Wireless Communications in Open-pit mines

from radio-propagation to network deployment strategies

Almeida, Erika Portela Lopes de

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

WIRELESS COMMUNICATIONS IN OPEN-PIT MINES: FROM RADIO-PROPAGATION TO NETWORK DEPLOYMENT STRATEGIES

BY
ERIKA PORTELA LOPES DE ALMEIDA

DISSERTATION SUBMITTED 2019

AALBORG UNIVERSITY
DENMARK

Wireless Communications in Open-pit mines: from radio-propagation to network deployment strategies

Ph.D. Dissertation

Erika Portela Lopes de Almeida

Dissertation submitted: September, 2019

Dissertation submitted: September 21, 2019

PhD supervisor: Assoc. Prof. Troels B. Sørensen
Department of Electronic Systems
Aalborg University

Assistant PhD supervisors: Prof. Preben Mogensen
Department of Electronic Systems
Aalborg University & Nokia Bell Labs, Denmark

Luis G. U. Garcia, Ph.D.
Nokia Bell Labs, France

PhD committee: Associate Professor Beatriz Soret Alvarez (chairman)
Aalborg University, Denmark

Master Researcher Henrik Asplund
Ericsson Research, Sweden

Principal Scientist Deepaknath Tandur
ABB Indian Corporate Research center, India

PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Electronic Systems

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-504-8

Published by:
Aalborg University Press
Langagervej 2
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2019

Curriculum Vitae

Erika Portela Lopes de Almeida

Erika Portela Lopes de Almeida obtained her degree in Communications Engineering in 2007, from University of Brasília, Brazil. In 2010, she obtained an Electrical Engineering M.Sc. degree from the same university. From 2011 to 2018, she worked as a researcher in Instituto de Desenvolvimento Tecnológico (INDT), previously known as Instituto Nokia de Tecnologia. In this period, she worked with cognitive radio concepts, coexistence in unlicensed spectrum bands and enhancements to Wi-Fi. From 2015, she is working torwards a Ph.D. degree in Wireless Communications, in Aalborg University (AAU), in Denmark, within a collaboration between INDT, AAU and Instituto Tecnológico Vale (ITV). She has authored or co-authored more than 20 technical papers, and 11 patent applications, in the field of wireless communications.

Abstract

Innovation and adaptation are paramount to any industrial business. Recently, the so-called 4th Industrial Revolution is pushing not only the development of new industrial processes and technologies, but also the improvement of wireless communication systems so that they are able to meet the requirements for automation. The telecommunications industry has, therefore, identified a promising business in industrial automation. As a result, industrial cases have been considered since the beginning in the development of the latest wireless communications standards. Mining is one of the verticals that has been gradually moving towards unmanned operations. Wireless communications have been long used in mines for ancillary narrowband services, such as telemetry and dispatch. From 2007, with the introduction of autonomous trucks in Chile, automation of machinery started to become a reality. Autonomous equipment will require more from the wireless communication networks, which are likely to become a central part of the entire mining business itself. With automation, the unavailability of the network can directly impact on the profitability of the industry, which makes it paramount to track the wireless network performance, and continuously optimize it to guarantee that the automation communication requirements are met.

In addition to the increased business impact related to the performance of the network, the mining scenario presents other challenges to wireless communications. Surface mines, albeit closer to well-known scenarios than underground mines, also presents unique challenges to radio-propagation modeling, such as the sharp height variation and continuous variability of the terrain, both inherent of the surface mining activity. This uninterrupted topographic change continuously modifies the radio propagation conditions, has an impact on the system performance, and raises the need to constantly re-deploy the network nodes. Despite continuous, the topographic variability is carefully planned by the mine planning activity, and it is, therefore, predictable. The main hypothesis of this work is that by assessing information from future mining activity, the terrain variability can be predicted, as well as it's effects on the large-scale radio-propagation. The influence of excavation on the network performance over the time can, then, be minimized by adapting the wireless network infrastructure, also minimizing the financial impact both in terms of profit losses, caused by network outages, and in required investments on the radio network infrastructure.

To validate this hypothesis, this study is divided in two parts, each addressing gaps in the literature regarding this topic. The first one was the lack of radio-propagation measurements and specific studies and models in this scenario. This part of the thesis is, therefore, dedicated to understanding the main propagation mechanisms in this environment, in different frequency bands below 6 GHz. An extensive experimental analysis of the large scale radio-propagation in surface is presented, based on measurements collected in two operational mining complexes in Brazil, considering different transmitter types (small and macro cells). The suitability of different large-scale path loss models is evaluated, and this study shows that the main propagation mechanisms in this frequency and environment are direct propagation, in the Line-of-Sight (LOS) path, and diffraction. A simple path loss model is proposed based on the first set of measurements, and validated by means of a second measurement campaign. With this model, the path loss can be accurately predicted in different moments of the mine exploration.

The second part of this thesis is dedicated to understanding to which extent the long-term variation of the scenario impacts on the performance of the network. At first, a framework to integrate mine planning information is proposed, and then the network performance is evaluated. This study is performed by means of computational experiments, static network simulations, which use the models defined in the first part of this thesis, as well as the information from mine planning. Different network deployments and features are evaluated. From the study of the topographic variability, it is shown that LOS tend to increase with the mine operation, increasing the coverage of the network, but also degrading the Signal-to-interference-plus-noise-ratio (SINR) in macro cell or heterogeneous deployments. Interference mitigation techniques, such as beamforming, can exploit this fact, being able to significantly reduce the outage in the network, and seem promising in this scenario. Finally, the Total Cost of Ownership (TCO) of different network deployments are compared, and put into the perspective of the lost profits caused by system downtime in this industry, justifying the investments in the wireless network infrastructure.

The studies and recommendations in this thesis can be used by both the mining industry and the telecommunications industry. The former benefits from understanding the effect of the mining activity on the wireless network performance, and from understanding the costs of not investing, accordingly and timely, on the network infrastructure. The latter, can also benefit from the studies and models, the planning recommendations and the suggested framework for integration of mine planning and network planning.

Resumé

Innovation og tilpasningsevne er altafgørende for enhver virksomhed. Den såkaldte fjerde industrielle revolution skaber udvikling inden for nye industrielle processer og teknologier hvilket også kræver udvikling af trådløse teknologier, da disse skal kunne opfylde de nye krav fra eksempelvis automatisering. Telekommunikations industrien har på baggrund af disse nye krav identificeret flere lovende forretningsmuligheder. De industrielle anvendelsesmuligheder har derfor været en del af udviklingen af den nyeste trådløse kommunikations standard. Minedrift er en af de brancher der gradvist har bevæget sig mod komplet automatisering. Trådløs kommunikation har været anvendt i miner længe til smalbåndstjenester som eksempelvis telemetri og kommunikation. Introduktionen af selvkørende lastbiler i 2007 i Chile betød at automatiseringen har været gradvis realiseret lige siden. Autonomt udstyr kræver mere af det trådløse kommunikations netværk, hvilket derfor højest sandsynligt vil komme til at have en mere central rolle i selve minedriften. I og med at det trådløse kommunikations netværk har en mere central rolle vil udfald og lignende have en direkte indvirkning på driften og dermed rentabiliteten. Det er derfor meget vigtigt konstant at overvåge og optimerer netværket således at kravene for automatiseringen kan opfyldes.

Ud over netværkets forøgede potentielle påvirkning af rentabiliteten giver minedrift også andre udfordringer for trådløse kommunikations netværk. Åbne miner, om end tættere på kendte scenarier end underjordiske miner, udgør unikke udfordringer for radioudbredelse modelleringen, såsom den skarpe højdevariation og kontinuerlige variation i terrænet, begge grudnet overflademinedriftsaktiviteten. Den konstante ændring af topografien og dermed ændrede radioudbredelses forhold har betydning for netværkspræstationen hvilket dermed kræver kontinuert flytning af netværks punkter. Dette på trods af at ændringer i topografien af minen er nøje planlagt og krævede ændringer dermed kunne forudses.

Hovedhypotesen for denne afhandling er derfor hvorledes information om fremtidig minedrift og terræn ændringer kan anvendes til at forudse konsekvenserne for radio udbredelsen. Indflydelsen af gravearbejde på netværkspræstationen over tid og denne kan minimeres ved at tilpasse den trådløse netværks struktur. Yderligere at de finansielle konsekvenser af afbrydelser i netværket kan opveje de krævede investeringer i netværk infrastrukturen.

For at efterprøve denne hypotese er er studiet opdelt i to dele, hvor begge adressere huller i den eksisterende litteratur. Den første del koncentrere sig om manglen af radiobølge udbredelses målinger og specifikke studier og modeller for dette specielle scenarie. Denne del af afhandlingen er derfor dedikeret til forståelsen af radiobølge udbredelses mekanismer i dette miljø, i forskellige frekvensbånd under 6 GHz. En omfattende eksperimentel analyse af radiobølge udbredelses karakteristik i åbne miner er præsenteret baseret på målinger foretaget i to forskellige operative mine komplekser i Brasilien foretaget med forskellige sender typer (små og makro celler). Anvendeligheden af forskellige radiobølge udbredelses modeller er evalueret i dette studie og de viser at den primære udbredelses mekanisme i disse frekvens bånd og miljø er den direkte uforstyrret udbredelses vej (LOS) samt diffraktion. Et sæt af udbredelses tabs modeller inklusiv en semi-deterministisk er foreslået efter den første målekampagne og valideret med den anden. Ved at anvende modellen kan udbredelsestabet nøjagtigt estimeres ved forskellige stadier af mine gravningen.

Den anden del af denne afhandling er dedikeret til forståelsen af hvorledes afvigelserne i miljøet over længe tid påvirker netværkspræstationen. Først er et værktøj til at integrerer minedriftsplanlægningen i netværksplanlægningen udviklet og dets anvendelighed vurderet. Dette studie er udført på baggrund af eksperimentelle simuleringer udført med modellerne udviklet i den første del af afhandlingen sammenholdt med informationer om den planlagte udgravning af minen. Forskellige netværks opsætninger og indstillinger er evalueret. Studiet af variationen i topografi viser en tendens til at den direkte uforstyrret udbredelses vej (LOS) øges som følge af udgravningen og dermed øger netværksdækningen men samtidigmed forværrer SINR i makro celle eller heterogene netværk. Interferens mindskningsteknikker som direktive antennesystemer kan udnytte dette til at kraftigt reducerer netværksafbrydelser grundet manglende dækning hvilket derfor er en lovende teknologi for netop dette miljø. Endeligt er den totale driftsomkostning (TCO) for forskellige netværks opsætninger sammenlignet og sammenholdt med et eventuelt økonomisk tab forsaget af netværksnedbrud eller manglende dækning, hvilket berettiger en investering i trådløs netværks infrastruktur.

Studierne of anbefalingerne i denne afhandling kan anvendes både af mineindustrien og telekommunikationsindustrien. Den først nævnte drager fordel af en bedre forståelse af minedriftens påvirkningen af det trådløse netværk og dets præstationsevne samt de eventuelle omkostninger ved ikke at investerer korrekt og tidssvarende i netværks infrastrukturen. Den sidstnævnte drager også fordel af disse studier og modeller i deres planlægning og foreslåede af løsninger til opsætning af netværk i miner.

Preface

This thesis is the outcome of my work since September, 2015, within a cooperation between Aalborg University (AAU), Instituto de Desenvolvimento Tecnológico (INDT), and Instituto Tecnológico Vale (ITV).

I couldn't have done this work alone, so I take this opportunity to express my gratitude to all those who have helped me along the way. First, I would like to thank my supervisors, Troels, Preben and Luis, for their support and patience, for finding solutions for all practical problems regarding this project and especially for the relevant discussions, which were fundamental for the completion of this thesis. Thank you also for the invaluable revision work in the weeks before this submission. I would especially like to thank Luis, for bringing this project to INDT, and for always being available for discussions despite the physical distance.

I thank also two non-official technical advisors. Ignacio Rodriguez, for being my PhD mentor. I am grateful for all discussions, invitations for crazy measurement campaigns and guidance. Ignacio's technical comments, *pickiness* and friendship were key to the conclusion of this thesis. Second, Robson Domingos, which has been my colleague, manager and friend for the past ten years. Thank you for taking care of the practical details of the project, for the technical discussions and friendship.

I would also like to express my gratitude to INDT and ITV for offering me the opportunity to come to Denmark. I extend this gratitude to the colleagues Sérgio Abreu, Marcelo Leite and Bruno Faria, that at some point assisted me on the project. A especial thanks to George Caldwell, without whom the measurement campaign would not have been possible. His efforts to guarantee that all measurements were collected were highly appreciated. His practical knowledge and sense of humor certainly helped making the experience of working in an open-pit mine unforgettable. From Vale and ITV, I would like to thank Vivianne, for opening a whole new world for me by explaining the mining activity and business, and for her assistance before the measurement campaign. I extend this gratitude to Gabriel, Rafael, and Pedro, for providing me all the information needed, whenever needed, and all others from Brucutu and Itabira mines that have assisted us during this

project.

Living abroad was also a challenge, so I thank all the colleagues from AAU that welcomed me with open arms: Mads (and Gitte), and Lars thank you for helping me in the very first days in Denmark. Dorthe Sparre, for offering me help with all practical matters, and also with the Danish language. *Tak for det hele!* A special thanks to my colleagues in the Wireless Communication Networks Section: Dereje, Lucas, Emil, Gilberto, Nurul, Fernando, Huan, Tomazs, Carles, Troels and Mohammed, and recently, Johannes. I also need to thank my friends, who made Denmark feel like home. First, the Brazilians: Yuri, Leticia, Milena, Rodolpho, Priscilla, Rafhael and Patricia. Special thanks to Felipe, whose friendship has been essential in the past few years, and the Paiva family (Rafael, Juliana, Helena and Teresa). I will never be able to express my gratitude for their friendship in the last years. Finally, the Danish friends, Nanna, Brian, Line, Charlotte and Martin, for welcoming me in their lives, and for showing me the Danish *hygge*.

Last but not least, I would like to thank my family. First, my mother, Rosamelia, whose love, strength and life example have been an inspiration to this journey. Thank you for traveling such a long distance to be with me while I wrote the last pages of this work. My brother, Fabio, thank you for friendship, emotional support, companionship for writing the last two papers, and for believing in me when I doubted myself. I am especially grateful for all the long Skype calls in which I was able to interact with my nephew, Dudu, who is still too young to realize how important those moments were. Luis, Lucimar, Claudia, Fabiana, Carlinhos: for the help on crucial moments. Kirsten and Poul Erik(s), Mogens, Anja and Martin: thank you for welcoming me in your family, and for always being there for me. Finally, Søren, my fiancé, meeting you was the best thing that happened in the past years. I cannot imagine finishing this thesis without you by my side. Thank you for your understanding, unconditional love, kindness, support, patience and for welcoming me (and the cats) in your life. Certainly, life became lighter and happier after I met you.

This thesis is dedicated to the memory of my father, José Nancides, who has always been my greatest inspiration, and to the memory of my grandmother, Terezinha, and my uncle, Wartene, who both encouraged me to pursue this Ph.D.

Erika Portela Lopes de Almeida
Aalborg University, September, 2019.

Thesis Details

Thesis Title:	Wireless Communications in Open-pit Mines: from Radio Propagation to Network Deployment Strategies
Ph.D. Candidate:	Erika Portela Lopes de Almeida
Ph.D. Supervisor:	Assoc. Prof. Troels Bungaard Sørensen Aalborg University
Ph.D. Co-Supervisor 1:	Prof. Preben Mogensen Aalborg University, Nokia – Bell Labs, Denmark
Ph.D. Co-Supervisor 2:	Luis Guilherme Uzeda Garcia, Nokia – Bell Labs, France

This thesis is based on a collection of papers, and submitted as a partial fulfillment of the requirements for the degree of Doctor of Philosophy (PhD) from Aalborg University, Denmark. The papers resulting in the main body of the thesis were published in peer-reviewed journals and conferences. The present work is the outcome of three and a half years of research, in the period Sep 2015 - Jan 2019, as a Industrial PhD fellow in the Section of Wireless Communications Networks, Department of Electronic Systems, Aalborg University.

This Ph.D. has been entirely funded by INDT, within the scope of a collaboration between Instituto Tecnológico Vale, ITV and Aalborg University.

The main body of this thesis consist of the following papers:

A E. P. L. Almeida, G. Caldwell, I. Rodriguez, S. Abreu, R. D. Vieira, V. S. B. Barbosa, T. B. Sørensen, P. Mogensen, L. G. U. Garcia. "Radio Propagation in Open-pit Mines: a First Look at Measurements in the 2.6 GHz Band", *2017 IEEE 29th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, PIMRC*, October, 2017.

B E. P. L. Almeida, G. Caldwell, I. Rodriguez, R. D. Vieira, T. B. Sørensen, P. Mogensen, L. G. U. Garcia. "5G in Open-pit Mines: Considerations on Large-Scale Propagation in Sub-6 GHz Bands", *IEEE Globecom Workshops (GW Workshops)*, December, 2017.

C E. P. L. Almeida, G. Caldwell, I. Rodriguez, R. D. Vieira, T. B. Sørensen, P. Mogensen, L. G. U. Garcia. "An Empirical Study of Propagation Models for Wireless Communications in Open-pit Mines", *IEEE 87th Vehicular Technnology Conference - VTC Spring*, June, 2018.

D E. P. L. Almeida, G. Guieiro, I. Rodriguez, T. B. Sørensen, P. Mogensen, L. G. U. Garcia. "Validation of the Vale Path Loss Model for Open-pit Mines in Different Stages of Mine Exploration", *IEEE 90th Vehicular Technnology Conference - VTC Fall*, September, 2019.

E L. G. U. Garcia, E. P. L. Almeida, V. S. B. Barbosa, G. Caldwell, I. Rodriguez, H. Lima, T. B. Sørensen and P. Mogensen. "Mission Critical Mobile Broadband Communications in Open-Pit Mines", *IEEE Communications Magazine*, Vol. 54, Nr. 4, April, 2016, p.p. 62-69.

F V. S. B. Barbosa, G. Caldwell, L. G. U. Garcia, E. P. L. Almeida, I. Rodriguez, T. B. Sørensen, P. Mogensen, H. Lima. "The challenge of Wireless Connectivity to Support Intelligent Mines", *24th World Mining Congress, Mining in a World of Innovation*, October, 2016.

G E. P. L. Almeida, R. D. Vieira, Gabriel Guieiro, I. Rodriguez, R. D. Vieira, T. B. Sørensen, P. Mogensen, L. G. U. Garcia. "Deployment Strategies for the Industrial IoT: A Case Study based on Surface Mines",*IEEE 90th Vehicular Technnology Conference - VTC Fall*, September, 2019.

According to the Ministerial Order no. 1039 of August 27, 2013, regarding the PhD Degree § 12, article 4, statements from each co-author about the PhD students contribution to the above-listed papers have been provided to the PhD school for approval prior to the submission of this thesis. These co-author statements have also been presented to the PhD committee and included as a part of their assessment.

In addition to the papers included in the main body of the thesis, a patent was submitted as part of the study during the PhD.

- Patent Application 1: L. G. U. Garcia, **E. P. L. Almeida**, I. Rodriguez, V. S. B. Barbosa and G. Caldwell. "Network planning method and mine planning method", WO2017152248A1, Issue date 10 March 2016.

Furthermore, the following papers have also been co-authored, and contributed to my understanding of: how to design measurement campaigns and process the data, how to model excess shadowing in vehicular networks, system level simulations as well as the challenges of future technologies. However, since they are not part of the thesis, they have not been included in the print.

a. I. Rodriguez, E. P. L. Almeida, M. Lauridsen, D. Assefa, L. Chavarria, H. C. Nguyen, T. Sørensen, P. Mogensen. "Measurement-based Evaluation of the Impact of Large Vehicle Shadowing on V2X Communications". *European Wireless 2016; 22th European Wireless Conference*, 2016.

b. A. N. Barreto, R. D. Vieira, R. Amorim, E. P. L. Almeida, B. Faria, I. Rodriguez, " 5G – Wireless Communications for 2020", *Journal of Communications and Information Systems*, Vol. 31, Nr. 1, 2016.

c. I. Rodriguez, R. Abreu, E. P. L. Almeida, M. Lauridsen, A. Loureiro, P. Mogensen, "24 GHz cmWave Radio Propagation Through Vegetation : Suburban Tree Clutter Attenuation.", *10th European Conference on Antennas and Propagation (EuCAP)*, 2016.

d. F. Abinader, S. Choudhury, V. A. Souza Jr., F. Chaves, A. Cavalcante, E. P. L. Almeida, R. D. Vieira, E. Tuomaala, K. Doppler. "Distributed Wi-Fi Interference Coordination for Dense Deployments". *Wireless Personal Communications*, Vol. 97, Nr. 1, 2017.

e P. H. O. Gomes, G. Guieiro, E. P. L. Almeida, L. G. U. Garcia, "Evaluation of Shadowing Caused by Mining Machinery in V2I Communications.", *IEEE 29th annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2018.

f. F. Abinader, V. A. Souza Jr., S. Choudhury, F. Chaves, A. Cavalcante, E. P. L. Almeida, R. D. Vieira, E. Tuomaala, K. Doppler. "LTE/Wi-Fi Coexistence in 5 GHz ISM Spectrum: Issues, Solutions and Perspectives.". *Wireless Personal Communications*, Vol. 99, Nr. 1, 2018.

