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Validation of the Vale Path Loss Model for Open-pit Mines in Different Stages of Mine Exploration

Erika P. L. Almeida[1], Gabriel Guieiro[2,3], Ignacio Rodriguez[1]
Troels B. Sørensen[1], Preben Mogensen[1], and Luis G. Uzeda Garcia[3]

[1]Department of Electronic Systems, Aalborg University (AAU), Denmark. [2] Vale S.A., Brazil.
[3]Federal University of Ouro Preto (UFOP), Brazil.

Abstract—**As in other vertical markets, wireless communications are expected to play a fundamental role in the digitalization of the mining industry. Akin to most industrial applications, careful and scenario specific understanding of the radio propagation conditions is key to plan and deploy a reliable wireless network. However, surface mining presents an additional challenge when compared to other industrial scenarios: inherent large-scale topographic variability. Therefore, it is necessary to validate if the radio propagation models remain accurate over large topographic change. In this work, we summarize and compare the results collected in two distinct measurement campaigns, with the predictions of a dedicated path loss model (Vale Model) previously derived from measurements in surface mines. The second measurement campaign is performed by means of an automated site survey, that takes advantage of operational wireless systems and mining equipment to collect data samples. The results show that even with different transmit frequencies, topographic variation, test equipment, and measurement methods (dedicated versus automated site surveys), the Vale model provides a good fit for path loss prediction in open-pit mines, with RMSE values in the order of 7 dB. Besides, this is the first time a radio propagation model has been validated over large topographic changes in a surface mining scenario.**

I. INTRODUCTION

In order to increase safety and reduce operational costs, the mining industry is undergoing a digital transformation. The fusion of operational (physical) and digital technologies, also known as Industry 4.0 [1] is shaping the factories of the future. Wireless connectivity is an essential element of the so-called fourth industrial revolution. Therefore, it is no surprise that mining and other verticals have been attracting the attention of the telecom industry. Mining companies are expected to dedicate circa 1.5% of their multi-billion dollar capital expenditure (CAPEX) on private networking in 2022 [2].

When compared to other industrial scenarios, surface mines are unique in many ways. First, they are essentially immense outdoor factories. Second, their landscape is constantly varying, since excavation, blasting and deposit of waste materials are inherent of the mining activity. These changes impact the radio propagation conditions and consequently the performance of wireless systems. Therefore, the authors believe that it is important to understand how the radio propagation conditions will be modified by topographic variation, in order to plan and optimize wireless networks deployed in surface mines.

The authors have conducted an extensive measurement campaign in the past, in two iron-ore mining complexes, two frequencies bands (700 MHz and 2.6 GHz) in macro- and small-cell deployments. From this dedicated measurement campaign, which took place in May, 2017 and is detailed in [3], the authors derived the *Vale Model* [4]. This model is an empirical path loss model based on the free space path loss, a diffraction component, an effective height component and a calibration constant. The accuracy of this simple model was verified and the resulting root-mean squared error (RMSE) was between 5.5 dB and 9.2 dB. Because the Vale model is a terrain-aware three-dimensional radio-propagation model, the hypothesis is that it should remain valid over time and thus useful at multiple development stages of open-pit mines.

In order to test this hypothesis, in this work we present the results of a second measurement campaign and compare the results to the Vale model predictions. The second measurement was performed after substantial additional exploration activity, 20 months after the one that originated the model, and it was performed by an automated site survey system. This site survey system takes advantage of the wireless system in operation in the mine to collect received signal strength indication (RSSI) measurements simultaneously from different receiver (RX) equipment. These measurements are further used to estimate the path loss, and the design of this automated measurement system is an additional contribution of this paper.

This work is the conclusion of the measurement and modeling activities presented in [3], [4] and it is organized as follows. Section II presents the site surveys methodologies, dedicated and automated, as well as the post processing of the data. Section III presents the results and discussions, and Section IV concludes this work.

II. METHODS

A. Dedicated Site Surveys

A common approach to collect radio-propagation data is a dedicated site survey or drive test. The purpose of these surveys is to collect measurements in diverse locations within the interest area, so that the measurements are not biased to specific, localized conditions. These measurements are used to understand the radio-propagation conditions in the environment and calibrate propagation models.

