the AB model fit in Table II vary from 7.9 dB to 13.8 dB. These values are different from the ones in [5], where we used the entire dataset in each group to fit the model. Here, we use these general models to fit the individual cases. Although the AB empirical models were derived from the data collected in the open-pit mines and give some insights about propagation in this environment, they are not able to capture the specific, localized characteristics of the scenario. Furthermore, since they rely only on the measured data, these models cannot be generalized for different mines.

B. Vale Model

Finally, the fit of the *Vale* model is evaluated in two different cases. In the first one (Vale All in Table II), we experimented a single value of the calibration constant k, that was able to minimize globally the value of RMSE in all cases. The value that gave the best results was $k = 5$. In this case, the RMSE varied from 5.9 dB to 9.8 dB, with a median value of 7.8 dB. This fit surpasses the ITU-R 526 model in most cases, and it approximates the results of the SPM model calibrated with all the available data. The average difference between the RMSE of *SPM All* and *Vale All* is 1.1 dB.



(a) Macro Cell 1, in Mine 1, at 700 MHz.

(b) Macro Cell 4, in Mine 2, at 2600 MHz.

Fig. 3: Difference between the predicted path loss PL_{Vale} and the measured path loss, L.

We continued the evaluation of the Vale model, by sweeping the values of k until we found the optimal value, i.e. the one that minimized the RMSE in each case. Considering the Macro Cells, disregarding the mine where they are located, the best value is $k = 3$. The best value for the Small Cells is $k = 7$, except for small cell 1, which is $k = 3$. This small cell is the one with the highest Tx-Rx altitude difference [4]. These optimized results give further insight as to the role of the effective antenna height compensation. As most cases in the Macro Cells are LOS, hence only characterized by FSPL in the context of the ITU-526 model, further compensation is needed to account for the impact of the undulating terrain. In Small Cells, obviously, a single knife-edge approximation is too simple to account for the undulating terrain (inside the first Fresnel zone), and compensation is therefore needed also in this case. However, since H_{eff} is higher in Macro Cells than in Small Cells, k values should generally be smaller than the ones for Small Cells, otherwise one would overcompensate the antenna height.

Although the optimal selection of k is able to enhance the model fitting, it is important to notice that the improvement is, in the best case, 1.1 dB. The median RMSE is reduced by 0.6 dB in comparison to the case with $k = 5$, *Proposed All*. In other words, the model is not too sensitive to k variation. Furthermore, it is worth mentioning that the calibration of the model does not require differentiation between LOS and NLOS data, since the compensation of H_{eff} decreases the RMSE in both situations.

Two visual examples of the Vale model fitting are shown in Figures 3(a) and 3(b), where we compare the estimated path loss, L, with the optimized proposed model for macro cell 1 (Mine 1) and macro cell 4 (Mine 2), respectively. In general, the difference between the prediction and the measurements is within -5 dB and 5 dB. In some cases, specially immediately below the location of the transmitters, the model underestimates the path loss. One of the possible causes is the simplified approach to calculate the diffraction.

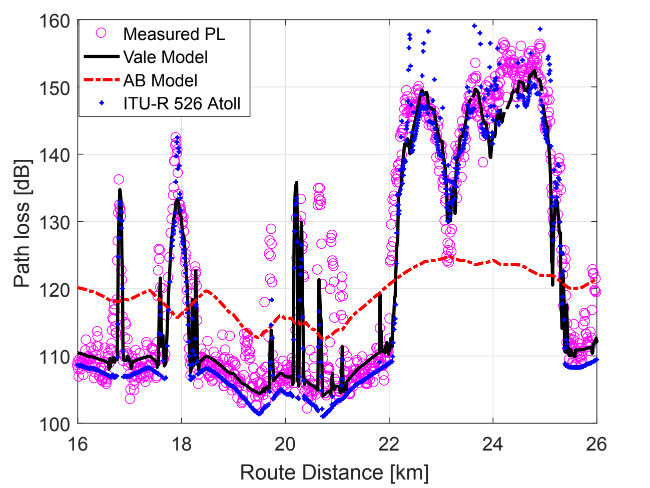
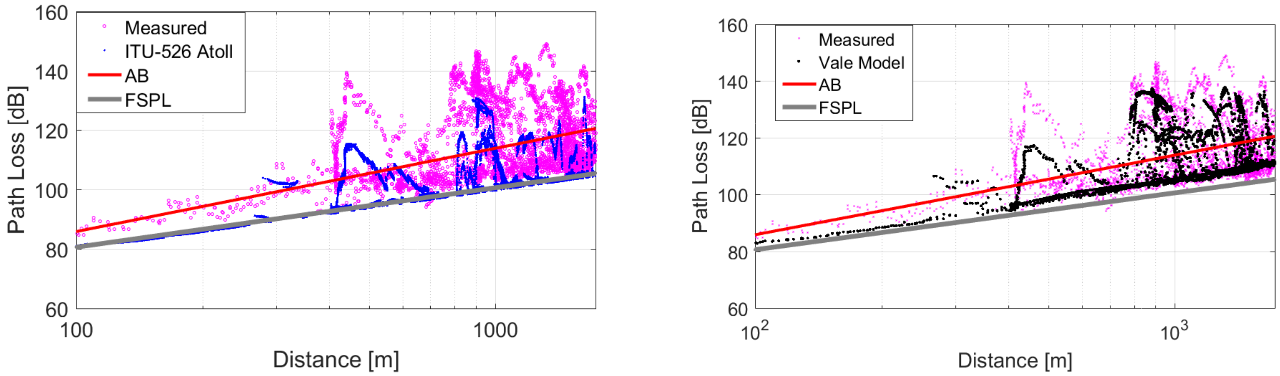