Acronyms

3GPP 3rd Generation Partnership Project

5G Fifth-generation of mobile communications

ABS Almost Blank Subframe

AoA Angle-of-Arrival

CAPEX Capital Expenditure

CCA Clear Channel Assessment

CoW Cell-on-wheels

CPS Cyber Physical Systems

CRS Coordinate Reference System

CW Continuous Wave

DL Downlink

DTM Digital Terrain Model

eICIC Enhanced Inter Cell Interference Coordination

EIRP Effective Isotropic Radiated Power

E-UTRA Evolved Universal Terrestrial Radio Access

FCC Federal Communications Commission

FDD Frequency Division Duplex

FSPL Free Space Path Loss

GIS Geografic Information Systems

GNSS Global Navigation Satellite System

GoS Grade-of-service

GPRS General Packet Radio Services

GSM Global System for Mobile communications

GTD Geometrical Theory of Diffraction

HD High Definition

HetNets Heterogeneous Networks

IIoT Industrial Internet of Things

IMPEX Implementation Expenditure

IMU Inertial Measurement Units

IoT Internet of Things

ISM Industrial, Scientific and Medical

IT Information Technology

ITU International Telecommunications Union

KPIs Key Performance Indicators

LIDAR Light Detection And Ranging

LOS Line-of-Sight

LTE Long Term Evolution

LTE-U LTE-A in Unlicensed Spectrum

LTE-A LTE-Advanced

MCPS Mobile Cyber-Physical System

MCS Modulation and Coding Scheme

MDS Mine Dispatch System

MDT Minimization of Drive Tests

ML Machine Learning

NLOS non-line-of-sight

OCC Operation Control Center

OPEX Operational Expenditure

OT Operational Technology

P25 Project 25

PER Packet Error Rate

PMR Professional Mobile Radio

ProSe Proximity-based Services

QoE Quality-of-Experience

QoS Quality-of-Service

RAN Radio Access Network

RF Radio Frequency

RMSE Root Mean Square Error

RRM Radio Resource Management

RSSI Received Signal Strength Indicator

RX Receiver

SF Shadow Fading

SINR Signal-to-interference-plus-noise-ratio

SNMP Simple Network Management Protocol

SNR Signal-to-noise-ratio

SPM Standard Propagation Model

TCO Total Cost of Ownership

TDD Time Division Duplex

TETRA Terrestrial Trunked Radio

TX Transmitter

UAV Unmanned Aerial Vehicle

UHF Ultra High Frequency

UL Uplink

URLLC Ultra-reliable Low-latency Communications

UTD Uniform Theory of Diffraction

UTM Universal Transverse Mercator

VSAT Very Small Aperture Terminal

WGS84 World Geodetic System 1984

Contents

Part I

Thesis Summary

Chapter 1 - Introduction

1.1 Background and Motivation

1.1.1 Mining Industry and Automation

Mining stretches back to prehistoric ages, and is one of the oldest human *industrial* activities. Quarrying, for example, dates back to 60,000 years ago, and evidence suggests that the oldest underground mines in the world, Chert Mines in Egypt, and Lion Cave in Eswatini, Africa, were dug around 50,000 and 40,000 years ago [1,2]. The process of extracting resources from Earth is itself deeply intertwined with homo sapiens evolution and the history of our civilization, and its importance is reflected in the name of major archaeological ages: Bronze, Stone and Iron Age [3].

In an activity that has been around for so long, it does not come as a surprise that mining methods and techniques have been subject to slow change during prehistory and most of modern history. Some important advances occurred still in the ancient times, such as hydraulic mining, which was already known by the Romans [1,4]. However, it was not until the Industrial Revolution, that the pace of innovation in this industry increased dramatically, when, following the invention of the steam engine, the demand for coal raised, and it became the fuel of the modern world. From the 18^{th} century on, this industry has been continuously driving innovation, and has become a multi-billionaire business, which employs globally more than 2.5 million people [5].

The mining industry, as other industrial segments, is currently on a transformation towards automation and integration of businesses and processes, also known as fourth industrial revolution, or Industry 4.0 [6]. Through a combination of technologies, such as Cyber Physical Systems (CPS) and Industrial Internet of Things (IIoT), the Industry 4.0 is expected to provide vertical, horizontal and end-to-end integration also in the mining business. It is envisioned that IIoT in the mining industry will consist of a collection of connected equipment that would continuously collect data, which, after processing would not only aid in optimizing the mining processes, but would

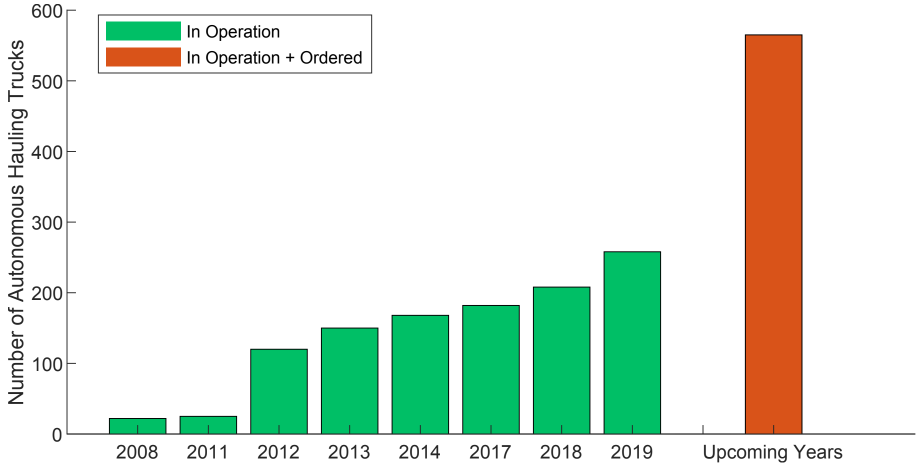


Fig. 1.1: Number of Autonomous Hauling Trucks from 2008 to 2019, and expected number for next 7 years, from [9,11–14].

also give insights for the business management [7].

Though a complete integration is still challenging in mining sites around the world [8], some technologies are already available and increasing operational efficiency and safety. For example, it is reported that an productivity increase of up to 21%, and maintenance savings of up to 17%, among other benefits, are achieved solely by replacing manual hauling trucks by autonomous ones [9,10]. The automation trend in the mining industry is shown in Fig. 1.1, which presents the number of Autonomous Hauling Trucks in operation from 2008 to 2019. The values until 2017 were taken directly from [9], and account for mines in Australia, Chile, United States. In 2017, additional autonomous trucks from the Brazilian mining company, Vale, were also considered [11]. From 2018 on, the figure considers the expected fleet growth from Vale, Rio Tinto, Fortescue and Suncor [12–14], i.e., the real number can be even higher.

As in other industries that demand flexible operations and mobility support, reliable wireless connectivity is paramount to enable automation in mines. Though wireless technologies have been used for decades in this scenario, automation will change the role of connectivity in the mining business, since the entire mine operation will *depend on* the availability of the wireless network [15,16]. Furthermore, the traffic characteristics, such as volume and criticality, are completely changed when the requirements of autonomous and tele-operated equipment are considered. For example, consider the Anglo-Australian Group Rio Tinto – the first company to implement autonomous hauling trucks through the *Mine of the Future* program – where the autonomous fleet and sensors are estimated to generate 2.4 terabytes of data every minute [12].

Therefore, it is not a surprise that the mining industry has been attracting the attention of the telecommunication industry, and it is expected to spend over US$ 2.9 billion, 1.5% out of total mining Capital Expenditure (CAPEX), on private networking in 2022 [17]. In fact, the Industry 4.0 has been a key driver to the development of the Fifth-generation of mobile communications (5G). 5G is, therefore, expected to bring major opportunities to different industries, by providing a unified communication platform and overcoming limitations of current communication technologies [18].

1.1.2 Mining Phases

Disregarding the technological choice, one central aspect in the determination of the availability of any wireless communication system is to understand the deployment scenario. In order to do so in such dynamic environment, some key aspects of the mining business are relevant.

First of all, the mining activity can be technically divided into four large phases: *Prospecting & Exploration*, *Development*, *Mining* and *Reclamation* [19]. The main objective of the first phase is to assess the viability of the project, by estimating the ore[1] reserves and quality in the chosen area, as well as the location of the deposits, by means of geological, geochemical and geophysical surveys [20]. The main objective of the *Development* phase is to enable the *Mining* phase, by building access roads, the infrastructure necessary to access resources such as power and electricity and the processing facilities. As expected, this process is repeated continuously also during the *Mining* phase, also known as *Exploitation* phase, which will actually extract the ore. Depending on the strip ratio, the ratio between the amount of ore and the amount of waste[2], the third phase will be carried on the surface or underground. Finally, the *Reclamation* phase consists in closing the mine and restoring the area to a more natural state.

In this work, the focus will be on surface, or open-pit iron ore mines, which are essentially large scale outdoor factories. Mining is, by definition, an activity that significantly changes the environment. Though these changes are continuous, especially in the *Mining* phase, they are carefully planned within a process known as *mine planning*; thus the topographic variation can actually be predicted. This process starts still in the *Exploration* phase where the samples collected in the surveys are combined with the topographic data, and are converted in a discrete model, in which each block is georeferenced, and stores information about the material (ore or waste, ore tonnage and

[1] Here, ore is defined as any material that can be extracted at a profit.

[2] Waste, on the other hand, is defined as any material that needs to be extracted but will *not* be sold at a profit.

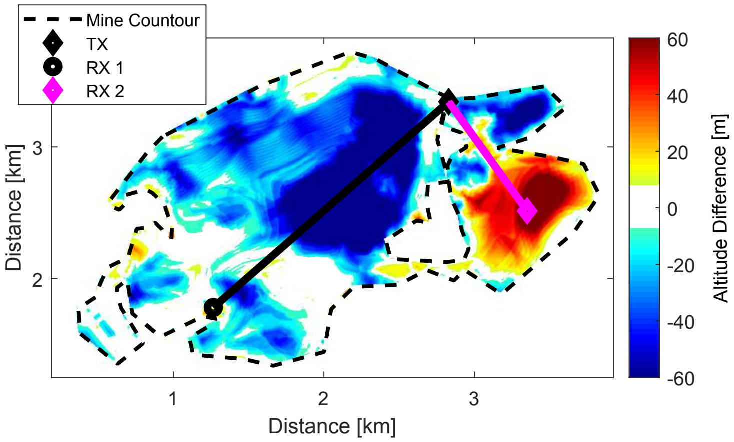


Fig. 1.2: Example of altitude variation in a mine during 5 years.

grade, and costs of mining). Once the theoretical model is built, mine planning becomes a combinatorial optimization problem, designed to determine the most profitable order to remove the blocks, constrained by the stability of the mine deployment [21]. Optimization of this problem is a key aspect of mine design and production scheduling [22].

1.1.3 Terrain Variability

To visualize the scale of the topographic change in this scenario over 5 years, Fig. 1.2 brings an example from a mine in Brazil. During this period, approximately 100 million m^3 of iron ore and waste were removed. The cool colors in the figure show the areas where this material was removed, deepening the terrain. The warm colors show areas where part of the waste was deposited.

Such dynamic scenario will certainly impact the availability and overall performance of wireless communications systems, either by forcing the relocation of the network nodes, or by changing their visibility conditions and modifying the overall interference levels of the network. In order to put the topographic variation into perspective, Fig. 1.2 also marks a position of a macro cell Transmitter (TX), and two Receiver (RX) positions. This transmitter location was chosen because it was not subject to mining activity during the evaluated period. The terrain profile variation in 2.5 years intervals considering two RX positions are shown in Fig. 1.3 and Fig. 1.4.

The first receiver, Fig. 1.3, is positioned in an area that also remained unchanged during the period. The terrain profile between this position and the TX, however, was subject to intense mining activity, which cleared the LOS between the TX and RX. Fig. 1.4, on the other hand, shows the profile between the same TX and the second RX position, located on top of the waste

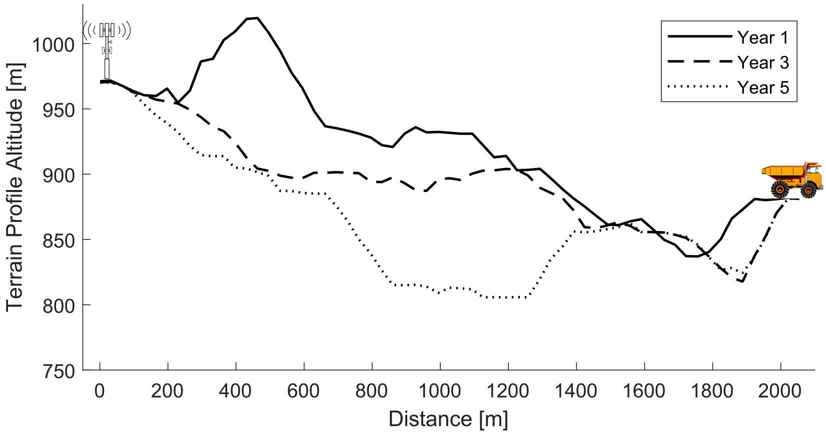


Fig. 1.3: Terrain profile variation between the TX and RX 1.

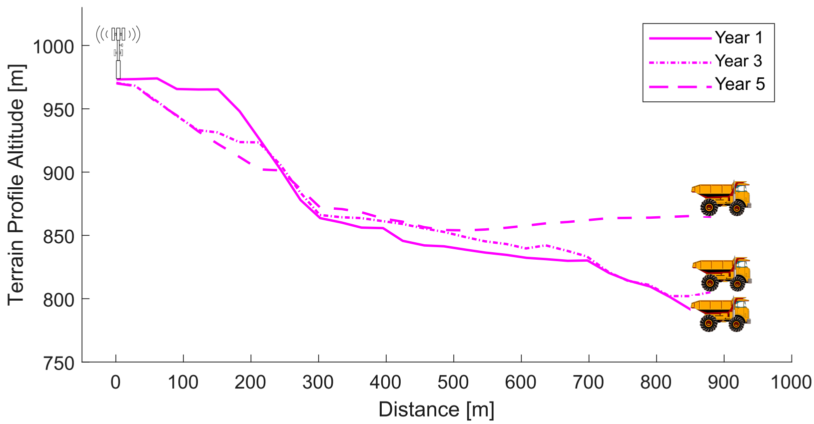


Fig. 1.4: Terrain profile variation between the TX and RX 2.

pile, which raised approximately 80 meters during the evaluated period.

The percentage of LOS in this mine, considering the 40 m tall transmitter in the previous figures, increased from 15% to 60% in this period. LOS is abundant in this scenario and tends to increase with the mining activity. This fact, combined with the requirements of initial wireless applications, such as professional voice services and fleet management, which required just a very few kbps, help to understand why, in general, wireless communications aspects in surface mines have been taken for granted [16].

1.1.4 Wireless communications and existing solutions

Historically, dedicated or purpose built communication technologies, wired or wireless, were developed to cope with different industrial requirements and scenarios [23], and this is also true for the mining industry [24]. Mining, nowadays, is a complex business based on a wide variety of applications that already require connectivity, including: mission-critical voice services, fleet management, real-time monitoring of mobile equipment telemetry, safety system monitoring and GPS-augmentation systems. However, connectivity is usually one of the least considered aspects when implementing innovative solutions in this industry [25].

Furthermore, many of the existing wireless networks were installed in order to support individual applications, and are not capable of providing the requirements of new services, or are discontinued by their manufacturers, which make it impossible to expand the network. A survey presented in [26], from 2013, identified the following distribution of wireless technologies in open-pit mines: mesh networks (27%), WiMAX (14%), WLAN (23%), 900 MHz transceivers (18%), Very Small Aperture Terminal (VSAT) (4%), Third Party Radio (9%) and Global System for Mobile communications (GSM)/General Packet Radio Services (GPRS) (5%). Terrestrial Trunked Radio (TETRA) and Project 25 (P25), usually designed for Public Safety applications [27], are also still very common in mining sites.

1.2 Scope, Objectives and Research Questions

This thesis is based on a collection of papers. It aims to create knowledge about radio-propagation in surface mines, how it is impacted by the constant topographic variation, and ultimately how it affects the performance of different network deployments.

This study hypotheses and research questions are:

- The long-term topographic variation on the mine impacts significantly the radio-propagation. These scenarios are interference limited and will be strongly affected by topographic variation over time.
  - What are the most relevant propagation mechanisms in this environment?
  - To what extent are traditional propagation models accurate to predict the path loss in open-pit mines?
  - To what extent does the antenna height impact the radio propagation?
- By integrating mine planning information with network planning information, the impact of the topographic variation on the radio propaga-

tion, and thus in the interference and performance of wireless networks, can be accurately predicted.

  - How are different network deployments affected by the topographic variation?
  - What are the most relevant/ efficient techniques to ensure the performance of wireless networks in this environment?

- The integration of mine planning information allows a cost and performance optimization of wireless networks in surface mine, which also minimizes the losses caused by network outages.
  - What are the network deployment costs associated with the terrain variability?
  - Does wireless network optimization in surface mines based on the mining planning information significantly impacts the losses caused by network outages?

In connection to these hypotheses, the objectives of this work are:

- To collect propagation data in open-pit mines: when this research project started, there was generally an absence of propagation studies in this specific environment. Therefore, one of the objectives of this work is to measure and model the path loss and shadowing in surface mines in the sub 6GHz spectrum, namely 700 MHz and 2.6 GHz frequency bands. Considering that different network deployments, i.e., macro or small cells, present different propagation characteristics, this study also aims to collect propagation data from different types of cells, and in distinct mining complexes.
- To analyze the collected data, identify the most relevant propagation mechanisms in this frequency band and environment, and to create a simple, yet accurate, path loss model, which allows predicting the path loss in different moments.
- To combine the results obtained in the propagation study with mine planning information, and calibrate simulations in order to assess the performance and costs of wireless networks in surface mines in different moments, providing deployment guidelines so that the performance is continuously met over the time.

1.3 Research Methodology

This thesis is the outcome of applied research, that can be divided in two parts: radio propagation characterization and cellular network performance assessment in surface mines.

In both parts, the research methodology consisted in addressing the hypothesis, by designing experiments that would permit to answer the research questions. In the first part, the key method is **experimental work**, which consisted of: Designing a measurement campaign, ensuring that the set of frequencies, transmitter locations, and measurement paths were representative of real deployments; conducting field trials, for testing the equipment and evaluating preliminary results. Experimental data collection and processing. This part also was done by means of analytic work, involving model synthesis and verification: based on observations of the data collection and processing phase, an empirical model was proposed. Model verification and test: the model was validated with the original data set, and verified on an independent data set.

The second part of the study was based on analytical study, by means of **simulations** to assess the impact of the topography variation on the performance, in terms of outage probability, of different network deployments. This part of the study consisted of: designing the simulation cases, considering the specific mining scenarios, traffic assumptions, assets locations and digital terrain maps. Implementing the model from the first part of the study, as well as specific features to be evaluated. Running the simulation campaigns, comparing the results with pre-validated scenarios. Collecting and evaluating the results.

1.4 Thesis Contributions and Outline

The contributions of this thesis, as presented in papers and partly in the thesis, are:

1. **Characterization of the large-scale radio-propagation in surface mines, including macro cell and small cell deployments, in the 700 MHz and 2.6 GHz frequency bands.**
2. **Identification of the main propagation mechanisms in these frequencies and scenarios and proposal of a simple propagation model.**
3. **Proposal of a framework to integrate mine planning information with network planning.**
4. **Assessment of the impact of long-term topographic variation in the performance, and costs, of different network deployments in open-pit mines.**

These contributions are presented in a collection of papers, summarized in Chapter 2 and 3. Chapter 2, provides background knowledge about radio-propagation, details and discusses the main results presented in **paper A**, **B**, **C** and **D**, as follows:

Paper A: this paper presents and analyses initial results of an extensive measurement campaign in two open-pit mines in Brazil considering the 2.6 GHz frequency band. Besides the presentation of this large measurements set, the contribution of this paper is the parametrization of statistical path loss models, considering both macro and small cell deployments. The results show that, considering macro cell deployments, the geometry of the mine impacts significantly the results. On small cell deployments, on the other hand, the results were similar and a single parametrization was proposed.

Paper B: This paper is a continuation of Paper A, and it further analyzes the results of the measurement campaign. Here, the parametrization of statistical path loss models is extended to the 700 MHz band, and values of shadowing standard deviation, autocorrelation distances and inter-frequency cross-correlation are also presented at the 700 MHz and 2.6 GHz frequency bands. The results are presented and discussed in light of their impact on the design of wireless system in surface mines.

Paper C: The motivation of this paper is to verify the accuracy of different propagation models in the prediction of path loss in surface mines. Based on the results, and on the observations from paper A and paper B, the main contribution of this model is a simple, empirical, extension of the ITU-526 model, in order to take into account the effective antenna height in the calculation of the path loss in this environment. The proposed model results in accurate predictions, with a reduced complexity when compared to the others.