Despite being very useful for planning and continuously optimizing wireless networks, dedicate site surveys are usually time-consuming and expensive even in urban deployments. In a mine site there are additional challenges, such as:

- assembling and configuring the transmit and receiving systems. Access in mining sites is very carefully controlled, and usually involves a long training process;
- training a driver, or using the time of an experienced driver, to conduct the drive test;
- using the time of a dedicated person to conduct the measurements;
- guaranteeing that the vehicle respects the driving rules and exclusion zones during the test.
- interrupting the drive test whenever needed, e.g. exclusive hauling trucks area or blasting, to ensure compliance with safety rules in the area.

Despite all these challenges, a dedicated site survey was conducted in two mining complexes in the time span of 30 days between April and May, 2017, and it is detailed in [3]. The drive test was conducted for 9 different transmitter locations, in macro cell and small cell deployments. The transmit signal, a continuous wave (CW) was generated by two Keysight signal generators, one in 2.6 GHz and the other in the 800 MHz band. The signal was amplified and transmitted by an omni-directional antenna, with 60° degrees elevation beamwidth, and 6 dBi and 4 dBi gain, respectively. The receiving antenna, omni-directional, with 3 dBi gain, was mounted on the rooftop of a pick-up truck, at 1.8 m. The received signal was recorded using a R&S TSMW Universal Radio Network Analyzer, at a rate of 150 samples/s. Each sample consisted of the received signal, a time-stamp and the position collected by a GPS. Some characteristics of the transmit and receiving characteristics of this dedicated site survey are in Table I.

B. *Automated Surveys*

To overcome the difficult, dirty and dangerous nature of site surveys in mine sites, a proprietary platform was developed to automate the data collection procedure. Based on synchronized time-stamps, the design fuses:

- Georeferenced data from the server that controls the Autonomous Haulage System (AHS).
- RF key performance indicators (KPIs) extracted from the client radios onboard the unmanned machinery.

High precision RAN-independent localization data is available in real time since each autonomous truck is equipped with two Global Navigation Satellite System (GNSS) receivers supporting Real Time Kinematic (RTK). In practice, this allows the position to be known with sub-centimeter resolution and to easily distinguish the front from the back of the trucks. This distinction is relevant because the cellular antennas are mounted in the front of the vehicles.

The RF measurement system is based on the IEEE 802.16e cellular infrastructure, also known as Mobile WiMAX, present in the mine. The considered time-division duplex (TDD) WiMAX network operates on two 10 MHz channels on the 1.5 GHz band and provides broadband wireless connectivity to the mining equipment. The system employs Rugged MAX^{TM} base stations equipped with 16 dBi directive antennas with known radiation diagrams, azimuth and elevation angles. RF KPIs, e.g. RSSI, SNR, are fetched directly from the client radios using a Simple Network Management Protocol (SNMP) server. The Siemens WIN 5100 Customer-premises equipment (CPE) employed supported SNMP v2.

Each module was carefully validated independently before and after the fusion took place. An independent and free-source software implementing the SNMP protocol (Paessler SNMP Tester) queried the client radios and the data was compared to the information reported by the network vendor's Operations, administration and management (OAM) tool. A perfect match was consistently observed. Despite being in continuous operational usage, and hence already field-proven, the positioning data stemming from the AHS server was compared to the data extracted from a second collocated and independent RTK rover whose data was directly read using a trusted reference equipment.

Once obtained, the data from both sources could be combined based on their time-stamps. Depending on the sampling rates, multiple hours of automated measurements can be seamlessly collected and synchronized. Because our focus is on large-scale propagation parameters, low sampling rates suffice to guarantee spatial separations between samples that are better than the resolution of the digital terrain models (DTM) employed and consistent with the maximum operational speed of the trucks.

Unlike the dedicated site-surveys from the previous years, the validation data was collected using a varied set of equipment, which led to different antenna heights to test the model under more general and closer to the operational conditions. A mining truck, a terrain leveler and the original pick-up were considered. Besides that, the path loss estimation was done based on the RSSI measurements reported by the equipment. According to the IEEE 802.16e standard, the RSSI values should be reported in steps of 1 dB increments, with a relative accuracy of ± 2 dB, and an absolute accuracy of ± 4 dB. This large uncertainty, when compared to the absolute accuracy of dedicated drive-test equipment in the order of ± 1 dB, may impact on the path loss estimation. However, as the number of samples for the estimation of the mean increases, the average of these results tends to be closer to the expected value. The data presented in this paper was collected during 12 hours of mine operation in Mid-December 2018, resulting in 10,553 valid samples. Some characteristics of the transmit and receiving equipment are in Table I.