Fig. 4: Measured L, PL_{Vale}, $P_{\alpha\beta}$ and $P_{ITU_{526}}$, as a function of the driven distance. Macro Cell 4 drive test, at 2.6 GHz.

However, the quality of the fit in other locations shows that the model is able to correctly predict the path loss in this environment, as supported by the results shown in Table I.

Figure 4 shows the measured path loss, in pink, and the predictions using the Vale model, in black, the AB model, in red, and the ITU-R 526 as implemented in Atoll, in blue, for one of the measured cases. This is an example of the results over a 10 km stretch of the drive test route. In this figure, one can notice that the AB model is able to predict the trend of the Path Loss variation. However, it is not capable of characterizing the variation due to localized characteristics of the scenario, as between the kilometers 22 and 26. Clearly, there is an obstacle in this path that leads to more than 20 dB losses when we compare the AB model with the measured PL, and with the proposed model. The diffraction-based models, on the other hand, are able to capture localized variations over the measured route. In this figure it is also possible to see that the inclusion of the H_{eff} term in the proposed model makes the prediction closer to the measured data in LOS conditions



(a) Measured data, AB, FSPL and ITU-R 526 as implemented in Atoll.

(b) Measured data, AB, FSPL and proposed model, with $k = 3$.

Fig. 5: Path loss as a function of the distance between Tx and Rx for Macro Cell 4, in 2.6 GHz.

(as in between 18 km and 22 km in the figure, when the PL is below 120 dB), than the ITU-R 526 model.

This observation becomes clearer in Figure 5. Figure 5(a) shows the comparison of the path loss results as a function of the distance between Tx and Rx. In blue, we see the results from ITU-526 model, and in pink the measured results. One can see that the ITU-526 model underestimates the PL for not considering the effect of the effective antenna height. On the other hand, Figure 5(b) shows the results from the proposed model, in black. Here, there is no underestimation of the path loss in LOS conditions, what leads to the lower RMSE values observed in Table I, when compared with the ITU-R 526.

C. Discussion

In this section, we presented a detailed study about the efficacy of a variety of propagation models to the open-pit mining scenario. The models can be ordered from the best fit to the worst fit, as: SPM-Individual, SPM-All, Proposed Model with optimized k, Proposed model with $k = 5$, ITU-R 526, AB, Okumura Hata and COST-Hata.

The choice for a given model depends on the desired application. For example, considering the implementation phase of the communication network, when drive test data is usually available, the SPM model brings advantages for its higher accuracy, despite the complexity of the calibration. On the other hand, if there are significant changes in the mine and there is no new drive test data available, we believe that the simple deterministic model proposed in this work can be very useful for optimization engineers. The initial use of the proposed model depends only on the availability of a DTM, which is a trivial requirement in the mining business. Furthermore, the model is also useful to study the evolution of the wireless network over the time.

V. Conclusion

In this paper, we verified the accuracy of different empirical and deterministic radio propagation models to measurements collected in open-pit mines, considering small and macro cell cases, in two frequency bands. The results show that the SPM model is able to a very accurate path loss prediction also in this scenario. However, the complex calibration of this model, and the insights provided by the comparative study showed here motivated us to propose a simple, yet accurate, deterministic model. The proposed model is based on an extension to the ITU 526 model, which considers a diffraction term, by including an effective height component. The results show that the model is capable of improving the median RMSE value down to 7.2 dB, and approximates the results obtained by SPM. The proposed model relies only on a digital map of the mine, and it is much simpler than SPM and the one in [3], which would also require detailed information about the materials in the mine to calculate precisely the reflected fields.

In our future work, we intend to use the results shown here to calibrate simulations of wireless systems in open-pit mines. These simulations will help us understand and design networks able to meet the strict requirements of machinery automation.

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