Paper D: In this paper, the accuracy of the model proposed in **paper C** in different moments of mining exploration is investigated. Because the Vale model is a terrain-aware three-dimensional radio-propagation model, the hypothesis is that it should remain valid over time. We compare the accuracy of the model with two data sets, collected 20 months apart, period during which 26 million cubic-meters were moved in the mine. The collected data varies in terms of frequency, location of transmitter, measurement equipment and methodology. Furthermore, in this paper, an automated site survey methodology is presented, taking advantage of the systems and equipment already deployed in the mine set. The results show that the Vale model, proposed in **paper C** continues to provide a good fit for the path loss prediction in open-pit mines.

Chapter 3 discusses the network performance under different simulation assumptions, using the models or insights provided by the papers summarized in chapter 2, presenting and summarizing the main results of **paper E**, **F** and **G**. Additionally, this chapter includes unpublished results about the TCO of a wireless network in an open-pit mine.

Paper E: this paper introduces and discusses the challenges posed by constant topographic variation in the planning and optimization of wireless networks in surface mines, considering the automation of mining operations. A framework to integrate mine planning and network planning was proposed, taking advantage of the predictability of this scenario. An initial assessment of the performance of wireless networks in this environment was presented, using a commercial radio-planning tool.

Paper F: the motivation of this paper is to introduce the challenges of wireless network planning to the mining public and initially assess the impact of topographic variation in the performance of wireless networks in open-pit mines. Here, the impact of seven years of topographic variation in the performance of a wireless network is assessed, also considering the data rate requirements of autonomous nodes. By the time of the publication of this paper, the measurement campaign was still ongoing, so we chose to use a radio-planning tool to predict the path loss and assess the network outage.

Paper G: This paper is a continuation of paper F. Through a series of network simulations, using detailed terrain models, realistic traffic volumes and the dedicated propagation model proposed in paper C, we compare the ability of different deployment strategies and network features to meet given performance targets with existing technology.

Chapter 4 wraps up the discussions, presents the main findings of this thesis, and discusses the future research directions. Besides the papers summarized above, one patent application was filed during this study:

- Patent Application 1: L. G. U. Garcia, **E. P. L. Almeida**, I. Rodriguez, V. S. B. Barbosa and G. Caldwell. “Network planning method and mine planning method“, WO2017152248A1, Issue date 10 March 2016.

Though not exactly a research result, one of contributions of this study was the interaction with the personnel of Brucutu Mine, the first autonomous mine in Brazil, and Itabira Mining Complex. A series of technical reports were delivered within the scope of this project, as well as a tool to aid in the network planning in this specific scenario.

Chapter 2 - Radio Propagation in Open-pit mines

This chapter presents an overview of topics related to radio-propagation, which are relevant for the discussion of the papers presented in Part II of this thesis. It also includes a brief description of the studies about radio-propagation in open pit mines, which were carried on three steps. The first step was to plan the measurement campaign, testing the setup and collecting the measurements. The second step is to process the collected data, and model the radio-propagation in this scenario, and the third one comprises validating the model in an independent measurement campaign.

2.1 The Wireless Communication Channel

In the paper *A Mathematical Theory of Communication*, Claude Shannon represented a generic communication system, as a diagram block containing five parts: a source, a transmitter, a channel (noise source), a receiver and a destination, as in Fig. 2.1. The source produces a message which is then converted into suitable signals for transmission in the desired channel by the transmitter. The channel is the medium used to transmit the signal, which is then reconstructed by the receiver, by performing the inverse operation done at the transmitter. The destination is the person or thing for whom the message was intended [28].

In a wireless communication system, the radio propagation channel consists of the antennas that transmit and receive the signals, as well as the environment that interacts with the electromagnetic waves. The noise sources can be divided in additive or multiplicative sources. The first can be either generated within the receiver, such as thermal noise, or externally, such as cosmic radiation.

The multiplicative sources, or channel distortions, arise from the interactions between the transmitted signal and the environment in which it was transmitted [29]. The main mechanisms that impact propagation in a wireless communication system are *reflection, diffraction* and *scattering*. Reflection

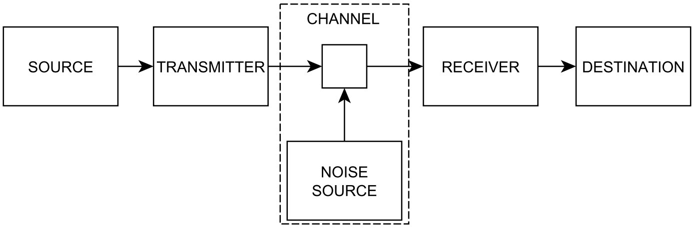


Fig. 2.1: Diagram of a generic communication system, adapted from [28].

occurs when a electromagnetic wave impinges on a smooth surface, much larger than the transmitted signal wavelength (λ). Diffraction occurs when the propagation path is obstructed by wedges (such as rooftops and hilltops). Scattering occurs when the electromagnetic wave impinges on a rough surface, or any surface whose dimensions are smaller than, or comparable to, λ [30].

These mechanisms cause fluctuations in the signal's amplitude, phase, angle of arrival and delay. These fluctuations are commonly referred as fading, and can be subdivided in two categories: large-scale and small-scale (or multipath) fading [31]. The first represents the average signal power attenuation due to motion over large areas, and can be further divided in *path loss*, local area mean signal attenuation vs distance, and *shadowing*, the variations about the mean. The second refers to variations over short distances, and also manifests in two mechanisms: time-spreading of the signal, and time-variant behavior of the channel, but these are outside the scope of this work. A representation of the large-scale fading in terms of path loss and shadowing, and small-scale fading, is shown in Fig. 2.2.

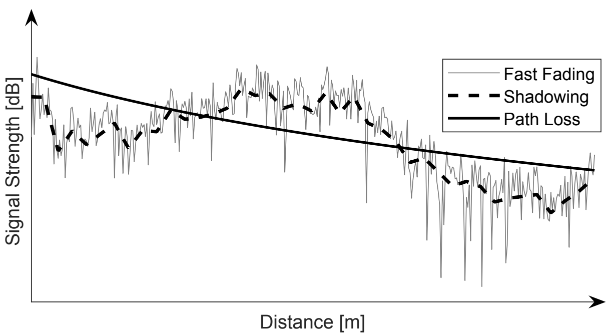


Fig. 2.2: Fading components, adapted from [29].

Neglecting the degradation due to additive noise, the received signal, $r(t)$, can be represented as [32]:

$$r(t) = r_0(t) \cdot m(t) \tag{2.1}$$

where, $r_0(t)$ is the small-scale fading component, $m(t)$ is the large-scale fading component. Eq. 2.1 is useful in the process of measuring, separating and characterizing the fading components. The large-scale fading component, for example, can be obtained from Eq. 2.1 by averaging $r(t)$ over a window of size $2L$, where the proper size of L should be between 10λ and 20λ [33]. In order to recover $r_0(t)$, Eq. 2.1 can be written in logarithmic scale as:

$$r_0(t)|_{dB} = r(t)|_{dB} - m(t)|_{dB} \tag{2.2}$$

2.2 Propagation modeling

Modeling the radio propagation channel is a fundamental step in planning, deploying and optimizing wireless networks. Channel models are usually developed considering specific deployment characteristics, such as the scenario – indoor, outdoor, urban, rural, suburban – and deployment configurations, such as point-to-point links, point-to-area with macro cell base stations, or small cell base stations. Radio wave propagation models can also be classified into large-scale propagation models, and small-scale propagation models. There are different kinds of propagation modeling, such as: empirical, deterministic and semi-deterministic models [34].

The simplest model to calculate the relationship between the transmitted power and the received power is the Free Space Path Loss (FSPL), which assumes that the region between the TX-RX pair is free of all objects, and that the atmosphere behaves as a uniform and non-absorbing medium. The received power, P_{RX} is given by the Friis Equation:

$$P_{RX}(d) = \frac{P_{TX}G_{TX}G_{RX}\lambda^2}{(4\pi)^2 d^2 L} \tag{2.3}$$

in which d is the distance between the TX-RX pair, P_{TX} is the transmitted power G_{TX} and G_{RX} are respectively the antenna gains of the TX and RX, and L is the non-propagation related system losses. The FSPL can be rewritten from Eq.2.3 in dB as:

$$PL_{FSPL}|_{dB} = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \tag{2.4}$$

In practice, since the TX and RX are not placed in open space, the effect of the terrain needs to be taken into account. Considering a flat terrain, the two ray model considers that the received signal is a combination of the direct ray and a reflected ray. The power of the reflected ray can be calculated based on λ, the antenna heights, reflection coefficient of the ground, distance between the TX-RX pair and grazing angle, which is the angle between the reflective surface and the incident ray. Under the assumption that the grazing angle is small, the received power decays with d^4 instead of d^2 as in Eq. 2.3. This theoretical model indicates that by doubling the antenna heights, the received power increases by 6 dB. This increase was not observed in practice in irregular terrains, and in [35], the author proposes a model to consider the irregularity of the terrain in the determination of the reflection points.

For most practical channels, however, the FSPL model and the two-ray model are inadequate. The choice of model usually depends on the trade-off between accuracy and computational complexity. Empirical models, for example, are derived from site specific measurement campaigns, and usually require a limited set of parameters, such as the system frequency and distance between the TX and the RX. One example of such a model is the floating-intercept model, with free linear fit to the data, given in Eq. 2.5:

$$PL_{AB}|_{dB} = 10\alpha\log_{10}(d) + \beta + X_{SF} \tag{2.5}$$

where α, the slope, is the path loss exponent, β is an offset and X_{SF} accounts for the Shadow Fading (SF). Usually, in urban environments, the path loss exponent ranges from 2 to 6 depending on the LOS conditions, and the shadow fading is usually in the range of 5-12 dB [29,36]. It is important to mention that the shadow fading is spatially correlated, since different paths may be subject to the influence of the same obstructions on the path profile.

Empirical models are useful for initial estimation of coverage margins and initial performance analysis. Multiple empirical models can be found for different kinds of scenarios. The Okumura model, for example, is one of the most quoted models in macro cell prediction and was derived from a series of measurement campaigns in different environments such as: open area, suburban area and urban area [37]. A number of correction factors were introduced to take into account the different environments, such as: effective base station antenna height, undulation height, average slope and mixed land-sea path parameter. The most important graphs derived from these measurements were then approximated by a set of formulae by Hata, and standardized by the International Telecommunications Union (ITU). This model was further extended to the 1.5 to 2 GHz frequency band, in the COST-Hata model [38]. Another example of model derived from extensive measurements campaigns is the Erceg model, which accounted for macro cell propagation in different environments: hilly terrain with moderate-to-heavy tree density, flat terrain with light tree density and hilly terrain with light tree density [39].

Despite their extensive use, empirical models have some disadvantages, such as only being able to be used over parameter ranges included in the original measurement set and not providing insights about the physical mechanisms by which propagation occurs [29]. Deterministic models, on the other hand, take into account terrain specific information and physical mechanisms in order to model the channel attenuation at the cost of higher computational complexity. They can also be divided in two groups: finite-difference models and geometric models. The first group uses electromagnetic theory to predict, in each interaction, the resulting electric field in a discretized (grid) version of the selected scenario. Different materials can be modeled by specifying distinct values of electric permittivity, magnetic permeability and electrical conductivity and, in order to have a good prediction, it is recommended that the discretization step should be at least six times smaller than λ [34]. The second group of deterministic models, the geometric, also take into account terrain specific characteristics in order to model the physical propagation mechanisms, such as reflection and diffraction. Diffraction, for example, is accounted using approaches like the Geometrical Theory of Diffraction (GTD) and Uniform Theory of Diffraction (UTD) [40,41]. The ITU recommendation P.526, for example, presents a series of models for the evaluation of the effect of diffraction on the received signal strength [42]. In geometric models, instead of discretizing the scenario like the previous models, the propagation is modeled through optical rays interacting with the environment. For each ray, the signal strength is attenuated in a specific propagation path, and the final received strength in each location takes into account the superposition of all rays. Geometric models can also be divided into ray tracing, ray launching, and dominant path models, and provide the best accuracy when compared to empirical models.

Combining the simplicity of empirical models and the accuracy of deterministic models, semi-deterministic, or semi-empirical models were proposed. As empirical models, the semi-empirical are proposed for particular scenarios, such as indoor and outdoor urban, but include deterministic characteristics of the environment to enhance the predictions. One example of such a model is the COST 231 Walfisch-Ikegami [38], which was proposed for macro cell urban propagation, combining the work from Walfisch, Bertoni and Ikegami [43,44]. The model considers the path loss in LOS and non-line-of-sight (NLOS), diffraction over the rooftops and additional reflections, which are computed taking into account the mean distance between buildings, as well as the street width and orientation. Another example is the Longley-Rice model, which computes the median path loss over irregular terrain, in the range of 20 MHz to 20 GHz [45]. The model can use detailed terrain information to compute, for example, the diffraction loss, or can estimate path-related parameters, such as the roughness indicator, based on the input type of terrain.

2.3 Radio-propagation in open-pit mines

As mentioned in Section 2.2, propagation models are usually developed considering specific deployment needs and scenario characteristics. When it comes to modeling radio-propagation in open-pit mines, there was generally an absence of empirical data. Only two references were found reporting measurement campaigns or radio propagation model in this environtment. The first, a geometric model, was proposed in [46] with a reported accuracy in the range of ±6 dB, but no data was provided, nor was the campaign described in this report. The second, published in [47], described the results from a measurement campaign in a mine in Sweden, taken with the objective of characterizing the channel impulse response. After the start of this PhD study, in [48], it was assumed that a two-ray ground reflection model could be used for LOS propagation in surface mines, while the NLOS could be modeled by Eq.2.5 with a path loss exponent of 5. The hypothesis is tested by means of measurements taken in a flat parking lot, with distances of 20 to 40 m from the vehicle, and transmitter placed 1.05 m to 2.60 m above the ground level. These conditions hardly resemble the ones in surface mines.

In order to fill this gap in the literature, the first part of this study was to plan and characterize large-scale propagation in open-pit mines. In this Section, a description of the measurement campaigns and the main results obtained in **paper A**, **paper B** and **paper C** are presented.

2.3.1 Measurement Campaign

The first activity of this study was to design a measurement campaign to explore the unique characteristics of surface mines. Surface mines differ from other natural surfaces and most man made structures. For example, though their terrain can be considered irregular as in many other scenarios considered previously in propagation models, surface mines present an altitude difference in the order of hundreds of meters in relatively short distances, in addition to the jagged discontinuities present in mine benches. Furthermore, from the topographic and lithologic perspective, each mine is unique, so the analysis shouldn't be concentrated in a single mine. Therefore, the measurement campaign was designed to:

- Investigate radio-propagation in different mines and frequencies: in order to avoid drawing conclusions for a specific mine, the campaign was performed in two operational iron-ore mining complexes located in Brazil. The complexes differ in size, depth, and also in pit characteristics, as detailed in **paper A**. The first mine complex, mine 1, contains 3 mining pits, each one resembles a hollow inverted pyramid. The second mine complex is located on a hillside. Additionally, the measurements were taken in two frequency bands: 700 MHz and 2.6 GHz.

- Capture the terrain characteristics, considering both the altitude difference between TX and RX, and the line-of-sight conditions. In the drive-tests, which took place in Spring 2017, different altitudes and LOS-NLOS conditions were explored in each deployment, as much as possible considering the available routes.

- Capture the effects of different types of network deployments. Usually, propagation over irregular terrains is modeled considering a macro cell deployment, where the macro cell is positioned in an elevated position with respect to the covered area. Despite the fact that macro cell deployments are present in different mining sites around the world, small cells are also very common in WLAN and Mesh networks, as discussed in Chapter 1. Thus, in the design of the measurement campaign, both macro cells and small cells were included.

Fig. 2.3 shows two examples of the transmitters used in the measurement campaigns. Part of the transmitters were mounted using the existing infrastructure in both mining complexes, such as the one in Fig. 2.3a. The other part of transmitters were deployed in different locations, by the use of a Cell-on-wheels (CoW) such as the one in Fig. 2.3b. These locations were chosen so that they were representative of real deployments in this scenario. For example, traffic intensive area (in terms of vehicles and data), such as the waste pile and the development area, were selected for the deployment of transmitters in the measurement campaign.

(a) Example of macro cell. **(b)** Example of small cell.

Fig. 2.3: Examples of infrastructure used in the measurement campaign.

In all cases, two Agilent signal generators, model E4438C and E4421B, were used to generate simultaneously two continuous wave signals, one at the 700 MHz band, and another in the 2.6 GHz band. The signal at the 2.6 GHz was amplified, and the signals were combined by a duplexer (Microlab BK-12D). The receiver was mounted in the vehicle also shown in Fig. 2.3b. Two different equipment were used to record the measured data: a R&S TSMW Universal Radio Network Analyzer, at a rate of 150 samples per second, and a FSH 8 Spectrum Analyzer, at a rate of 400 samples per second. The TSMW recorded data simultaneously at both frequency bands, while the FSH 8 frequency was switched from time to time. The vehicle was driven at an average speed of 35 km/h.

After an extensive testing and calibration of the setup, the drive tests occurred in Spring 2017, and in total, approximately 800 km were driven. Measurement data was collected considering 5 macro cells and 4 small cells deployments. In this environment, to take into account the irregularity of the terrain, small cells are defined as those cells deployed closer to the ground level, below the median altitude of the covered area, while a macro cell is defined as the one placed at an elevated position, above the median altitude of the covered area [49].

2.3.2 Modeling Activities

The first approach taken in modeling the propagation in surface mines was to parametrize an empirical model in the form of Eq. 2.5, in **paper A** and **paper B**. This simple statistical model captures the overall trend, the differences between mines, as well as the different deployments (macro and small cells), as shown in the path loss exponents in Tab. 2.1, and gives some insights for quick capacity estimation, link budget and network deployment.

Paper A presents a detailed analysis of the results in the 2.6 GHz band, where the path loss exponents were calculated individually for each transmitter [49]. In this paper, three groups of path loss exponents were found. The first group contained the transmitters with α close to 2. These transmitters were macro cells located in the first mining complex, that resembled an inverted pyramid. In the second group, macro cells located in the second mining complex, α was found to be between 2.7 and 2.9. In the two first groups, the percentage of LOS in the drive tests varied from 43% to 78%. The third group, small cells deployed in both mining complexes, the path loss exponent was found to be between 3 and 3.6, and the percentage of LOS varied from 19% to 54%.

Although the first two groups contain the results from macro cells, the results are quite different from one mine to the other. Furthermore, there was no clear breakpoint between LOS propagation and NLOS propagation, since it strongly depends on the topography of the mine, as well as on the

Table 2.1: Channel characterization results and their implication on system design.

	Macro Cell				Small Cell			
	Complex 1		Complex 2		LOS		NLOS	
Frequency [GHz]	0.7	2.6	0.7	2.6	0.7	2.6	0.7	2.6
Path Loss Exponent	2.3	2.1	3	2.8	2.4	3.7	2.5	3.7
β	36	62.7	8.9	29.8	30	38.5	4.9	15.9
$RMSE$ [dB]	10.7	12	10.7	12.4	7	8.7	6	7.9
σ_{SF} [dB]	10	12.3	9.5	11	8.4	7.5	7.5	7.2
SF Correlation Distance [m]	78.6	80.3	68.3	63.5	19.3	15	16.6	13.7
Inter-frequency Correlation	0.87		0.92		0.81			
LOS [%]	65.1				25.5			

geometry between TX and RX. Therefore, the approach on **paper B** was to propose two single-slope empirical models for the propagation of macro cells in surface mines, one for each mine. **Paper B** extends the analysis for the 700 MHz band as well. Considering the macro cell results from the mining complex 1, the path loss exponent was similar in different frequency bands, 2.3 and 2.0 for the 700 MHz and 2.6 GHz respectively [50]. Despite the high percentage of LOS samples, and the values of α close to the one in FSPL, the values of β equal to 36 and 62.7 dB, respectively, indicate that there is a strong influence of NLOS propagation in the results and even in LOS, propagation in this scenario might be much more complex than simple FSPL, since this difference is higher then the expected from the FSPL in both frequencies. In the second mine, the one located on a hillside, the values of α are also similar at the 700 MHz and 2.6 GHz band, 3.0 and 2.8 respectively, with β between 8.9 dB and 29.8 dB.

The results of small cells, on the other hand, were similar disregarding the mine were the small cells were located, so one dual-slope model for the propagation of small cells was proposed, to account for the propagation in LOS and NLOS conditions. In LOS, α was found to be 2.4 in the lowest frequency band, and 2.5 in the highest. The frequency dependent offset between the path loss in each frequency is 8.5 dB, compared from the 10.2 dB expected from the FSPL difference. As expected, in NLOS conditions, α was higher than in the LOS case, equal to 3.7 in both frequency bands.

The path loss exponents give important insight to network planning in this environment. As in urban scenarios, the differences between macro and small cell path loss exponents, for example, can be exploited in the planning of heterogeneous networks. However, the macro cell path loss exponent differences between the transmitters in different mines, indicates that the model cannot be generalized for macro cell propagation in surface mines. Furthermore, the high values of Root Mean Square Error (RMSE) also indicates that the model is not able to capture specific localized characteristics of the terrain.