C. *Post-processing*

In order to estimate the path loss in each case, the following preparation and post-processing steps were carried out:

- Obtain and pre-process the maps in each occasion: the obtained maps might be in different formats, coordinate reference systems (CRS) and resolutions. To guarantee the consistency of the path loss estimation procedure, the original SAD69 digital terrain models (DTM) are converted to a common format. In this work we used

TABLE I: Summary of the RX and TX configuration in the dedicated and automated site surveys.

		Dedicated Site Survey		Automated Site Survey
TX	Frequency [MHz]	700	2600	1500
	Half-power beamwidth H. [°]	Omni	Omni	90
	Half-power beamwidth V. [°]	60	60	8
	Gain [dBi]	4	6	16
	Downtilt [°]	-	-	2
	Antenna Height agl [m]	between 5 and 42		30
	EIRP [dBm]	20	48	50
	Transmitted Signal	CW		OFDM, 10 MHz BW
RX	Antenna	Omni		
	Gain [dBi]	3		8.5
	Antenna Height agl [m]	1.8		1.8
				4.1
				7.1
	Receiving Equipment	R&S TSMW		Siemens WIN 5100

the software QGIS [5] to pre-process the maps with a 1 m × 1 m resolution. The chosen CRS was a Universal Transverse Mercator (UTM) CRS, using the WGS84 ellipsoid, to be compatible to GPS data.

- Obtain the transmitter and receiver information: consisting of antennas models and patterns, azimuths, elevations, cable losses, transmit powers, receiver equipment, antennas, antenna gains, vehicle height, etc.
- Data segmentation: This step comprises selecting the interest data-set in terms of RX equipment, TX ID, frequency, etc. For example, the data-set collected in the automated site survey consisted of information gathered from different receivers (with different antenna heights), and different TX IDs. In this work, we only consider one TX ID, because there was only one transmitter in a given frequency, so we can guarantee that the measured RSSI comprises only the target transmitter.
- Spatially-filtering the data. This step was used in the post-processing of the data collected in the dedicated site survey. The received signal was sampled with a high sampling rate, and a separation of the large-scale fading and small-scale fading components was possible through a moving-average filtering, also described in [3] and [6]. In the automated survey, the RSSI values, which are a wideband power measurement, were collected with a sampling rate in the order of 1Hz. In this case, the values were only spatially averaged in the locations were the vehicle was stopped for a long period, resulting in samples with less than 40λ (where λ is the wavelength).
- Estimating the path loss. Using all the information collected in the previous steps, and the processed version of the collected measurements, it is possible to estimate the path loss (L) as:

$$L_{[dB]} = P_{TX_{[dBm]}} - P_{RX_{[dBm]}} - L_{\text{cables}_{[dB]}} + G_{TX_{[dB]}}(\theta,\phi) + G_{RX_{[dB]}} \tag{1}$$

where P_{TX} represents the transmitted power, P_{RX} represents the local mean received power or the RSSI, L_{cables} represents the combined cable losses in both Tx and Rx sides, $G_{TX}(\theta,\phi)$ and G_{RX} are the Tx and Rx antenna gains, respectively. The estimation of $G_{TX}(\theta,\phi)$ is done by combining the transmitter characteristics with the receiver positions, and elevation obtained from the area DTM.

Keeping the main objective of this paper in mind, the last step in our post-processing pipeline is to compare the values estimated from the measurement campaigns, with the ones predicted by the Vale model.

The Vale model was derived from the observations and results collected in the dedicated site survey, mentioned in Section II-A. The model is defined as a function of the free space path loss (FSPL), $FSPL = 20\log_{10}(\text{distance}_{[m]}) + 20\log_{10}(\text{frequency}_{[\text{MHz}]}) - 27.55$, a diffraction loss component, L_D, and an effective height component, h_{eff}:

$$PL_{VALE} = FSPL + L_D + k\log_{10}(h_{eff}) \tag{2}$$

In this model, k is a calibration constant whose value is considered to be $k = 3$ for macro cells and $k = 7$ for small cells, according to the calibration also presented in [4], and assumed in this work.

The comparison between the predicted path loss and the path loss estimated from the measurements is done by means of a root-mean-squared error (RMSE), given by:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(L_n - PL_n)^2}{N}} \tag{3}$$

in which L_n represents the n^{th} path loss estimated from the measurements by Eq. 1 point, PL_n is the estimated path loss at the same location, by the model in Eq. 2 and N is the total number of measurement points.