Continuing with the results obtained in **paper A** and **paper B**, Tab. 2.1 also contains the modeling of SF. Here it is important to mention that the RMSE represents the residuals of the model, considering the entire dataset, while the SF represents the residuals considering the local average (in segments of 50m). Assuming that the shadow fading can be modeled as a zero-mean Gaussian random variable, the standard deviation σ_{SF}, was found to be in the range of 9.5 to 12.3 dB for macro cells. In this case, higher values of SF were observed in the upper frequency band, as reported in [51], and recommeded in [52] . SF standard deviation in small cells, was in the range of 7.2 and 8.4 dB. The σ_{SF} is important in the calculation of link budgets and system margins, higher values of standard deviation on higher fading margins to achieve the same level of system availability.

Besides the standard deviation, the correlation distance of the shadowing was also characterized in **paper B**. It is calculated as the distance where the shadowing autocorrelation reaches the value of $1/e$. And the results are consistent with the exponentially decaying model proposed by Gudmundson, and in use by 3rd Generation Partnership Project (3GPP) [53,54]. The macro cell results are between those recommended for macro cells deployed in urban environment (UMa), 50 m, and those recommended for rural areas (RMa), 120 m, both in NLOS. The correlation distance of small cells in mine environments, between 13.7 m and 19.3, are slightly higher than those in urban scenarios (UMi), where the distances are between 10 and 13 m. Proper modeling of shadowing correlation distance is important for accurate performance evaluation, power control procedures and for the parametrization of handover. Finally, taking advantage of the synchronized measurements on both frequency bands, the inter-frequency correlation of the shadowing in the 700 MHz and 2.6 GHz bands was also characterized. In all cases, we found a correlation coefficient higher than 0.8. The high correlation limits the potential benefits in terms of availability brought by inter-frequency multi-connectivity techniques, as discussed in [55], and implies that higher frequency bands need to be considered in order to combat the negative impact of shadowing.

As mentioned earlier in this chapter, the choice of a given propagation modeling approach is generally a trade-off between the accuracy and the computational complexity, which is usually related to the level of detail ex-

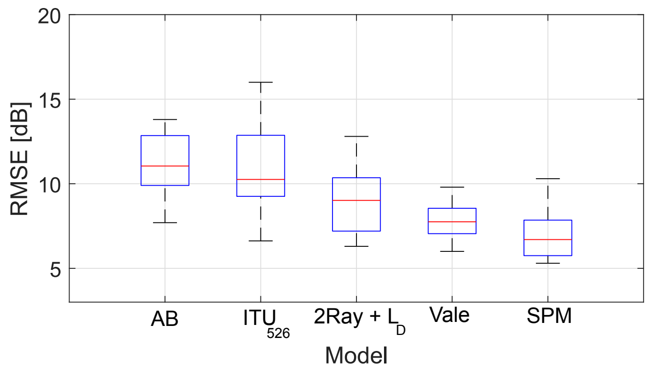


Fig. 2.4: RMSE of different propagation models and path loss estimates from the measurements.

tracted from the scenario and considered in the predictions. Although the models detailed in Tab. 2.1 are useful to provide insights about the propagation in surface mines, the high values of RMSE between the empirical models and the path loss estimated from the measurements, indicate that this approach is far too simple to describe propagation in this scenario.

Therefore, the next step in this study, in **paper C**, was to investigate models – available in radio planning tools – that could be suitable for predicting the radio propagation in this scenario. Since none of the models was actually developed or reportedly used in this environment before, a wide range of models were tested: ITU-526, Okumura Hata, Longley Rice, Erceg-Greenstein, ITU-1546 and Standard Propagation Model (SPM) [56,57]. In **paper C**, the predictions were done in the radio planning tool Atoll [58].

The RMSE of the predictions of some of the models evaluated in **paper C** (AB, ITU and SPM) are summarized in Fig. 2.4. In this figure, the median is represented in red. In blue, the upper and the lower quartiles are shown, containing 50% of the samples. The upper and lower whiskers, which mark the highest and lowest values respectively, are shown in black. From the original models in the paper, the best fit was the one from the SPM model, followed by the ITU-526 model. Both models consider diffraction losses in the path loss computation, indicating that diffraction is a important propagation mechanism in this scenario. To evaluate the effect of ground reflection, a prediction with the two ray model was done in the software WinProp [59], also considering additional term to account for diffraction loss. Though the two-ray model is able to slightly decrease the RMSE, when compared with the ITU model – that considers only diffraction – the values are still as high as 13 dB.

The SPM model is detailed in **paper C**, and requires the calibration of 7 free parameters, which adjust factors such as distance, diffraction losses, effective antenna heights of the TX and RX, among others. The calibration process in Atoll is basically a curve fitting exercise, which makes it harder to understand the physical meaning of the model. Motivated by this, and by the fact that both the ITU-526 model and the SPM model include the effect of diffraction, in **paper D**, an empirical model, named *Vale* is proposed. The model is an extension of the ITU-526, or simplification of the *SPM* model, which combines the effect of FSPL and diffraction, by also including a term to take into account the effective antenna height, H_{eff}:

$$PL_{VALE} = FSPL + L_D + k \times \log_{10}(H_{eff}) \tag{2.6}$$

where L_D is the diffraction loss and k is a calibration constant. The results in the figure consider the same value of k, $k = 5$ for all the transmitters. Even with a simplified calculation of the diffraction loss, considering a knife-edge diffraction, the results are very close to the ones obtained by the SPM model. It is important to mention that in this scenario, even small cells are subject to a significant height variation, as detailed in **Paper E**.

2.3.3 Validation of the proposed model

The objective of the study presented in this chapter was to characterize large-scale propagation in surface mines, so that the path loss could be accurately predicted in different moments of the mine development. The main assumption of this study is that the model in **paper C** would be accurate even considering the future mining activity, if detailed information about the terrain is available.

In order to confirm this assumption, in November 2018, one and a half years after the original measurement campaign, an independent measurement campaign was performed in Brucutu mine, using a radio-monitoring tool, described in [60]. The tool was developed to monitor the Received Signal Strength Indicator (RSSI) of a WiMAX network, operating at the 1.5GHz band, in 10 MHz bandwidth, which supports part of the actual autonomous operation of the vehicles in this mine. The systems uses the Simple Network Management Protocol (SNMP) to query network information, such as RSSI, Signal-to-noise-ratio (SNR) and host name, with a periodicity of 1 Hz, from different network users. In this study, the RSSI of hauling trucks, bulldozers and trucks, whose heights varies from 2 to 7.1 meters above the ground level, were monitored for a period of 2 hours. Since these vehicles were in their normal operation in the mine, there was no control over their routes. In this second Drive Test, only 13% of the collected samples corresponded to NLOS. The complete description of this study, as well as the results are detailed in **paper D**, and repeated below for convenience.

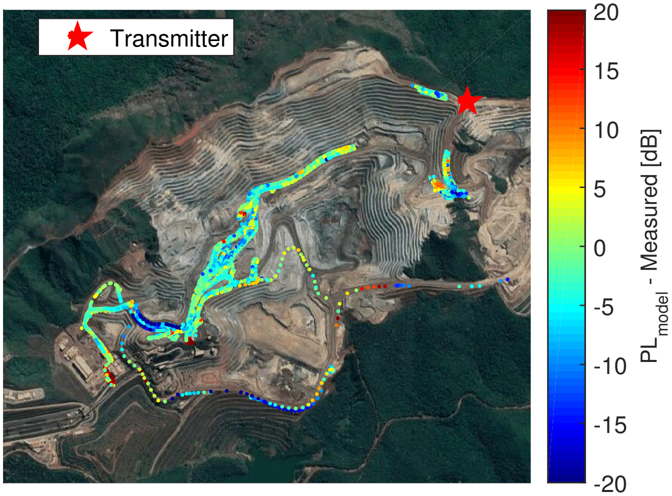
A comparison of the path loss estimated from these measurements and the model detailed in Eq. 2.6 is presented in Fig. 2.5, considering all the data available from the 3 types of vehicles. The values of RMSE were, respectively, 6.9 dB, 5.12 dB and 6.8 dB, for hauling trucks, bulldozers and trucks. Fig. 2.5a shows the difference between the value predicted by the proposed model and the estimated from the measurements, in the map. The figure shows the match between the predicted results and the estimated path loss in most locations within the measurement path.

Fig. 2.5b shows the path loss as a function of the distance driven in a route. In blue, the path loss estimated from the measured data. In black, the results from the predicted model (Eq. 2.6) and in red, the results with the model in Tab. 2.1, with a correction to account for the difference in the FSPL between the frequencies in the model, and 1.5 GHz. This figure shows that the accuracy of the model is maintained for both LOS and NLOS conditions.

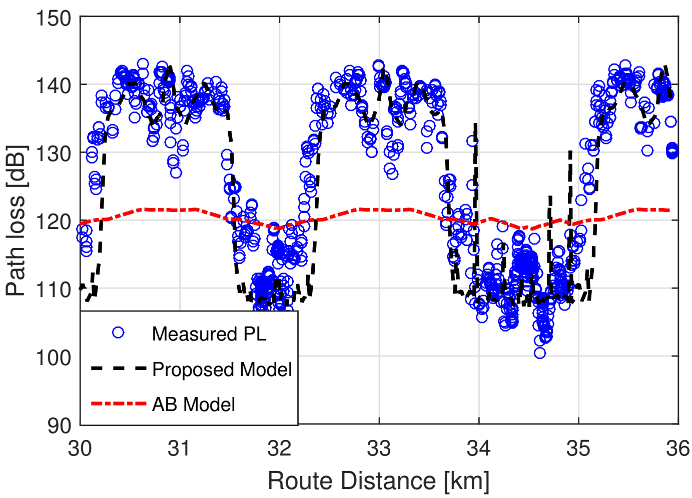
These results, collected in a different stage of the mine development, in a different frequency, and with a different transmitter location, show that the model is able to capture different mine conditions in the calculation of path loss.

2.4 Summary

In this Chapter, a review of topics related to radio-propagation was presented, and the study related to radio propagation in open-pit mine was detailed. A set of empirical path loss models, and a simple semi-deterministic model were proposed. The accuracy of the latter was verified in different mines, frequency bands and stages of mine development. In the next Chapter, this model will be used in network simulations in order to assess the performance of different wireless networks deployments in this scenario.



(a)



(b)

Fig. 2.5: Results of the independent measurement campaign. a) Difference between the value predicted by the proposed model, and the measurements. b) Path loss as a function of the driven distance.

Chapter 3 - Radio Network Performance Evaluation and Deployment Insights

This chapter presents an overview of topics related to radio-network planning in open-pit mines, which are relevant for the comprehension of **paper E**, **paper F** and **paper G**. The studies presented in this part of the thesis were based on network simulations, described in Appendix A. This chapter presents, therefore, in Section 3.1 the traffic assumptions, based on the characteristic of the autonomous equipment present in mines, and the scenario characteristics, focusing on the effect of terrain variability on the large scale radio-propagation. Section 3.2 details the contributions of each one of the papers, in terms of radio network planning and performance insights. Section 3.3 details the still unpublished study on TCO.

3.1 Traffic assumptions and Scenario

3.1.1 Mining internet of things

Paper E and **F** present a brief discussion about the different levels of automation in the mining industry which is extended in this Section. According to [61], the interaction between the human operator and mining equipment can be divided in three categories: lower level automation, mid level automation and full automation.

Disregarding the level of automation, autonomous or semi-autonomous machines need to comply with a number of safety requirements in order to operate: i.e. they should always operate in a *safe state*. The document ISO/DIS 17757 defines a safe state as: *condition, whether or not an autonomous machine or semi-autonomous machine is operating or is shut down, such that a hazardous safety, health and environment event is at an acceptable level of risk based on a risk assessment*. This document also defines the safety requirements for machines used in earth-moving and mining operations, and their systems, which consider, among others [62]:

- Safety requirements: all-stop and remote stop systems, audible alarms and visual indicators of operational mode;
- Positioning and orientation, such as: Global Navigation Satellite System (GNSS), sensors, radars, Inertial Measurement Units (IMU) or Light Detection And Ranging (LIDAR).
- Digital Terrain Model (DTM): it is optional, but when it is used for maintaining a safe state, it should be ensured that the maps are up-to-date.
- Perception: includes the ability of the system to interact with the operational environment through the installed sensors.
- Navigation System: use absolute or relative position of the autonomous system to navigate a predetermined or dynamic path.

The level of automation depends on the kind of activity performed. For example, as mentioned in Chapter 1, autonomous hauling trucks, such as the ones from Kommatsu and Carterpillar, fall into the *fully autonomous* category [63,64]. Drills and bulldozers, on the other hand, still operate with different levels of automation, requiring human control in the process. Furthermore, auxiliary machinery such as light vehicles and water trucks, all with lower level automation, are also present in autonomous mines.

The different levels of automation lead to distinct data-rate requirements. For example, in **paper F**, it was estimated that fully autonomous equipment would require ca. 500 kbps in the uplink to operate, while semi autonomous equipment would require ca 3500 kbps to support video transmissions. A more realistic estimate, based on the equipment in operation in autonomous mines, is shown in **paper G**. The estimate is that fully autonomous equipment and auxiliary machinery will require approximately 200 kpbs in the uplink, to exchange positioning information with the network, and semi-autonomous equipment will require betwen 2000 and 3200 kbps, depending on the purpose of the video transmission: control the equipment, or monitor it.

In an autonomous mining environment, different equipment with different levels of automation interact. And this interaction is controlled by the wireless network. In general, due to the combination of positioning techniques, awareness modules, exclusion zones and all-stop systems, these autonomous systems are able to cope with latency in the order of tens to hundreds of milliseconds. In case of tele-operated equipment, which require audio and video feedback to the remote operator, the operator can cope with latency between 200 and 300 ms, maintaining, in some cases, a comparable performance between the on board and remote operation [65]. These latency values can be achieved with WiMax or LTE technologies [66,67]. All the simulations presented in this chapter assume an LTE network.

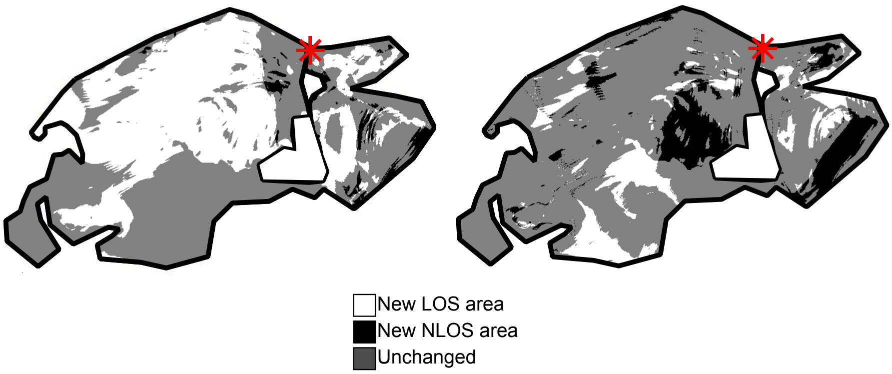
However, it is important to note that the latency tolerance depends on the risk assessment, as stated in the ISO standard. The maximum acceptable duration of a loss of communications depends on the machine speed, current operating environment and risk assessment. In case of a long communication loss, the only way to maintain the system in a safe state is to shut down the equipment until recovery, and this might impact all other equipment in operation in the region. Additionally, despite the number of protection layers, and safety requirements, accidents may still happen due to network outages. A practical example occurred in February, 2019 in a mine in the Pilbara region, where an autonomous truck crashed into a parked truck due to the Wi-Fi network outage [68].

3.1.2 Simulation scenario and models

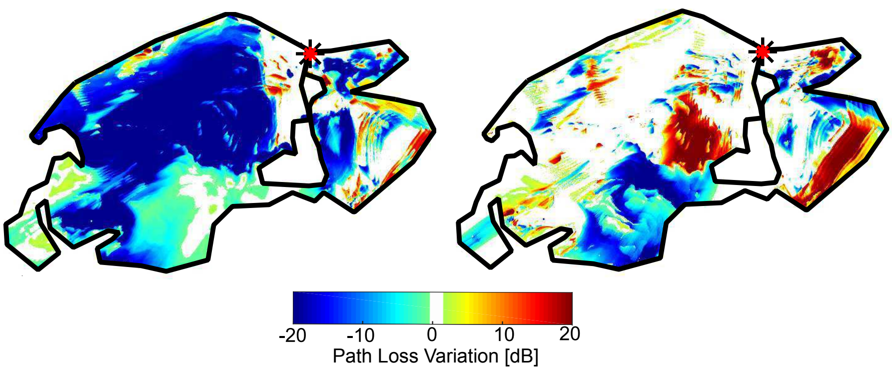
The results presented in **Paper E**, **F** and **G**, as well as the data processing of the measurements considered high resolution DTMs, obtained from the operational areas of Vale, within the scope of this industrial partnership. The chosen scenario is the second mining complex used in the measurement campaign detailed in the previous chapter, due to the availability of maps in different moments. In the remainder of this section, some details of these maps are presented, as well as an example of the influence of the terrain variability on the large-scale radio propagation.

The original DTM had resolutions of 1 m $\times$ 1 m or 2 m $\times$ 2 m, a cartesian Coordinate Reference System (CRS), considering either the South American Datum 69 (SAD69) or the *Sistema de Referência Geocêntrico para as Américas* (SIRGAS 2000) Datum. Both datums are used in the Universal Transverse Mercator (UTM) zone 23K, which includes the areas of the mining complexes where the measurement campaign took place. A reprojection of these CRS to consider the World Geodetic System 1984 (WGS84) datum, widely used by GNSS systems, was necessary, so that the data obtained from the measurement setup was consistent to the DTM data. These reprojections were done using the software QGIS, an open source Geografic Information Systems (GIS) [69].

These maps allowed not only to highlight the differences between the surface mining scenario and urban scenarios, extensively explored in studies about radio-network planning and performance, but also to evaluate the terrain variation over a given period of time, and it's effect on radio-propagation. This variation is explored in the simulations presented in **paper F** and **paper G**. One example is shown in Fig 3.1, for the same mine depicted in Fig. 1.2, for a macro cell in the 700 MHz band. The figures show the variation of LOS and path loss in two segments of 2.5 years. The path loss results were obtained through a series of predictions in Matlab, using the model proposed in Eq. 2.6. Though the development of each mine is unique, as well as its topography, this example helps understanding the specific conditions that can be explored in radio planning and optimization in surface mines.



(a) LOS variation. Left: from year 1 to year 3. Right: from year 3 to year 5.



(b) Path loss variation. Left: from year 1 to year 3. Right: from year 3 to year 5.

Fig. 3.1: Impact of terrain variation on LOS and path loss, over 5 years of mining activity.

Fig. 3.1a shows the variation of LOS from year 1 to year 3, and from year 3 to year 5. Considering this macro cell position, the percentage of LOS increased significantly from year 1 to 3 – from 15% to 59% – while it was kept almost unaltered during the subsequent period – from 59% to 60%, though LOS conditions in specific locations within the mine have changed. This variation of LOS conditions is one specificity of this scenario that influences on the performance of the radio network and can be explored in the radio planning, as it will be discussed in Section 3.2. The predominance of LOS, for example, motivated the investigation of the use of beamforming in **paper G**. Additionally, this characteristic is also important for the backhaul. Due to the mining activity and consequent terrain variability, the only option for small cells is wireless backhaul links, which can easily be deployed and re-deployed providing the necessary flexibility in this scenario. Though there are NLOS point-to-multi point backhaul solutions, certainly LOS conditions are desirable. Macro cells, on the other hand, depending on their location, have also the option to be connected through fiber, which provides higher capacity. A discussion of the different types of backhaul links is in [70].

Continuing with the evaluation of Fig. 3.1, the variation of LOS impacted on the path loss, which decreased up to 20 dB in most of the area within the mine from year 1 to year 3, as shown in the left plot in Fig. 3.1b. This was due to a removal of a hill that was obstructing the signal transmitted from this macro cell. In a single macro-cell deployment, as in this case, the removal of this hill would indicate an increase of radio-network coverage. In a multi-cell environment, however, this fact would potentially decrease of the SINR, degrading the performance of the network. In the subsequent years, in the right plot in Fig. 3.1a and Fig. 3.1b, despite the fact that the volume of moved terrain was similar, the change in propagation conditions were not, being concentrated in specific areas within the mine. In order to continuously guarantee a given Grade-of-service (GoS), the effects of the mining activity on the radio-propagation conditions need to be predicted, and considered in radio-network planning and optimization.

3.2 Radio network planning in surface mines

The last sections described the nodes that are in operation in an autonomous mine, as well as the expected variation of the scenario due to the mining activity. One of the objectives of this thesis is to investigate and understand how to continuously meet the communication requirements, considering the scenario variability and the transformation brought to the mining industry by automation. This investigation was done by means of simulations, which are presented in **paper E**, **paper F** and **paper G**.

It is important to notice, however, that the study presented in **paper E** and **paper F** were conducted before, or simultaneously to, the activities and studies presented in Chapter 2. So, despite their relevance to understanding the environment and challenges associated to the deployment of wireless networks in surface mines, it lacked the insights provided by the measurement campaign, modeling activities and interaction with the mining personnel. Furthermore, from a radio network planning perspective, the background from urban scenarios influenced the definition of traffic assumptions, the network deployments and conclusions reached in these papers. These studies are presented in Section 3.2.1.

The second part of the research was, on the other hand, conducted after the conclusion of the studies in Chapter 2, and consider not only a dedicated propagation model, insights from the impact of terrain variation on the path loss, but also other lessons learned during the Ph.D. In the remainder of this chapter, the results and conclusions of each stage of the research are presented. Finally, unpublished results about the costs associated with the deployments discussed in this part of the study are also presented. This discussion is presented in Sections 3.2.2 and 3.3.

3.2.1 Initial radio-planning insights

The main objective of **paper E** and **paper F** was to introduce the discussion of broadband connectivity to support autonomous equipment in open-pit mines.

All the results presented in these two papers were done with the radio-planning software Atoll [58], and considered specific network deployments. The calibration of the SPM model was done with RSSI data collected from a WiMax network in a drive test of one macro cell and one small cell, as mentioned in **paper E**.

Paper E targeted the wireless communications community, with the intent of presenting the specificity of this environment, also highlighting the paradigm shift that automation brings to wireless network planning in this industry. It introduced important concepts of the surface mining industry, such as mine planning and the different stages of mining development, as well as a view of the narrowband and wideband wireless network technologies which are common in mining sites. In line with the discussions presented in the last section, which showed that the topographic variation in the mine has an impact on the radio-propagation conditions, this paper proposes an integration framework between mine planning and network planning, to support the continuous radio-network planning and optimization. This framework also inspired a network and mine planning method which was filed as a patent [71], and would consist of:

- An awareness module: which would act as an interface between the real-world environment and the framework. This would be a module for, for example, collecting and analyzing radio-propagation measurements and Key Performance Indicators (KPIs) from the radio-network and information about mine planning, such as planned volume and location of extracted material, and mine maps.

- An unified database: which would store the information processed by the awareness module, as the location of users, network conditions, and would interact with the processing module, receiving parameters to be optimized by the network.

- A processing module: which would combine the information about the location of users, KPIs, future mining plans, and make decisions towards radio-network planning and optimization, so that the requirements are continuously served by the network.

- A delivery module: would deliver the necessary actions to optimize the network, such as the number and location of network nodes, their configuration, and a prediction of the network TCO.

Paper E was the first published within this Ph.D., and this framework to integrate mine planing and network planning served, to a large extent, as a guide to the activities and studies presented in this thesis. For example, the measurement campaign and processing described in **paper A**, **paper B**, **paper C** and **paper D**, comprise some of the activities necessary for the awareness and processing module. The analysis of the influence of topographic change on the radio-propagation conditions, such as LOS and path loss, described in the example in Section 3.1.2, and their consequences on the radio network coverage and capacity, which will be explored in **paper F** and **paper G** would be part of the processing module. The actions to optimize the network performance, such as increasing the number of nodes, or updating the network features were also explored in **paper G**. Finally, the TCO analysis part of the delivery module is left for Section 3.3.

Apart from the proposal of this framework, this paper also shows the potential gains of the use of small cells in autonomous mining environments, to increase the capacity. By using Monte Carlo simulations available in Atoll, briefly detailed in Appendix A, and assuming HD transmissions for 30 users uniformly distributed within the mining area, initial capacity evaluations were provided. The network deployment considered an LTE 5 MHz Frequency Division Duplex (FDD) network, with a single macro cell in 700 MHz and small cells in 2600 MHz. The assumption is that each small cell consisted of 3 sectors, and was placed 20 m above the ground level. By placing six small cells on strategic locations where the traffic is expected to be located (such as waste piles, crusher, and closer to the roads), up to 80% of the traffic was offloaded to small cells, and the requirements could be served by the network.

This observation will be further explored in **paper F** and **paper G**. As mentioned at the beginning of this chapter, some of the assumptions of the simulations presented in this work were inherited from the urban scenario radio-network planning mindset. For example, there are limitations on the height and power of small cells deployed in mines. Small cells in this scenario are nomadic, due to the mining activity, with limited access to power sources. Therefore, the assumption of 3 sectors and 20 m height antennas are unrealistic in real deployments. Additionally, the data rates and the distribution of nodes was not consistent with the reality of the mine. These aspects were partially addressed in **paper F** and fully addressed in **paper G**.

Paper F targeted the mining industry audience, and its purpose was to introduce concepts of wireless communications, such as coverage and capacity, and discuss the communication requirements of autonomous equipment also addressing the topographic variation. This discussion is important because there is still a belief that maximizing the LOS and increasing the transmit power is the best approach to enhance the radio-network performance in this industry, without evaluating the potential SINR degradation and the channel access mechanisms of different technologies.

This is clear, for example, in the work presented in [72], published in 2018, which proposed an algorithm to support initial transmitter layout design in open-pit mines, based solely on the LOS probability, referred to as Fresnel Index. For a given combination of candidate positions, the one that provides LOS conditions in a larger area is chosen. While this might be an adequate deployment strategy if there are sufficient non-overlapping channels or if interference mitigation techniques are used, this would not be the best approach when the different nodes contend for channel access, such as in the depicted case of WLANs. Besides the degradation of SINR, the system would be influenced by the Clear Channel Assessment (CCA) procedure, whose performance decreases with the increase in the number of nodes [73,74]. These aspects need to be considered when choosing the radio technology and planning the wireless network.

Therefore, in **paper F**, an initial evaluation of an LTE network performance is presented. This choice of technology was made due to different reasons. First, LTE is a technology that uses licensed spectrum, though it can also benefit from aggregated channels in unlicensed spectrum. Second, but derived from the first observation, LTE it is a non-contention based technology, where the network has full control of the resources can adjust the scheduling based on the traffic priorities. These two facts give some performance predictability which is paramount to serve the automation requirements. Additionally, LTE, and more recently 5G, are evolving to support the needs of mission-critical and industrial applications [75]. Finally, since the start of this Ph.D. LTE networks have been deployed in mines worldwide [76–78].

Paper F also discusses the data-rate requirements of a Conventional Mine, which requires support for narrowband applications such as telemetry and dispatch, when compared to the requirements of an Intelligent Mine, with support for autonomous nodes and the data rates specified in Section 3.1. In this specific case, the increase of the required traffic would be in the order of 44%. Additionally, in this paper, the users are placed within specific areas of the mine, such as roads, waste dump, crusher and development areas, which are close to the real locations of the users in a mine. The topographic change on the course of seven years of mining activity is also briefly discussed in this paper, and special attention is given for the paradigm shift of planning the radio network to support a conventional mine and an intelligent mine.

The study starts with the assumption of an omnidirectional macro cell transmitter placed in an elevated position, in the center of the mine, which corresponded to the real location of the macro cell. The topographic change in the period led to an increase of LOS and coverage of the LTE network. If a conventional mine was to be considered, this increase of coverage would be sufficient to continue providing the required capacity, and no changes to the wireless network would be required. However, with the introduction of autonomous nodes, if the network is left unchanged, the percentage of satisfied users would be less than 40%. Different strategies for increasing the capacity of the network are discussed, such as modifying the position of the macro cell, adding more spectrum to the network and reusing the spectrum by introducing small cells.

The paper only presents one set of results, which comprises: the modification of the macro cell to a location on the contour of the mine and the use of four small cells, deployed in the same frequency band as the macro transmitter. Moving the macro cell is not optimal, due to the very high costs associated with disassembling the structure, moving it to a new location and all the costs associated with the required civil works to rebuild it. Despite the high costs of the re-deployment, which will be estimated on Section 3.3, sometimes the action is necessary due to the need to mine the area in which the tower is placed. Therefore, choosing a location that minimizes the need for re-deploying macro cells is advised. As in **paper E**, this paper also considers 20 m tall, 3 sectors small cells. Additionally, the in-band small cell deployment is motivated by the high costs associated with obtaining access to more spectrum. The results show that with this new deployment, the percentage of satisfied users increases from 37.8% to 98.3%. Even in in-band deployments, the use of a heterogeneous network is interesting in this scenario, despite the outage levels still being above the expected for reliable applications.

3.2.2 Radio-network deployment strategies

The second moment of the investigation of radio-network performance and deployment strategies in surface mines was after the measurement campaign described in Section 3.2.1, and interaction with the mining personnel. Similar to the study in the last section, this study also considers two distinct moments of mining exploration, 5 years apart. This period was chosen due to the significant topographic variation. This study is published in **paper G**. There are some key differences in the simulators, simulation assumptions, and objectives of this paper.

First, a new simulator was used. While the simulations from Section 3.2.1 used a commercially available planning tool, the ones presented in this chapter used a dedicated network simulator from past Ph.D. studies carried out in Aalborg University [79,80]. Besides allowing the use of the proposed path loss model, this simulator also permitted the development and the evaluation of new features. A brief description of this simulator and the implementation of DL beamforming is given in Appendix A.

Second, as mentioned earlier in this chapter, the traffic assumptions were different from paper F. Besides considering the traffic of autonomous equipment, it is also necessary to consider the traffic from all other equipment in the mine, such as water trucks and small support vehicles. In real-world autonomous systems for the mining environment, all nodes need to be visible for the controlling system. An example of such a system is the Caterpillar Command for Hauling [63], which defines autonomous operation zones, in which access is controlled. All vehicles, autonomous or not that operate in this zone needs: to be equipped with the controlling software, positioning systems, and proximity detection, to be able to capture and submit terrain survey data.

Third, real-world limitations of small cells deployed in surface mines were also considered, as mentioned in the last section. The assumption is simple omnidirectional small cells, 5 m above the ground level. Additionally, the macro cells were placed in the contour of the mine, where it wouldn't be necessary to move them in the evaluated period, which in this case, comprised ten years of mining activity. Finally, a Time Division Duplex (TDD) deployment is considered, to cope with the traffic imbalance between Downlink (DL) and Uplink (UL) required data rates.

Finally, the objectives of **paper G** were to understand the influence of the topographic variation on the performance of the network, and to evaluate the performance of different deployment strategies, such as: macro cells only, heterogeneous networks with in-band and out-of-band small cells, and as well as the use of interference mitigation techniques. In all scenarios, the deployment of small cells considered the same location obtained for the in-band heterogeneous case, which is given in Appendix A.

Below, some of the main findings of this study are given:

- **Macro cell deployments:** can benefit from the LOS propagation, which is abundant in this scenario. The results show that single macro-cell deployments are more affected by the mining activity, which modifies the network coverage and capacity. Multiple macro cells can reduce the DL and UL outage significantly, compared to the single macro cell case. For example, with 2 macro cells the outage in the DL is reduced from 20% to approximately 3%, despite the SINR degradation. The topographic variation still affects the performance of the network, not only by changing LOS, path loss, and consequently the SINR but also by changing the distribution of the users. In the example in the paper, the mining area is significantly expanded over the years. Despite the traffic increase during the evaluated period and degradation in the SINR, the outage in year 10 is reduced. This reduction occurs because, due to the removal of the obstacle between the two macro cells, the traffic could be better balanced between the two macro cells. It is, however, tricky to find positions that will not be impacted by the mining activity at some point. Therefore, it is advised to place the macro cells in the contour of the mine, if possible.

Additionally, if the coverage is continuously guaranteed, the impact of the topographic variation in the outage of the network is reduced, and the network can even benefit from the mining activity. In the example, three *future proof* locations were found, but the performance of the system is actually degraded with the introduction of the third macro cell. As in urban scenarios [81,82], the optimization of the antenna tilt also plays a very important role in the deployment of macro cells a surface mine. This becomes even more important when considering the contrast between the altitude of macro cells and the users. A simple tilt variation from 4° to 12° can lead to a decrease in the outage of more than 3%, in the case with two macro cells. Additionally, if sufficient spectrum is available, for example 15 MHz or 20 MHz TDD, the outage can be further reduced in this scenario, but not without costs.

- **Heterogenous deployments:** three different cases were explored.
  - The first one comprised **in-band heterogeneous deployments**, in the 2.6 GHz band, to reuse the spectrum. The introduction of in-band small cells degrades the SINR, shifting the curve as much as 10 dB, as shown in Fig. 3.2, for both time periods explored in **paper G**[1]. This also explains the outage degradation observed in the UL when compared to the 2 macro cells cases: with 5 macro cells, more users transmit on the UL, increasing the interference levels. To compensate for the SINR degradation, it is important to guarantee that sufficient capacity is introduced in the network, which occurs with the deployment of extra small cells. In this scenario, the DL and UL outage is reduced with the increase of small cells, but this reduction is modest: the outage in the DL is reduced from approximately 3% (5 small cells) to 1% (11 small

[1]The SINR degradation in Fig. 3.2 is different from the one shown in paper G. In the former, the SINR is calculated only at the users locations, in 500 realizations. In the latter, the SINR values are shown for all locations within the mining contour.

cells).

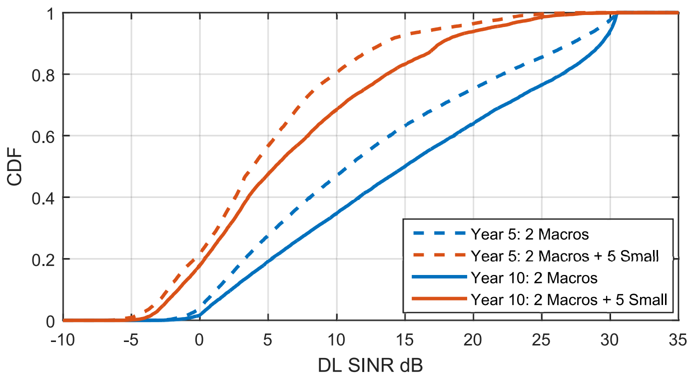


Fig. 3.2: DL SINR degradation with the introduction of in-band small cells, in two different moments of mine operation.

– The second case consisted of an **out-of-band heterogeneous deployments**. The assumption is that the 700 MHz band would be used by the macro cell layer, and the 2.6 GHz band would be used by the small cell layer. As in the macro cell case, increasing the available spectrum reduces the DL and UL outage significantly, and levels below 1% are achieved already with 5 small cells. As commented before, the drawback with this alternative is the costs, and difficulty of acquiring licensed spectrum in this industry, which would be hardly compensated by the decrease of the number of small cells.

– The third and final case consisted of an **in-band heterogeneous deployment, with interference mitigation techniques**. In Fig. 3.2, it was shown that introducing small cells significantly degrade the SINR and that the outage reduction is limited with this approach. Therefore, the last deployment comprised the combination of heterogeneous networks and interference mitigation techniques: time domain Enhanced Inter Cell Interference Coordination (eICIC), by the use of Almost Blank Subframe (ABS), and beamforming. In ABS, the use of DL subframes is coordinated between the macro cell layer, and the small cell layer so that the interference is reduced. In beamforming, the macro cell beam is steered to the location of specific users, also reducing the interference to users camped in different cells. The use of beamforming is especially beneficial in this scenario, due to the high percentage of LOS. Additionally, from the measurement data and modeling activities from Chapter 2 it is clear that the direct path is the main contributor in the signal propagation in the investigated mines. One simplification in the simulations was, therefore, to consider a perfect Angle-of-Arrival (AoA) estimation. These two techniques, ABS and beamforming alone, were not able to further enhance the performance when compared to the in-band heterogeneous deployment case. First, the use of ABS was capable of significantly increasing the SINR. However, the increase of the SINR was not sufficient to compensate for the loss of time-resources for transmission. The second case, using macro cell beamforming alone, was also not enough to enhance the performance of the network. Though the SINR was improved the majority of the cases, it was degraded in the lower percentiles. If no coordination between scheduling the small cells users and macro cell users is assumed, which was the case in these simulations, steering the beam towards a user served by the macro layer, can also increase the interference to a user served by the small cell layer. By combining both techniques, the performance was significantly enhanced, as shown in the comparison in Fig. 3.3.

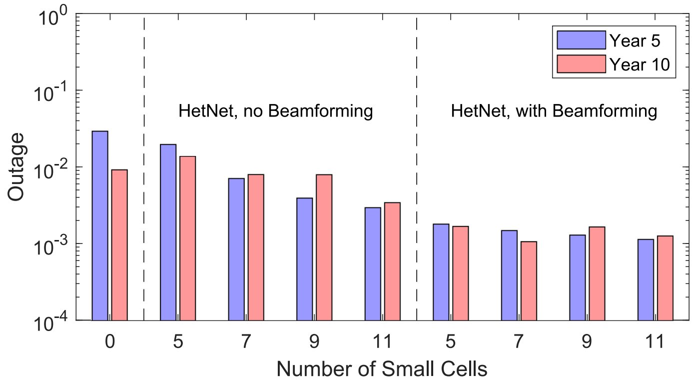


Fig. 3.3: UL outage in different deployments, in year 5 and year 10.

3.3 Cost Analysis

In this section, the costs of the radio access network in the 10 MHz deployments discussed in Section 3.2.2 are compared. The costs are given in terms of CAPEX, Implementation Expenditure (IMPEX) and Operational Expenditure (OPEX), in the course of 5 years, and are an approximation based on previous research and estimates from the Brazilian Market [79,83,84]. The cost breakdown is given in Tab. 3.1[2]. In this industry, the CAPEX, especially in terms of civil works, dominates the TCO[3].

Table 3.1: Cost breakdown per type of base station in k€.

		Macro Cell		
		no BF	with BF	Small Cell
CAPEX	RF Equipment	21	29.4	5.5
	Backhaul	10	10	4.5
	Civil Works	52.9	52.9	23
	Total	83.9	92.3	33
IMPEX	Eq. Installation	13	16.9	0.44
	Initial NW planning	5	6	0.912
	Site Preparation	5	6.5	1.02
	Total	23	29.4	2.372
OPEX	Operation and Maintenance	20	22	1
	Electricity	1.12	1.12	0
	Backhaul Maintenance	4.5	4.5	0
	Total	25.62	27.62	1

The TCO is given by [85]:

$$c_i = \sum_j \left(N_j^i c_j^{\text{capex + impex}} + \left(\sum_{k=0}^{i} N_j^k \right) c_j^{\text{opex}} \right) \tag{3.1}$$

In which N_j^i is the number of nodes of type j, for example macro cells, small cells, or macro cells with beamforming, deployed in year i, $c_j^{\text{capex + impex}}$ and c_j^{opex} are the CAPEX, IMPEX and OPEX respectively. These costs are aggregated in a TCO, to give the decision-makers an idea of the long-term financial impact of the investments in the wireless network infrastructure. The TCO of the different network deployments discussed in last section are given in Tab. 3.2, for the estimated OPEX in a five-year period.

One direct consequence of the mining activity is the need to constantly re-deploy the network. The cost associated with moving a small cell, for example, is estimated at 100 € (considering the necessary manpower, car rental, fuel consumption, among others). This value represents less than

[2]The OPEX values do not consider the costs of moving the nodes due to mining activity.

[3]These values were obtained through the partnership with Vale. For small cells, the civil works cost consider, for example, the value of the CoW.

Table 3.2: TCO estimate for different network deployments

	TCO, 5 years [k€]	
	Without Beamforming	With Beamforming
Only Macro Cells	470	519.60
HetNet 5 Small Cells	671.86	721.46
HetNet 7 Small Cells	752.60	802.2
HetNet 9 Small Cells	833.34	882.95
HetNet 11 Small Cells	914.1	963.7

0.3% of the TCO of a small cell. The cost of moving a macro cell, on the other hand, is estimated at 25 k€, taking into account the necessary civil works for disassembling and assembling the structure, installing the equipment and preparing the new site. This value represents approximately 10% of the TCO of a macro cell in five years. Therefore, it is recommended that the relocation of macro cells is minimized. One strategy to achieve that is to place them at the border of the mine, where the mining activity will not cause the need to relocate the base station.

In an industrial scenario, on the contrary of urban deployments, there is no revenue associated to investing on the wireless network infrastructure. The gains of investing in the wireless network come in the form of avoiding lost profit damages caused by the network outage. Therefore, when choosing a given network infrastructure, it is important to keep in mind not only the costs associated with the wireless network, but also the potential losses caused by the network outage.

There is no direct way to map the results in Fig.3.3 in the production downtime. First, the simulations are static and do not consider other types of outages that could impact the performance of the network, such as those caused by small scale fading, handover, and blocking by other vehicles. Second, the outage level represents individual outages and do not necessarily would impact on the unavailability of the network. Third, only two snapshots in five years are considered in this study, so the small changes in the topography and consequent impact on the network performance, as well as the relocation of nodes in the short term are not accounted in the results. Finally, it is common to have buffer piles in mines, so that the production does not stop completely in case of unavailability of parts of the system. However, it is possible to estimate the potential lost profit damage caused by hours of network outage, and compare it with the TCO of different wireless network infrastructures evaluated in the last section. This comparison helps decision-makers evaluate the long-term financial impact of the investments in the wireless network, in light of the potential losses caused by the unavailability of the systems.