III. RESULTS AND DISCUSSION

Fig. 1 shows the topographic change during this period. Fig. 1(a) shows an aerial image of this mining complex during the first, dedicated, site survey. Fig. 1(b) shows the aerial image during the second, automated, site survey, and Fig. 1(c) shows the volumetric variation between them. In this figure, the cold colors show the area in which this mine was excavated, i.e. ore and waste were removed, while the red colors represent the areas were waste was deposited in the mine. In this period, more than 26 million cubic-meters were moved, resulting in an dramatic topographic change: in some locations, the altitude varied more than 50 meters. In order to evaluate if this topographic change is captured by the Vale model, we compare the estimated path loss from the measurements (Eq. 1) to the estimated path loss from the Vale model (Eq. 2). The results from the first measurement campaign, detailed in [4], are partially reproduced here for convenience. The difference between the estimated path loss PL_{VALE} and the measured path loss collected in the drive-test from May 2017 is shown in Fig. 2(a), and the same result for the drive-test collected in December 2018 is shown in Fig. 2(b). In this figure, one can notice important differences between an automated and a dedicated drive test:

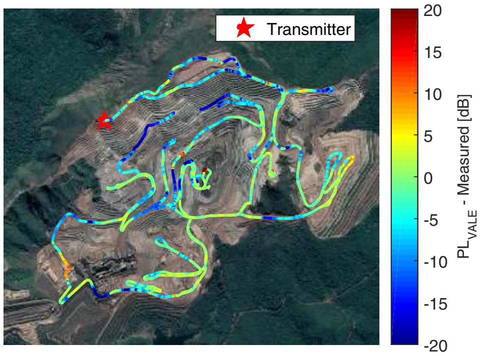
(a) Mine topography, May, 2017. (b) Mine topography, December, 2018. (c) Altitude variation between May, 2017 and December 2018.

Fig. 1: Mine topographic variation between both measurement campaigns. The area of interest spans 3 by 4 km

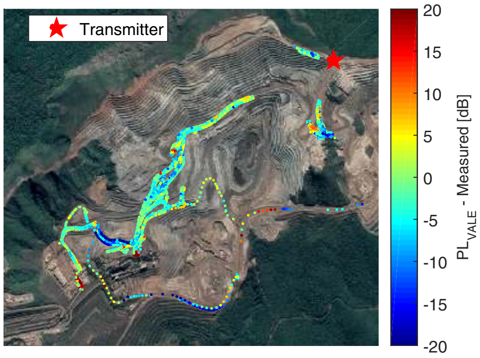
- Transmitter locations: in a dedicated drive test, the transmitter location may be different from the transmitters in a real deployment. In the drive-test on May 2017, the transmitters were positioned in locations that were convenient for the test (for example, in terms of proximity to power sources, in terms of probability of line-of-sight (LOS), and in locations that were accessible for the measurement crew). This specific transmitter shown in Fig 2(a), for example, was mounted on top of a relocatable platform positioned in the highest location within the mine.
- Drive test routes: there is also a difference in the drive test routes. While dedicated drive test routes are designed to cover varied locations within the interest area, balancing LOS and non-line-of-sight (NLOS) areas, automated drive test routes follow the routes driven by the mining equipment. This is clear when comparing both cases. In this particular result, one can see that the vehicles traffic in this mine is concentrated in the excavation area shown in Fig. 1(c).

In these plots, cold colors represent locations in which the measured path loss is higher than the predicted (*under-estimated*) path loss, and red colors represent locations in which the predicted (*overestimated*) path loss is higher than the measured. The adherence of the model is higher when the difference between the measured and the predicted path losses is closer to zero.

In the first case, in Fig 2(a), the locations with increased model error were close to the mining benches, where there were multiple diffraction. The implementation of the Vale model used for the predictions, uses a simplified diffraction calculation, by a single knife-edge model. In the second case, in Fig 2(b), there are other effects to be considered such as the antenna mounting and the truck direction during these measurements. In the bottom of this figure, it is possible to notice that some samples present an error of more than 20 dB when compared to the predicted path loss. This error is due to the fact that the truck direction is not considered in the estimation of the path loss. The RX antenna is mounted on the front of the truck, which can be shadowed depending on the truck direction in relation to the TX antenna, results of the excess loss in the vicinity of hauling trucks are presented in [7], considering different conditions (full or empty truck) and frequencies.