For example, the assumption in the mine in the case study of the last section is that each hauling truck carries 600.5 tons of ore per hour (already discounting the amount of waste carried). The revenue of a mine deployment will depend, therefore, on the volume of material carried by the entire fleet in a year, the operational and transportation costs, the value of the iron ore in the market, among other variables. In December 2018, the value of the iron ore was 61 € per metric ton [86]. Considering a profit margin of 32%, the profit associated with one ton would be 19.56 € [87]. In this scenario, each truck in operation would generate a profit of 11,745 € per hour. One hour of downtime of the system, for example, would generate a lost profit damage of approximately 152,700.00 €, considering the operation of 13 trucks as in **paper G**. In other words, in a mine of this size, one hour of downtime is 15% more costly than the macro cell TCO in one year, considering the values in Tab.3.2.

Figure 3.4 shows a comparison of the TCO of different network deployments from Tab.3.2. The values in red, represent the TCO of the infrastructure considering the use of beamforming. This figure also shows the lost profit damage of 1-hour downtime and 13 hours downtime, in one year for example, for comparison. Considering the values in the table, the TCO of the radio access infrastructure in five years is equivalent to 3.1 (macro cell only case) and 6.3 hours (HetNet with 11 small cells) of operational downtime. Even when the costs of the infrastructure are duplicated, the case shown in black in Fig. 3.4, the most expensive deployment cost is equivalent to the lost profit damage of 13 hours of operation downtime. The overestimated five years TCO of the HetNet with beamforming ,and 5 small cells would be equivalent to the lost profit of 9.4 hours downtime, even in the overestimated case.

In this example, the revenue of the mine in one year could be calculated as:

$$r_t(outage) = 24 \cdot 365 \cdot U \cdot (A - outage) \cdot r_h \tag{3.2}$$

In which r_h represents the revenue of the mine in one hour, A represents the availability of the autonomous system. Outages in the wireless network would impact on the availability of the autonomous system, as well as the time spent in maintenance and technical assistance. The utilization, U, on the other hand, corresponds to how the system is used during the available hours. The time the equipment is not in use due to blasting, heavy rain,

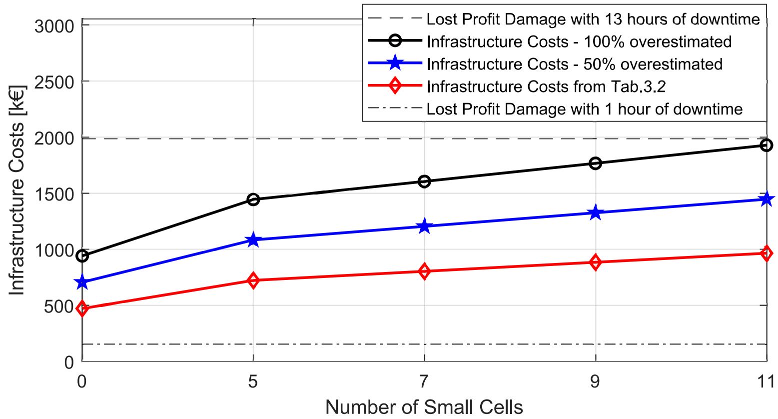


Fig. 3.4: TCO of different wireless network deployments in five years.

blocked roads, or fueling, is accounted in the utilization time [88]. Considering, for example, availability of 90%, and utilization of 80%, the five years TCO of the deployment with 5 small cells and beamforming, would be equivalent to 0.15% of mine profit in one year. The conclusion is that, if there is room for improvement of the wireless network to decrease the probability of outage of the autonomous system due to network failure, it is worth investing in it.

As said before, there is no direct mapping between the outage given by the network simulations presented in the last section into system downtime in an autonomous mine. However, in order to put those values in perspective of the costs of downtime, as well on the wireless network TCO over the time, a simple exercise is done. The objective is to clarify the benefits of investing in a given network infrastructure. What would, for example, a given percentage of system unavailability represent in terms of the revenue of this industry in one year? Is it worth investing in the network infrastructure to avoid this outage? What is the best strategy when it comes to balancing the investment costs in the network infrastructure and the losses caused by the network outage?

In this exercise, the values obtained in **paper G** are used as an example. Here, the long-term investment is also evaluated, by means of a discounted cash flow analysis of different network deployment strategies. The net present value (NPV) is calculated as [85]:

$$NPV = PV(revenues) - PV(costs) = \sum_{t}^{T-1} = \frac{(r_t(x) - r_t(0)) - c_t}{(1+d)^t} \tag{3.3}$$

In which c_t is given by Eq.3.1. In order to consider the effects of inflation, price erosion, and project risks, d is a discount rate, here assumed to be 8%, which is within the range provided in [89]. r_t is given by Eq.3.2 and $r_t(0)$, in this example, is given by the ideal case, in which no outages from the wireless network are considered. $r_t(x)$, on the other hand, considers the outages obtained in the simulations. Here, $(r_t(x) - r_t(0))$ always assumes negative values, so the best deployment strategy is the one that gives the least negative NPV in a given year. A comparison of the NPV in different strategies and network deployments are shown in Fig.3.5, not considering beamforming, and in Fig. 3.6, considering beamforming.

In these figures, the blue bar represents the NPV of a HetNet deployment with 2 macro cells and 5 small cells, that is kept static over the years. In magenta, in year 1, the same deployment is considered, but two new small cells are added to the network per year. In gray, a deployment with 2 macro cells and 11 small cells is considered since year 1. The dashed line marks the value of 10 million euros. In black, the discounted network TCO is given. The conclusions from the analysis of these two figures do not change when compared to the conclusions drawn from Fig. 3.4: the investment in the network infrastructure is irrelevant when compared to the potential losses caused by the network outages. Additionally, the comparison between the results provided by different network infrastructures provides extra insights. Not investing in the network can seriously impact the business in the long term. It is also advised to invest as early as possible in the network, to avoid the accumulated losses due to unavailability of the autonomous system. Finally, the investment in beamforming seems to have a much better return then the investment in small cells.

3.4 Summary

This Chapter presents the simulation assumptions, in terms of scenario and traffic, of the studies presented in **paper E**, **paper F** and **paper G**. In this Chapter, a summary of the main results obtained in each paper is presented, and a comparison of the performance of different wireless network infrastructures is presented. Finally, the last part of this chapter is dedicated to present a comparison of the five years TCO in each network infrastructure, with the lost profits due to system unavailability in this industry.

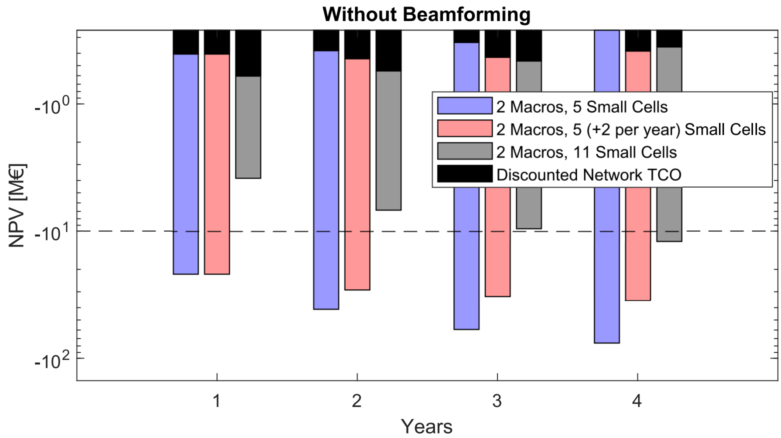


Fig. 3.5: NPV in 4 years, for different network infrastructures, not considering beamforming.

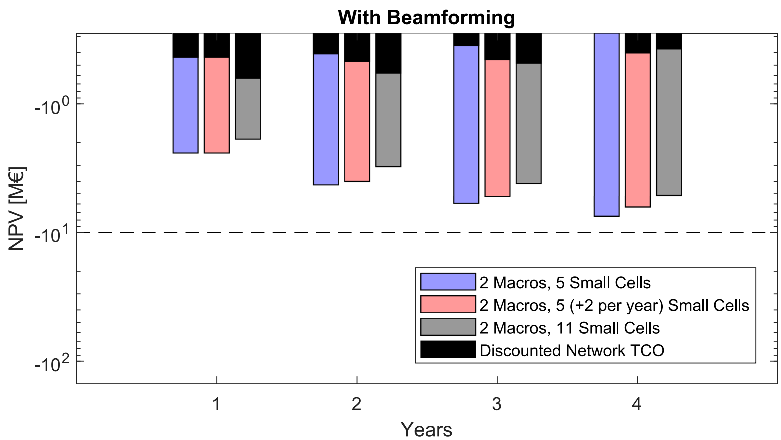


Fig. 3.6: NPV in 4 years, for different network infrastructures, considering beamforming.

Chapter 4 - Conclusions

The introduction of autonomous equipment in surface mines is increasing the role of wireless communications in the mining industry: constant network failures might impact directly on the productivity of autonomous mining sites. The open-pit mine scenario poses a number of challenges to the deployment of wireless networks for the support of intelligent systems. This thesis focuses on some of these challenges such as: lack of large-scale radio-propagation measurements and characterization in this scenario, continuous terrain variability, and lack of studies about the network performance under specific network deployment strategies and features. In order to tackle each of these points, this thesis is divided in two parts: radio-propagation characterization and network performance evaluation.

In the first part of the thesis, large-scale radio-propagation in this environment was investigated. An extensive measurement campaign was planned and performed, and two sets of models were proposed. The first set of models consisted of a free linear fit to the data, and it provided insights to the propagation in this scenario, considering both macro cell and small cell deployments, in different mines and frequency ranges. First, the topography of the mine, in terms of obstacles in the propagation path as well of the altitude difference between transmitters and receivers, plays an important role in the radio propagation. Second, there is a path loss exponent difference between macro and small cells, which can be exploited in heterogeneous deployments. However, this difference is reduced when compared to the urban scenario, for example, which suggests that there is a limit to the interference-containment provided by small cell deployments. Additionally, some insights obtained from evaluating the path loss in different moments of the mine exploration are very useful for the network planning study, in the second part of the thesis. For example, it was shown that the LOS conditions tend to increase with the development of the mine site, benefiting the coverage of macro and small cells.

Following the insights provided by the first modelling approach, as well as the results obtained when comparing the fitness of well-known propagation models to the measurement data, a second model was proposed. This model combined the two main propagation mechanisms identified in this scenario - direct propagation, in the LOS path, and diffraction - with an extra term to account for the effective antenna height between transmitters and receiver. This simple extension of a semi-deterministic model was able to characterize the path loss in two open-pit mining complexes, as well as in different deployments: macro and small cell,resulting in RMSE values between 5.5 dB and 9.8 dB. Initially, the assumption was that, since this model was based on already available topographic characteristics of the mines, it should be able to correctly characterize the path loss in different stages of mining exploration. This assumption was confirmed by measurements obtained in an independent measurement campaign, in one of the mines used for the development of the model, but considering different a transmitter location, transmitter and receiver equipment, as well in a different frequency. In this second evaluation, the RMSE values of 7.2 dB.

In the second part of the thesis, a framework to integrate mine planning and radio-network planning was proposed, so that the predictability of the topographic variation could be also used to aid planning and optimization of the wireless network. Additionally, the wireless network performance is evaluated in different moments of the exploration of a mine, considering the throughput requirements for different types of nodes in an autonomous mine. The main performance indicator is the outage considering a minimum required data rate, in the DL and in the UL. First, in terms of the data-rate requirements of autonomous nodes in this industry, it is shown that the capacity provided by 4G networks is sufficient, even when considering a fully autonomous mine.

Different network deployment strategies were evaluated in this work: macro cell deployments, and heterogeneous deployments with and without interference mitigation techniques. Considering a macro cell only case, it was shown that the performance of the system improves with the mining activity due to the increase in LOS. Deploying macro cells at the border of the mine site, in locations that would not be affected by mining, is preferred due to the high costs associated with the re-deployment, it is estimated that the cost of moving a macro cell represents approximately 10% of its TCO in five years. In a macro cell only scenario, outage values in the order of 10^{-3} can be obtained if sufficient nodes or spectrum are added to the network. However, considering the real world limitations of spectrum dedicated to industrial communications, as well as the costs associated with obtaining licenses for utilizing the spectrum, other alternatives are preferred to the increase of the spectrum.

Despite the general increase of LOS with time, new NLOS areas can also be created with excavation, modifying the coverage of the network. Therefore, in addition to the performance of macro-cells, the performance of heterogeneous deployments were also investigated in this work. Compared to macro cells, the cost of moving a small cell is estimated at 0.3% of its TCO in five years, which makes it an interesting alternative to adapt the network to the topographic changes in the mine. As in urban scenarios, small cells even in in-band deployments, improve the capacity and performance of the network. However, the performance gain obtained by introducing in-band small cells is limited due to the decrease in the SINR, which is not entirely compensated by increasing the capacity of the network.

The last set of results comprises the investigation of the performance of heterogeneous networks, in a 10 MHz bandwidth scenario, when combined with interference mitigation techniques: eICIC and beamforming. When these techniques are investigated alone, there is no performance gain. In the first case, the use of eICIC improves the SINR, but reduces the capacity of the network, since the macro cell layer is temporarily muted. In the second case, with macro cell beamforming, if there is no coordination between the scheduling of users served by the macro and small cell layers, users associated with the small cell layer can be interfered by the macro cell beam. When combining both techniques the outage level is in the order of 10^{-3}: the same level as the outage obtained in the macro cell deployment with 20 MHz spectrum bandwidth.

Finally, a brief evaluation of the TCO of the radio access network is provided for different network infrastructures, and put into the perspective of the costs of the downtime in a mining site. The estimated TCO of the best performing radio access network infrastructure in a five years time frame, for example, is equivalent to the profit loss in 5 hours of system downtime in the mine evaluated in this work. The investment in the wireless network is minimal when compared to the potential profit losses caused by outages in the system. Not mentioning the potential accidents that can occur in the scenario, in case of network outages. Therefore, the costs of investing in the network infrastructure and features are justified by the potential impacts in the business.

As future work, there are different research areas that could be investigated. In radio-propagation, for example, this work focused on the characterization of large-scale propagation in sub-6GHz frequencies. The investigation of the role of reflection in this scenario can also be used to further extend the proposed model, considering the different types of materials, and their electromagnetic properties. This characterization can also aid the calibration of ray-tracing simulations for more detailed evaluations, if needed. Additionally, the large and small scale wideband characterization can result in new models for this scenario, providing further insights of the system performance under different conditions. Considering the recent development of 5G systems in the millimeter wave frequency band, up to 52 GHz, one research area that can be explored is radio-propagation in higher frequencies, where more bandwidth is available. This scenario, rich in LOS, is ideal for the propagation in millimeter wave. One network feature that can be especially benefited is beamforming, since more antenna elements can be used in higher frequency bands, resulting in narrower beams, and AoA estimation also improves in LOS conditions.

From a wireless network planning and optimization perspective, there are also different areas to be further explored. For example, considering the fact that the traffic in this scenario is dominated by UL transmissions, techniques that can improve the UL could be particularly interesting. One of them is the decoupling of DL and UL in heterogeneous networks, which cannot only reduce the transmit power in the UEs, but also increase the SINR in the UL, improving the utilization of resources and the network performance [90]. Additionally, the integration of the mining and RF planning systems, which was proposed in **paper E**, can be further developed. Recently, the concept of digital twin, a dynamic digital replica of physical assets which allows the prediction of the performance of machines and systems, is starting to be applied in IIoT [91]. The same framework could be extended to predict the network performance, and optimize it accordingly. In the specific case of mines, this framework can take advantage of the already existing amount of sensors and monitoring devices. Another promising area is Machine Learning (ML), which can combine data from the wireless network and mine planning, to extract traffic and user patterns that can be continuously used to optimize the use of resources, as in [92].

References

[1] M. Coulson, *The history of mining: The events, technology and people involved in the industry that forged the modern world*. Harriman House Limited, 2012.

[2] Y. Dionne, "5 oldest mines in the world: a casual survey." https://www.promine.com/blog/5-oldest-mines-in-the-world-a-casual-survey, accessed: 2018-12-12.

[3] I. Tattersall, "Homo sapiens." https://www.britannica.com/topic/Homo-sapiens, accessed: 2018-12-13.

[4] P. Lewis and G. Jones, "Roman gold-mining in north-west spain," *The Journal of Roman Studies*, vol. 60, no. 1, pp. 169–185, 1970.

[5] M. Coderre-Proulx, B. Campbell, and I. Mandé, "International migrant workers in the mining sector," International Labour Office, Tech. Rep., 2016.

[6] M. N. Sishi and A. Telukdarie, "Implementation of industry 4.0 technologies in the mining industry: A case study," in *Industrial Engineering and Engineering Management (IEEM), 2017 IEEE International Conference on*. IEEE, 2017, pp. 201–205.

[7] J. Lee and K. Prowse, "Mining & Metals + Internet of Things: Industry opportunities and innovation," http://www.marsdd.com/news-and-insights/mining-industry-IoT-technology, accessed: 2019-01-16.

[8] T. Hanley, A. Daecher, M. Cotteller, and B. Sniderman, "The Industry 4.0 paradox: Overcoming disconnects on the path to digital transformation." https://documents.deloitte.com/insights/DigitalTransformationSurvey, accessed: 2019-01-16.

[9] O. Gölbaşı and K. Dagdelen, "Equipment replacement analysis of manual trucks with autonomous truck technology in open pit mines," in *Proceedings of the 38th International Symposium on the Application of Computers and Operations Research (APCOM 2017)in the Mineral Industry*, 2017.

[10] J. Parreira, "An interactive simulation model to compare an autonomous haulage truck system with a manually-operated system," Ph.D. dissertation, University of British Columbia, 2013.

[11] Vale, "Vale terá a primeira mina operando somente com caminhões autônomos no brasil," http://www.vale.com/brasil/PT/aboutvale/news/Paginas/vale-tera-a-primeira-mina-operando-somente-com-caminhoes-autonomos-no-brasil.aspx, accessed: 2018-12-17.

[12] C. Duckett, "Rio tinto expands autonomous trucking fleet, aims for 100 trucks this year," https://www.zdnet.com/article/rio-tinto-expands-autonomous-trucking-fleet-aims-for-100-trucks-this-year/, accessed: 2018-12-17.

[13] W. Grayson, "Cat's fleet of autonomous mine trucks is about to get a lot bigger," https://www.equipmentworld.com/cats-fleet-of-autonomous-mine-trucks-is-about-to-get-a-lot-bigger/, accessed: 2018-12-17.

[14] P. Moore, "Suncor commits to 150 strong autonomous fleet," https://im-mining.com/2018/01/31/suncor-commits-150-strong-autonomous-fleet/, accessed: 2018-12-17.

[15] D. Kumar, "Emerging tools and techniques for mine safety and disaster management," in *Natural and Anthropogenic Disasters*. Springer, 2010, pp. 332–365.

[16] L. G. U. Garcia, E. P. L. Almeida, V. S. Barbosa, G. Caldwell, I. Rodriguez, H. Lima, T. B. Sørensen, and P. Mogensen, "Mission-critical mobile broadband communications in open-pit mines," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 62–69, 2016.

[17] ABI Research, "Private networks for the mining industry," https://www.abiresearch.com/press/us-29-billion-market-opportunities-lte-vendors-min/, accessed: 2018-12-18.

[18] W. Haerick and M. Gupta, "5G and the factories of the future," *5G-PPP White Paper*, 2015.

[19] H. L. Hartman and J. M. Mutmansky, *Introductory mining engineering*. John Wiley & Sons, 2002.

[20] W. A. Hustrulid, M. Kuchta, and R. K. Martin, *Open pit mine planning and design, two volume set & CD-ROM pack*. CRC Press, 2013.

[21] A. Parra, N. Morales, J. Vallejos, and P. M. V. Nguyen, "Open pit mine planning considering geomechanical fundamentals," *International Journal of Mining, Reclamation and Environment*, vol. 32, no. 4, pp. 221–238, 2018.

[22] R. Dimitrakopoulos, "Stochastic optimization for strategic mine planning: a decade of developments," *Journal of Mining Science*, vol. 47, no. 2, pp. 138–150, 2011.

[23] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0," *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 17–27, 2017.

[24] L. Bandyopadhyay, S. Chaulya, and P. Mishra, *Wireless communication in underground mines: RFID-based sensor networking*. Springer Science & Business Media, 2009.

[25] A. Boulter and R. Hall, "Wireless network requirements for the successful implementation of automation and other innovative technologies in open-pit mining," *International Journal of Mining, Reclamation and Environment*, vol. 29, no. 5, pp. 368–379, 2015.

[26] S. Vellingiri, D. Tandur, and M. Kande, "Communication architecture for remote monitoring and diagnostics in open pit mine." in *ETFA*, 2013, pp. 1–6.

[27] G. Baldini, S. Karanasios, D. Allen, and F. Vergari, "Survey of wireless communication technologies for public safety," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 619–641, 2014.

[28] C. E. Shannon, "A mathematical theory of communication," *Bell system technical journal*, vol. 27, no. 3, pp. 379–423, 1948.

[29] S. Simon and A.-Z. Alejandro, "Antennas and propagation for wireless communication systems," *John Wiely & Sons*, 2007.

[30] T. S. Rappaport *et al.*, *Wireless communications: principles and practice*. prentice hall PTR New Jersey, 1996, vol. 2.

[31] B. Sklar, "Rayleigh fading channels in mobile digital communication systems. I. Characterization," *IEEE Communications Magazine*, vol. 35, no. 7, pp. 90–100, 1997.

[32] W. C. Lee, "Elements of cellular mobile radio systems," *IEEE Transactions on Vehicular Technology*, vol. 35, no. 2, pp. 48–56, 1986.

[33] W. C. Y. Lee, "Estimate of local average power of a mobile radio signal," *IEEE Transactions on Vehicular Technology*, vol. 34, no. 1, pp. 22–27, 1985.

[34] X. Chu, D. López-Pérez, Y. Yang, and F. Gunnarsson, *Heterogeneous Cellular Networks: Theory, Simulation and Deployment*. Cambridge University Press, 2013.

[35] W. C. Lee, "Studies of base-station antenna height effects on mobile radio," *IEEE Transactions on Vehicular Technology*, vol. 29, no. 2, pp. 252–260, 1980.

[36] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[37] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE transactions on Vehicular Technology*, vol. 29, no. 3, pp. 317–325, 1980.

[38] Action, COST, "231,Digital mobile radio towards future generation systems, Final Report," European Communities, EUR 18957, Tech. Rep., 1999.

[39] V. Erceg, L. J. Greenstein, S. Y. Tjandra, S. R. Parkoff, A. Gupta, B. Kulic, A. A. Julius, and R. Bianchi, "An empirically based path loss model for wireless channels in suburban environments," *IEEE Journal on selected areas in communications*, vol. 17, no. 7, pp. 1205–1211, 1999.

[40] J. B. Keller, "Geometrical theory of diffraction," *JOSA*, vol. 52, no. 2, pp. 116–130, 1962.

[41] R. G. Kouyoumjian and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface," *Proceedings of the IEEE*, vol. 62, no. 11, pp. 1448–1461, 1974.

[42] ITU, "Recommendation ITU-R P.526-14 Propagation by diffraction," 2018.

[43] J. Walfisch and H. L. Bertoni, "A theoretical model of uhf propagation in urban environments," *IEEE Transactions on antennas and propagation*, vol. 36, no. 12, pp. 1788–1796, 1988.

[44] F. Ikegami, S. Yoshida, T. Takeuchi, and M. Umehira, "Propagation factors controlling mean field strength on urban streets," *IEEE Transactions on Antennas and Propagation*, vol. 32, no. 8, pp. 822–829, 1984.

[45] A. G. Longley and P. L. Rice, "Prediction of tropospheric radio transmission loss over irregular terrain. a computer method-1968," Institute for Telecommunication Sciences Boulder CO, Tech. Rep., 1968.

[46] J. Aitken, "Development of a radio propagation model for an open cut mine," in *20th International Electronics convention & exhibition*, 1985.

[47] R. Nilsson and J. van de Beek, "Channel measurements in an open-pit mine using USRPs: 5G—Expect the unexpected," in *Wireless Communications and Networking Conference (WCNC), 2016 IEEE*. IEEE, 2016, pp. 1–6.

[48] A. Tomasi, "Reliable communication in mine environments for autonomous vehicles," 2016.

[49] E. P. Almeida, G. Caldwell, I. Rodriguez, S. Abreu, R. D. Vieira, V. S. Barbosa, T. B. Sørensen, P. Mogensen, and L. G. U. Garcia, "Radio Propagation in Open-pit mines: a first look at measurements in the 2.6 GHz Band," in *28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,(PIMRC)*, 2017.

[50] E. P. L. Almeida, G. Caldwell, I. Rodriguez, R. D. Vieira, T. B. Soerensen, P. Mogensen, and L. G. U. Garcia, "5G in Open-Pit Mines: Considerations on Large-Scale Propagation in Sub-6 GHz Bands," in *Globecom Workshops (GC Wkshps), 2017 IEEE*. IEEE, 2017, pp. 1–6.

[51] W. C. Jakes and D. C. Cox, *Microwave mobile communications*. Wiley-IEEE Press, 1994.

[52] ITU, "Recommendation ITU-R P.1406-2 Propagation effects relating to terrestrial land mobile and broadcasting services in the VHF and UHF bands," 2015.

[53] M. Gudmundson, "Correlation model for shadow fading in mobile radio systems," *Electronics letters*, vol. 27, no. 23, pp. 2145–2146, 1991.

[54] "Study on channel model for frequencies from 0.5 to 100 GHz (Release 14)," 3GPP, Standard, 2017.

[55] D. Öhmann, A. Awada, I. Viering, M. Simsek, and G. P. Fettweis, "Achieving high availability in wireless networks by inter-frequency multi-connectivity," in *Communications (ICC), 2016 IEEE International Conference on*. IEEE, 2016, pp. 1–7.

[56] ITU, "Recommendation ITU-R 1546-4 Method for point-to-area predictions for terrestrial services in the frequency range 30–300 MHz," 2009.

[57] S. I. Popoola, A. A. Atayero, N. Faruk, C. T. Calafate, E. Adetiba, and V. O. Matthews, "Calibrating the standard path loss model for urban environments using field measurements and geospatial data," 2017.

[58] Forsk, "Atoll: Technical reference guide for radio networks v3.2.2," 2015.

[59] "WinProp - ProMan," https://altairhyperworks.com/product/FEKO/WinProp---ProMan, accessed: 2018-12-11.

[60] G. Guieiro, "Desenvolvimento de ferramenta de análise de qualidade de rede sem fio para veículos não tripulados em mina a céu aberto," Escola de minas, Universidade Federal de Ouro Preto, Tech. Rep., 2018.

[61] T. Horberry and D. Lynas, "Human interaction with automated mining equipment: The development of an emerging technologies database," *Ergonomics Australia*, vol. 8, no. 1, pp. 1–6, 2012.

[62] International Organization for Standardization (ISO), "Draft international standart iso/dis 17757, earth-moving machinery and mining — autonomous and semi-autonomous machine system safety," pp. 1–47, 2018.

[63] Caterpillar, "Cat® command for hauling," http://s7d2.scene7.com/is/content/Caterpillar/C10338825, accessed: 2019-08-14.

[64] Komatsu, "Autonomous haul system (ahs)," http://www.komatsu.com.au/AboutKomatsu/Technology/Pages/AHS.aspx, accessed: 2019-01-14.

[65] J. J. Dudley, "Enhancing awareness to support teleoperation of a bulldozer," Master's thesis, The University of Queensland, 2014.

[66] M. P. Wylie-Green and T. Svensson, "Throughput, capacity, handover and latency performance in a 3GPP LTE FDD field trial," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*. IEEE, 2010, pp. 1–6.

[67] J. M. Westall and J. J. Martin, "Performance characteristics of an operational WiMAX network," *IEEE Transactions on Mobile Computing*, vol. 10, no. 7, pp. 941–953, 2011.

[68] C. Jamasmie, "Not so autonomous: Wifi outage results in driverless truck crash at Fortescue mine." https://www.mining.com/driverless-trucks-not-flawless-two-crash-fortescue-mine-australia/, accessed: 2019-08-14.

[69] QGIS, "A Free and Open Source Geographic Information System," https://qgis.org/en/site/, accessed: 2019-01-16.

[70] A. H. Jafari, D. López-Pérez, H. Song, H. Claussen, L. Ho, and J. Zhang, "Small cell backhaul: challenges and prospective solutions," *EURASIP Journal on Wireless Communications and Networking*, vol. 2015, no. 1, p. 206, 2015.

[71] L. G. U. Garcia, E. P. L. Almeida, I. Rodriguez, B. V. S. B, and G. Caldwell, "Network planning method and mine planning method," 2017, WO 2017/152248 Al. [Online]. Available: https://patents.google.com/patent/WO2017152248A1/en

[72] J. Baek and Y. Choi, "A New GIS-Based Algorithm to Support Initial Transmitter Layout Design in Open-Pit Mines," *Energies*, vol. 11, no. 11, p. 3063, 2018.

[73] T.-E. Wu, D.-J. Deng, and K.-C. Chen, "Quality of experience in dense CSMA networks," in *2015 IEEE International Conference on Communication Workshop (ICCW)*. IEEE, 2015, pp. 1759–1764.

[74] A. M. Cavalcante, E. Almeida, R. D. Vieira, S. Choudhury, E. Tuomaala, K. Doppler, F. Chaves, R. C. Paiva, and F. Abinader, "Performance evaluation of LTE and Wi-Fi coexistence in unlicensed bands," in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*. IEEE, 2013, pp. 1–6.

[75] R. Ferrus and O. Sallent, "Extending the LTE LTE-A Business Case: Mission-and Business-Critical Mobile Broadband Communications," *IEEE Vehicular Technology Magazine*, vol. 9, no. 3, pp. 47–55, 2014.

[76] Daniel Gleeson, "Sandvik and Nokia team up to offer miners LTE and 5G networks," 2018, accessed: 2019-8-18. [Online]. Available: https://im-mining.com/2018/12/04/sandvik-nokia-team-offer-miners-lte-5g-networks/

[77] Ericsson, "5G business value: a case study on automation in mining," 2018, accessed: 2019-8-18. [Online]. Available: https://www.ericsson.com/en/trends-and-insights/consumerlab/consumer-insights/reports/a-case-study-on-automation-in-mining

[78] Australian Mining, "Komatsu shifts AHS towards dedicated private LTE network," 2019, accessed: 2019-8-18. [Online]. Available: https://www.australianmining.com.au/news/komatsu-shifts-ahs-towards-dedicated-private-lte-network/

[79] C. Coletti, "Heterogeneous deployment analysis for cost-effective mobile network evolution:-an lte operator case study," Ph.D. dissertation, Aalborg Universitetsforlag, 2013.

[80] G. Micallef, "Energy efficient evolution of mobile broadband networks," Ph.D. dissertation, Aalborg Universitetsforlag, 2013.

[81] H. Eckhardt, S. Klein, and M. Gruber, "Vertical antenna tilt optimization for lte base stations," in *2011 IEEE 73rd Vehicular Technology Conference (VTC Spring)*. IEEE, 2011, pp. 1–5.

[82] N. Dandanov, H. Al-Shatri, A. Klein, and V. Poulkov, "Dynamic self-optimization of the antenna tilt for best trade-off between coverage and capacity in mobile networks," *Wireless Personal Communications*, vol. 92, no. 1, pp. 251–278, 2017.

[83] E. J. Oughton, Z. Frias, S. van der Gaast, and R. van der Berg, "Assessing the capacity, coverage and cost of 5g infrastructure strategies: Analysis of the netherlands," *Telematics and Informatics*, vol. 37, pp. 50–69, 2019.

[84] Analysys Mason, "Total cost of ownership (TCO) of beamforming enabled WiMAX systems," 2009, accessed: 2019-8-18. [Online]. Available: https://pdfs.semanticscholar.org/c8ca/8f966147e2894a8aa688e390a8c69b8e26ca.pdf

[85] B. Timus, J. Hultell, and M. Nilson, "Techno-economical viability of deployment strategies for cellular-relaying networks," in *VTC Spring 2008-IEEE Vehicular Technology Conference*. IEEE, 2008, pp. 2259–2263.

[86] I. Mundi, "Iron Ore Monthly Price - Euro per Dry Metric Ton," https://www.indexmundi.com/commodities/?commodity=iron-ore&months=60&currency=eur, accessed: 2019-01-14.

[87] M. Trends, "VALE S.A Profit Margin 2006-2019," https://www.macrotrends.net/stocks/charts/VALE/vale-sa/profit-margins, accessed: 2019-08-14.

[88] E. J. Balt, "Cost management of the availability and utilization of mining earth moving equipment."

[89] L. D. Smith, "Discounted cash flow analysis methodology and discount rates," 2002.

[90] F. Boccardi, J. Andrews, H. Elshaer, M. Dohler, S. Parkvall, P. Popovski, and S. Singh, "Why to decouple the uplink and downlink in cellular networks and how to do it," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 110–117, 2016.

[91] Y. He, J. Guo, and X. Zheng, "From surveillance to digital twin: Challenges and recent advances of signal processing for industrial internet of things," *IEEE Signal Processing Magazine*, vol. 35, no. 5, pp. 120–129, 2018.

[92] A. Azari, M. Ozger, and C. Cavdar, “Risk-aware resource allocation for urllc: Challenges and strategies with machine learning,” *IEEE Communications Magazine*, vol. 57, no. 3, pp. 42–48, 2019.

Appendices

Chapter A - Simulation Tools

In this work, two different simulation tools were used. The simulation process is similar in both cases, by using the Monte Carlo method. The first one, used in **Paper E** and **F** is the network planning tool Atoll, and the second one, used in **paper G** is a semi-static system level simulation tool, described in detail in [1]. A brief description of both simulators is given below.

A.1 Atoll

Atoll is a multi-technology wireless network design and optimization platform, used in the wireless network industry worldwide. It contains a variety of propagation models and radio access networks (RANs) that can be used to support radio planning and optimization. The Monte Carlo simulation module was used to obtain the results in **paper E** and **paper F**.

To initiate a Monte Carlo simulation in Atoll, it is necessary to include a DTM of the interest area, to specify a propagation model, to determine user traffic and geographic distributions, to include information about the network topology and configuration. For a given network topology, each iteration consists of:

- Deploying users according to the specified distribution.
- Calculating the path loss matrices between the base stations and each user.
- Calculating the SINR.
- Each user attempt to connect one by one to network transmitters.
- In case of an LTE network, intelligent scheduling and radio resource management is used.
- Calculating the performance metrics.

The process is repeated until the simulation converges. The results can be visualized in different ways: statistics for the entire network, for each base station, or even per UE. In case of the simulations performed in Atoll, the results were obtained using a SPM model, calibrated with data obtained through a drive test of the WiMAX system, in which measurements collected from one macro cell and one small cell were evaluated. A brief description of this drive test, done prior to the start of this thesis, is given in **paper E**, and details about the calibration of the SPM model are given in **paper D**.

A.2 System level simulator

The second simulation tool consists of an LTE system level simulator developed in Matlab. The process of configuring a simulation is similar to the one described in Atoll, and it is detailed in Fig.A.1, which shows the simulation flow.

The first step of the simulation consists in initializing the network scenario, which consists of loading the area DTM and the location of the transmitters, both macro and small cells, and their configuration, in terms of transmit power, antenna patterns and gains and feeder losses. In this step, path loss maps, pre-calculated according to the Vale model, from **paper D** are also loaded for each transmitter. The path loss maps are generated considering omni-directional antennas, and the antenna gain is added in this step of the simulator, according to the configuration.

From the second step on, all the steps are repeated in each iteration, or snapshot, of the simulation. The second step consists in distributing users according to pre-defined polygons which represent the roads of the mine, development and exploration areas, the crusher and the waste pile. The DTM is also considered in the distribution of the users, to avoid placing users on slopes between the mining benches for example. Specific users are distributed uniformly within the relevant polygons. The third step consists in calculate link budgets between all the transmitters and all the receivers, based on the path loss and antenna patterns.

For each user, the best server is determined according to the received power in the downlink. The best server in the downlink, is used in the uplink. In this step, the cell range extension bias is also applied in order balance the load between the macro cell and the small cell layer, according to the parameters of the specific simulation. After the determination of the best server, the next step is to calculate the SINR. In **paper G**, the SINR is calculated in two ways:

- Using the configured antenna pattern. In this case, the azimuth and the elevation of the base station antennas is retrieved from the simulation configuration, and matches the one used in the calculation of the

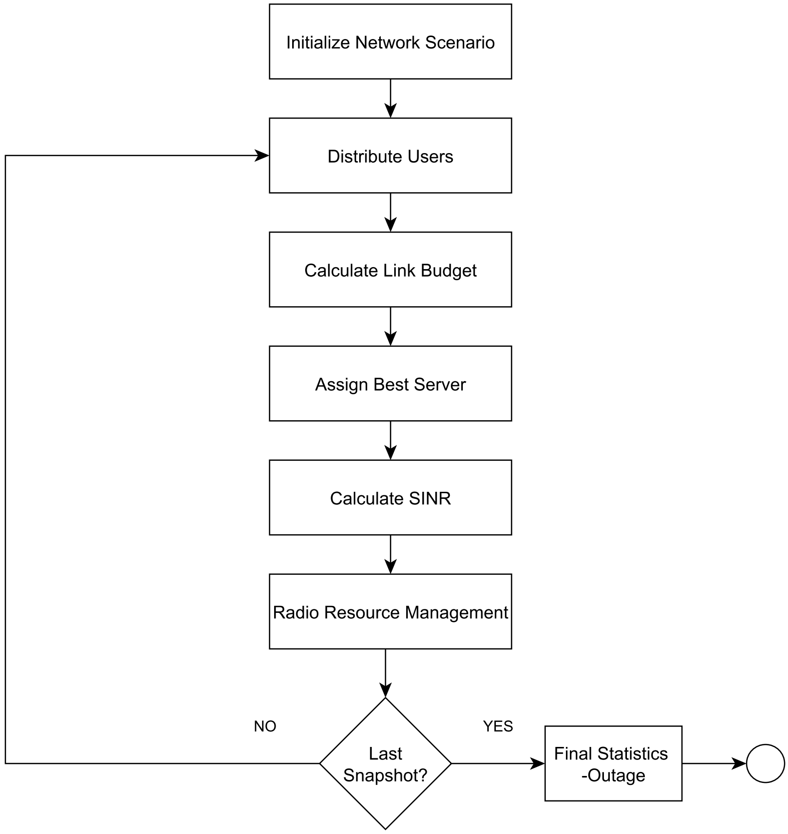


Fig. A.1: Simulation flow, adapted from [1].

.

link budget. The interference in each user is calculated considering the contribution of all cells in the simulation, but the serving cell.

- Using macro cell beamforming. In this case, the signal from macro cell transmitters depend on the azimuth and elevation of the antenna, and on the direction of the each served user. The antenna pattern and gains are derived from [2], considering 5×4 antenna elements. The antenna is steered to a given user, and the interference to nodes served by other cells in the simulation is calculated based on the resulting pattern. An example of the pattern is given in Figure A.2.

In the uplink, the SINR is calculated in a slightly different manner. For each served UE, a new Monte Carlo simulation of 50 snapshots is ran. In

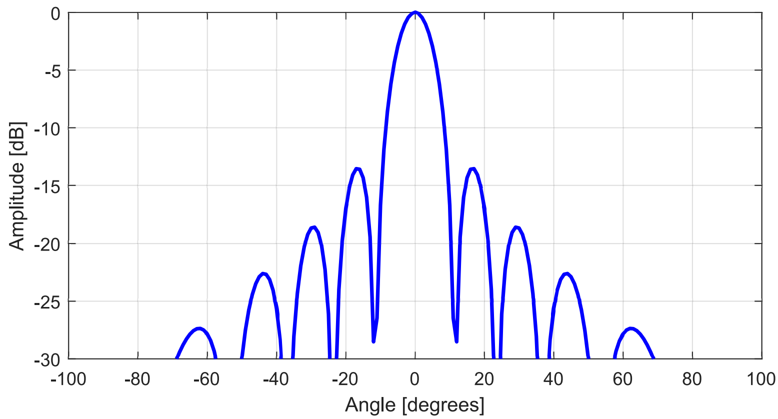


Fig. A.2: Horizontal antenna pattern considering 5×4 antenna elements.

each of these snapshots, the interference from other cells is accounted based on the probability of scheduling users of that other cell. This probability takes into account the uplink traffic, as well as the resources on that cell. In each simulation snapshot, the uplink SINR for each user is considered as the average of the SINR in these Monte Carlo Simulations, as detailed in the Algorithm 1. In this algorithm I is the interference, N is the noise.

The scheduler performs the radio resource management. In this simulation, downlink and uplink resources are assigned based on a minimum required data rate. First, resources are allocated for UEs with the highest SINR, to guarantee that they will be served with a minimum data rate, defined according to the UE type. When all the UEs are served with a minimum data rate, the remaining resources are distributed also observing the SINR sorting. If some UEs cannot be served, they are accounted in the outage statistic for that snapshot.

The results presented in the thesis are obtained after 500 drops. After the last snapshot, the statistics are calculated, considering all nodes in the simulation. The DL or UL outage are obtained by means of a sample mean estimator, considering all simulation drops in the Monte Carlo simulation.

$$\hat{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{A.1}$$

where x_i is the DL or UL outage in each simulation snapshot, and N is the number of snapshots in the simulation. The sample variance is defined as follows:

Algorithm 1 Uplink SINR calculation.

```
for each drop do
    Distribute users
    Calculate the path loss from all users to all servers
    Get the best server
    Associate users to best server
    for each base station b do
        n = 0
        INR_b = 0
        repeat
            for each base station ≠ b do
                n ← n + 1
                Calculate the probability of any user being served
                if any user is served then
                    INR(n) = 1 / (I_mW + N_mW)
                else
                    INR(n) = 1 / N_mW
                end if
                INR_b = INR_b + INR(n)
            end for
        until n = 50
        for each served user by base station b do
            SINR_UL = RxPower_dBm + 10 · log10(INR_b / 50)
        end for
    end for
end for
```

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{N} (x_i - \hat{x})^2}{N - 1} \tag{A.2}$$

Figure A.3 shows the values of $\hat{x}$ considering different numbers of simulation snapshots. This comparison considers the uplink outage in the HetNet scenario with 5 small cells, and macro cell beamforming presented in **paper G**.