(a) Drive Test on May 2017.



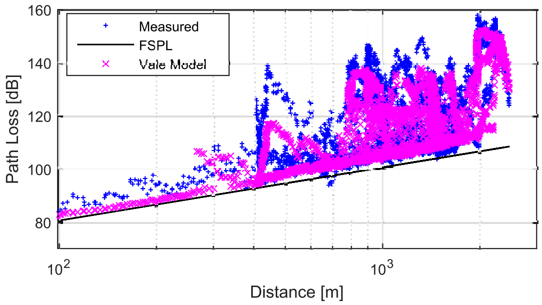
(b) Drive Test on December, 2018.

Fig. 2: Error between the path loss estimated from the measurements, and the predicted by the Vale model.

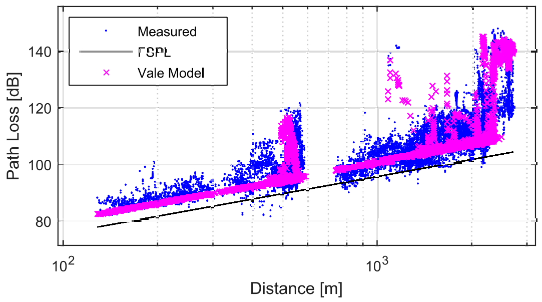
The results are also shown in a different perspective in Fig.3, in which the estimated and the predicted path loss are plotted as a function of the distance between the TX and the RX. In both figures, the black line represents the FSPL, the blue dots, the PL estimated from the measurements and the magenta dots, the PL predicted by the model. A summary of the results is given in Table II.

From these results we conclude that:

- The automated site survey system is capable of collecting RSSI samples that can be continuously used in estimating the path loss. This information can be very



(a) Results from May, 2017.



(b) Results from December, 2018.

Fig. 3: Path loss as a function of the distance between TX and RX.

TABLE II: Summary of the results.

	May 2017	December 2018
# Samples	5,776 from dedicated survey	10,553 from automated survey
Purpose	Derivation and calibration of the model	Temporal and topographical validation
Frequency [GHz]	2.6	1.5
RMSE [dB]	6.9	7.2
Mean [dB]	4	2
Standard Deviation [dB]	6.7	7

useful when calibrating propagation models, and planning and optimizing the network, requiring much less human effort than the dedicated site survey. Furthermore, the site survey done with mining equipment provides insights about the in-site conditions that could be improved. For example, the position of the antennas on the top of the hauling trucks causes self-shadowing depending on the driving direction.

- The Vale model is suitable for large-scale propagation characterization in open-pit mines. This model, derived from measurements from different mining complexes, topographic characteristics, transmitter deployments and frequencies, continues to provide a good fit for the radio-propagation in open-pit mines, even when considering the scenario variability.

When combined, the automated site survey system and the Vale Model provide a powerful tool for aiding the planning and optimization processes of wireless networks deployed in open-pit mines. Mining is a carefully planned activity, in which, at given moment in time, the future development of the excavation, and the position of the UEs are known to the system. By using the excavation plans and maps, the Vale Model can provide a good estimate for the received signal level. This information is useful when planning and re-positioning the small cells, or simulating the performance of new features to be added to the network, for example, such as in the study presented by the authors in [8]. The automated site survey, on the other hand, helps collecting real-time data, that can be used to continuously calibrate the propagation model, and check the performance of the system, which is especially critical when considering the recent development of mining automation.

IV. CONCLUSIONS

In this paper, we presented the temporal validation of the Vale model, a path loss model derived from measurements in iron-ore surface mines. The results were compared using data collected in two distinct moments of the mining exploration. The first data set, obtained by means of a dedicated site survey, was collected in May, 2017. The second data set, obtained by means of an automated site survey, was collected in December, 2018. During this period, more than 26 million cubic meters of ore and waste were moved in this mine. On top of a distinct measurement methodology and the updated mine topography, the data set also differs in transmitter location, frequency band, sampling equipment and drive test vehicles. When comparing the model predictions to the path losses estimated from the field measurement campaign, the RMSE values remain between 6.9 dB and 7.2 dB, thus confirming that the Vale model is suitable for the path loss prediction in surface mines. The combination of an automated site survey methodology with an accurate radio propagation model is a powerful tool for planning and optimizing wireless networks that support advanced industrial robotics applications in this particular environment.

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