The average network outage does not vary significantly with the number of simulation drops. However, it is important to evaluate the statistical relevance of this set of results. According to the Law of Large Numbers, when the number of trials, $n \to \infty$, the sample mean converges to the population mean, η [3]. Using the sample mean, estimated in Eq. A.1, and the sample variance estimated in Eq. A.2, it is possible to calculate the confidence interval which might contain η with a certain probability.

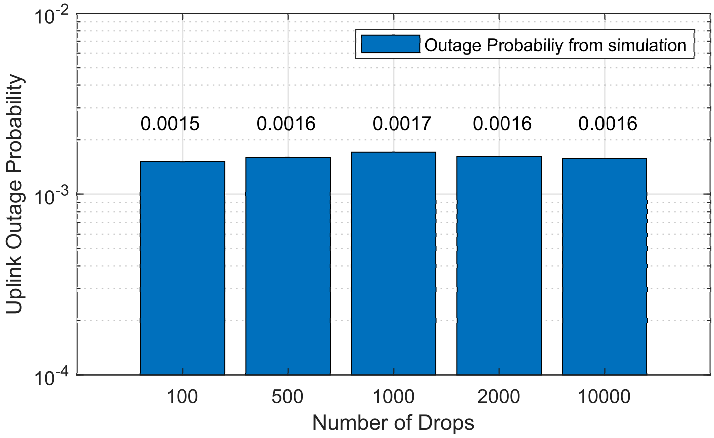


Fig. A.3: Probability of outage with different number of snapshots.

Assuming the normal distribution, the confidence interval can be represented as:

$$P[\hat{x} - z_{1-\frac{\delta}{2}} \frac{\sigma}{\sqrt{n}} < \eta < \hat{x} + z_{1-\frac{\delta}{2}} \frac{\sigma}{\sqrt{n}}] = 1 - \delta = \gamma \quad \text{(A.3)}$$

the confidence interval is given by: $\hat{x} \pm z_{1-\frac{\delta}{2}} \frac{\sigma}{\sqrt{n}}$, in which $z_{1-\frac{\delta}{2}}$ is the standard normal percentile, considering a confidence coefficient of γ. Considering a normal distribution, the value of $z_{1-\frac{\delta}{2}} \frac{\sigma}{\sqrt{n}}$ for a 99% confidence is given by $2.57 \frac{\sigma}{\sqrt{N}}$. For the case with 500 snapshots, used in the results of the thesis, the confidence interval is given by $\hat{x} \pm 1.54 \cdot 10^{-6}$. The confidence interval decreases with the increase of the number of drops, but this variation does not change the results and the conclusions of this work.

References

[1] C. Coletti, "Heterogeneous deployment analysis for cost-effective mobile network evolution:-an lte operator case study," Ph.D. dissertation, Aalborg Universitetsforlag, 2013.

[2] ITU, "Modelling and simulation of IMT networks and systems for use in sharing and compatibility studies," *Recommendation ITU-R M.2101-0*, 2017.

[3] A. Papoulis, "Random variables and stochastic processes," *McGraw Hill*, 1976.

Part II

Papers

Paper A

Radio Propagation in Open-pit Mines: a First Look at Measurements in the 2.6 GHz Band

Erika P. L. Almeida, George Caldwell, Ignacio Rodriguez,
Sergio Abreu, Robson D. Vieira,
Viviane S. B. Barbosa, Troels B. Sørensen, Preben Mogensen
and Luis G. Uzeda Garcia

Published at the *28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE PIMRC 2017)*

Abstract

In this paper we present the results of an extensive measurement campaign performed at two large iron ore mining centers in Brazil at the 2.6 GHz band. Although several studies focusing on radio propagation in underground mines have been published, measurement data and careful analyses for open-pit mines are still scarce. Our results aim at filling this gap in the literature. The research is motivated by the ongoing mine automation initiatives, where connectivity becomes critical. This paper presents the first set of results comprising measurements under a gamut of propagation conditions. A second paper detailing sub-GHz propagation is also in preparation. The results indicate that conventional wisdom is wrong, in other words, Radio Frequency (RF) propagation in surface mines can be far more elaborate than plain free-space line-of-sight conditions. Additionally, the old mining adage "no two mines alike" seems to remain true in the RF domain.

I Introduction

Mining is as old as human civilization, and still remains one of the most essential industrial activities, being responsible for 1% of the workforce worldwide and a revenue of more than 400 billion dollars per year. In traditional operations, radio network planning and optimization are afterthoughts, typically carried out on a reactive basis via trial-and-error procedures. Consequently, coverage holes and data service outages are common. When bespoke Wi-Fi solutions become an insurmountable bottleneck, self-healing IEEE 802.11 mesh networks augmented by proprietary algorithms are the go-to solutions for the vast majority of miners [1]. In short, radio propagation was little more than a nuisance.

However, the decreasing prices of ores, combined with a highly competitive market have been pushing this industry to increase its operational efficiency. In this context, remotely operated, autonomous equipment and systems have emerged as the technical solution promising a broad range of benefits, including enhanced employee health and safety conditions, higher productivity, and reduced environmental impacts. But, given the mobile nature of surface mining equipment, wireless networks have taken center stage as they form the backbone of unmanned operations. As such, proper planning and constant optimization can no longer be overlooked [2,3]. The quality of radio network planning depends on the accuracy of RF propagation models, and, while channel characterization for underground mines have been widely investigated [4,5], the same cannot be said about open-pit mines, in which only two references were found. In [6], a geometric model is proposed based on the complete knowledge of the environment, so that the direct, reflected and diffracted fields are calculated and used for the prediction of the received field strength at a specific location. In [7] the authors present a study of the channel impulse response in the 2.4 GHz band, based on a set of wideband measurements. Their conclusion is that the increased delay spread limits the performance of OFDM systems such as LTE and Wi-Fi with standard cyclic prefix values.

More empirical data is clearly needed, in order to develop and validate large-scale and small-scale channel characterization. While GIS, ray-tracing techniques and models such as the one proposed in [6] can also play an important role in characterization and optimization of smaller areas, we believe that a simplified model can be helpful for quick determination of link budgets, dominance areas and network capacity in open-pit mines. Our paper presents a first look at large-scale channel characterization in open-pit mines, considering both macro cell and small cell deployments operating at the 2.6 GHz band. These results, collected in distinct scenarios, is used as a starting point for the definition of simple propagation models in this atypical industrial environment.

The remainder of this paper is organized as follows. Section II describes the measurement scenarios and setup. Section III details the data processing and calibration procedures. In Section IV we discuss the measurement results and present empirical path loss models considering the distinct scenarios and base station deployment configurations. Finally, Section IV concludes the paper and outlines future research directions.

II Measurement Scenario, Setup and Challenges

The selected mines are located in the Iron Quadrangle region in Minas Gerais, Brazil. This region supplies approximately 200 million metric tons of iron ore per year. In order to study the propagation characteristics in open-pit mines, extensive drive-tests were carried out in April and May 2017 (dry weather periods). It is important to mention the many practical challenges associated with measurement campaigns in such restricted and risky industrial environments: rigorous safety and security protocols, rock blasting procedures that constrain and interrupt the measurement process, unpaved roads and tracks, absolute traffic priority given to haul trucks and large machinery, limited infrastructure for this kind of activity due to the mutant nature of mines, and business pressures. These difficulties might help explain the lack of empirical data in the literature. Considering all these impediments, the criteria used for selecting the transmitter locations were:

- Coverage planning: with the help of a commercial prediction tool, transmitters were positioned with the aim to cover all relevant areas in the mine (crusher, waste piles, pits)

- Accessibility and safety: regular cars may not access all areas of the mine, especially during the periods when haul trucks are allowed to drive at high speed. Furthermore, the location of transmitters, especially small cells, needs to be safe, blocked and properly signaled. Therefore, this criterion was important in selecting the transmitter locations in different periods of the day.
- Infrastructure availability: we used the existing infrastructure in terms of power sources, towers and CoW.
- Coverage holes: prior to the field work, a series of coverage predictions were made in order to determine the ideal location of small cells. The final decision combined this information with suggestions from mine personnel.
- Scenario diversity: whenever possible, small cell locations were chosen to cover distinct scenarios within the mine.

A. Measurement Scenario

Despite all challenges, a vast amount of measurement data was collected: in total, more than 800 km were driven. Fig. A.1 and Fig. A.2 illustrate the location of the transmitters in mining complexes 1 and 2, as well as the measurement routes. The scale is in meters.

The complex in Fig. A.1 has been mined since 1942 and spans a 12 km long and 5 km wide area. The second mine shown in Fig. A.2 was inaugurated in 2006 and is at an earlier stage of life. It consists of a single pit and covers an area that is 4 km long and 2.3 km wide.

Besides the differences in dimensions and lifetime, the mines also differ in terms of terrain profiles. Figures A.3 and A.4 show, in blue, the altitude of the terrain profile, in meters, as a function of the two-dimensional distance between one of the transmitters and the lowest altitude receiver position for mines 1 and 2, respectively. Mine complex 1 is characterized by the three deep pits, each resembling a hollow inverted pyramid, while mine's 2 pit is actually located on a hillside. For this reason, we will denote mines 1 and 2 as the inverted pyramid mine and the hillside mine, respectively.

B. Measurement Setup

The transmitted signal, a Continuous Wave (CW), was generated by a Keysight signal generator, and transmitted by an omnidirectional antenna, with 60° elevation beamwidth and 6 dBi gain. Additionally, in macro cell deployments, a power amplifier was used in order to extend the measurement range. The Effective Isotropic Radiated Power (EIRP) in each transmitter is described

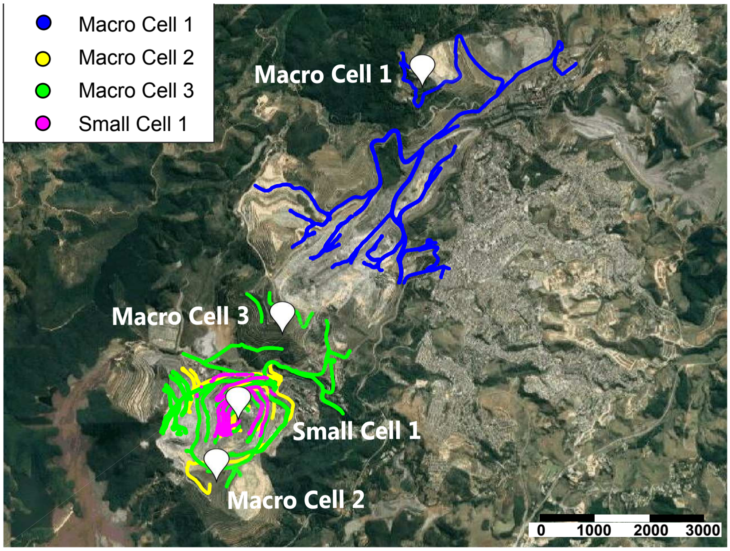


Fig. A.1: Measurement routes and transmitter locations at mine 1.

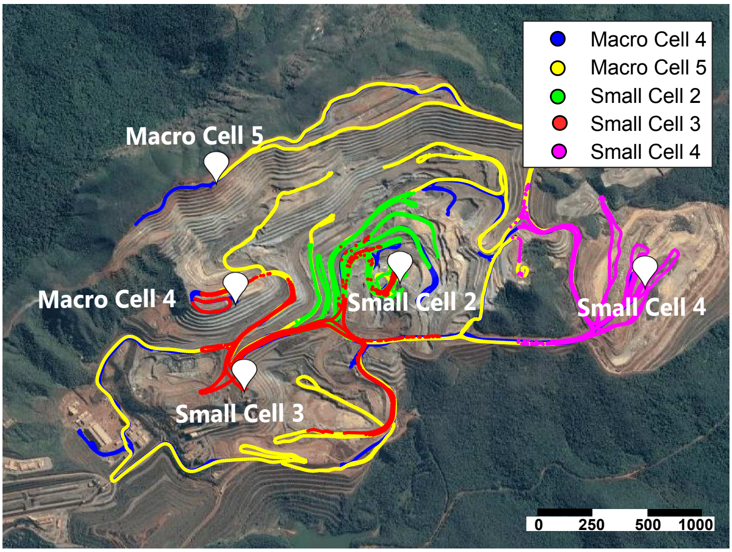


Fig. A.2: Measurement routes and transmitter locations at mine 2.

in Table A.1, as well as the antenna heights in each case. The receiver was mounted on a vehicle and the omnidirectional antenna, with 3 dBi gain, was placed on the rooftop, at 1.8 m. This vehicle was driven at an average speed of 35 km/h and all the routes were traversed at least twice. The received signal strength and GPS locations were recorded using the R&S TSMW Universal Radio Network Analyzer at a rate of 150 samples/s. In total, more than 8 million raw samples were collected during this measurement campaign.

Mine	Transmitter Type	Tx height above ground level [m]	EIRP [dBm]
1	Macro Cell 1	55	47
1	Macro Cell 2	5.5	48
1	Macro Cell 3	42	48
2	Macro Cell 4	40	50
2	Macro Cell 5	5	50.1
1	Small Cell 1	5.5	17.1
2	Small Cell 2	5	17.2
2	Small Cell 3	5	17.2
2	Small Cell 4	3.5	17.3

Table A.1: Transmitters setup

III Data Processing

From the measurements, the the path loss (L) can be estimated by:

$$L_{[dB]} = P_{TX_{[dBm]}} - P_{RX_{[dBm]}} - L_{\text{cables}_{[dB]}} + G_{TX_{[dB]}}(\theta) + G_{RX_{[dB]}} \quad \text{(A.1)}$$

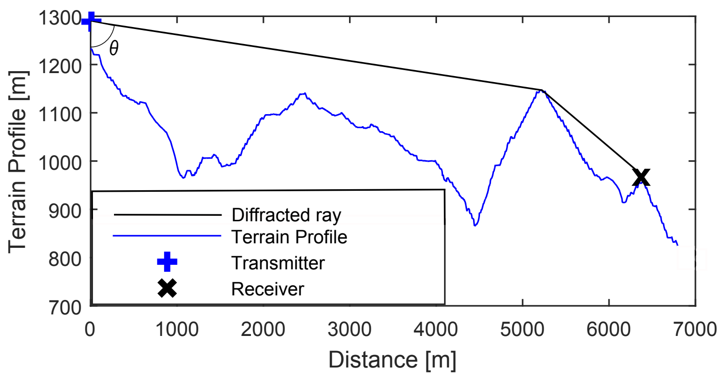


Fig. A.3: Altitude of the terrain profile between the transmitter in Macro Cell 1 and the lowest receiver position at the inverted pyramid mine. The figure also shows the diffracted ray and the angle, θ, considered in this NLOS case.

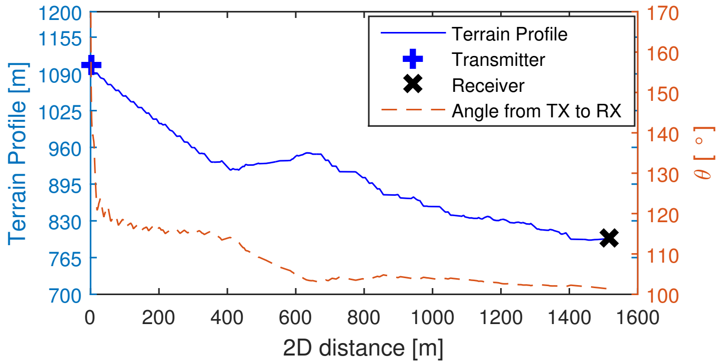


Fig. A.4: Altitude of the terrain profile between the transmitter in Macro Cell 5 and the lowest receiver position at the hillside mine. The right y-axis shows the variation of the angle, θ, in this route.

where P_{TX} represents the transmitted power, P_{RX} represents the local mean received power, averaged over distance ranges of 40λ [8–10], L_{cables} represents the combined cable losses in both Tx and Rx sides, $G_{TX}(\theta)$ and G_{RX} are the Tx and Rx antenna gains, respectively.

Both the Tx and the Rx antennas used in this study are omni-directional in the azimuth plane. Therefore, their gains depend only on the elevation angle, θ, which is calculated based on the transmitter and receiver positions. Fig. A.4 shows, in red, an example of the elevation angle variation within one of the measurement routes. In that path, the elevation angle varies from 180°, in locations below the transmitter, to 100° in locations far away from it. In order to account for this variation, the gain of the transmitter antenna is compensated accordingly, when there is LOS between transmitter and receiver. If the LOS is obstructed, the elevation angle depends on the diffracted ray, i.e. it also depends on the position and height of the obstacle relative to the transmitter. This case is illustrated in Fig. A.3, where we show an example of a diffracted ray and the considered elevation angle. Besides compensating for the transmitter's antenna pattern in LOS and NLOS conditions, we only consider samples collected within the half-power beamwidth (HPBW) of the vertical beam of the transmitter antenna. On the receiver side, we always assume the maximum antenna gain since the of angle-of-arrival cannot not be easily estimated due to the multiple received paths. Moreover, measurements below the sensitivity level of -115 dBm were filtered out during the post-processing stage. The analysis proceeds with the parametrization of a statistical large-scale path loss model. We are aware of the existence of different statistical models, such as the alpha-beta (AB) model, the close-in (CI) free-space reference distance model, and the CI model with a frequency-weighted path loss exponent (CIF) [11]. Although the CI and CIF models provide better parameter stability, in this work, we chose the AB model in order to highlight the differences between the considered scenarios (different mines and deployments). The model consists in a linear regression of the L_{dB} estimates considering a floating intercept. The path loss ($PL_{[dB]}$) is modeled as:

$$PL(d)_{[dB]} = \alpha \times 10\log_{10}(d_{[m]}) + \beta \tag{A.2}$$

The path loss exponent α and the floating intercept β can be obtained by a least squares linear regression of the path loss, L, estimates obtained in Eq. D.1:

$$\alpha = \frac{\sum_{n=1}^{N}(D_n - \overline{D})(L_n - \overline{L})}{\sum_{n=1}^{N}(D_n - \overline{D})^2} \tag{A.3}$$

$$\beta = \overline{L} - \alpha \times \overline{D} \tag{A.4}$$

where $D_n = 10\log_{10}(d_{n_{[m]}})$ is the 3D distance, in logarithmic scale, between the transmitter and the n^{th} average distance range, and $\overline{D}$ represents the average distance, also in logarithmic scale, over the considered data set. L_n represents the path loss estimate at the n^{th} average point, and $\overline{L}$ represents the average path loss over the considered data set. In order to evaluate how well the model fits with the measurement data, we also consider the RMSE:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(L_n - PL_n)^2}{N}} \tag{A.5}$$

Finally, shadow fading, σ_{SF} is also calculated to account for random variations around the mean path loss:

$$\sigma_{SF} = \sqrt{\frac{\sum (L_n - l_n)^2}{N-1}} \tag{A.6}$$

where l_n is the mean path loss over segments of 50 meters.

IV Results and Discussion

The results are shown for macro and small cells separately. However, although the deployment of macro and small cells is a reality in open-pit mines [1], there is no clear definition of what a small cell and a macro cell are in this scenario. Macro and small cell scenarios are normally defined considering heterogeneous networks deployed in urban environments. In that case, from a radio propagation perspective, macro cells are defined as those deployed in elevated outdoor position, above the rooftop of the building, typically, with transmit power higher than 24 dBm. Small cells, on the other hand, are defined as those deployed below rooftop of the building in

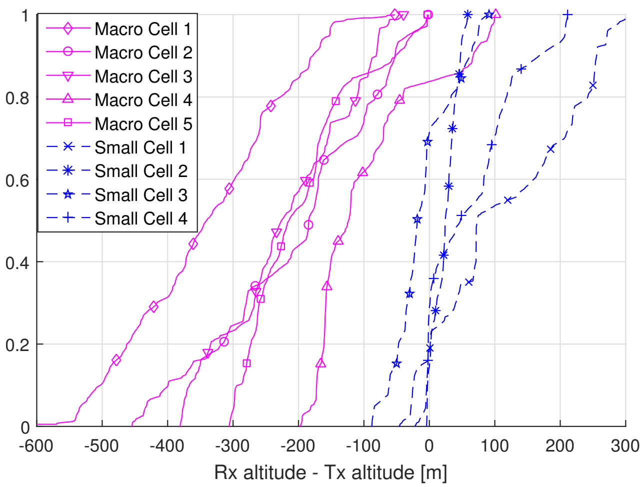


Fig. A.5: CDF plot of the difference between the receiver altitude and the transmitter altitude for all transmitters.

outdoor or indoor positions, with lower transmit power [12]. The use of the same definition is clearly not possible in this scenario.

Therefore, we propose the following definition, based on the transmitter location relative to the terrain profile: a small cell deployment is defined as the one where the transmitter is placed close to the ground level, below the median altitude of the covered area. The macro cell deployment, on the other hand, is defined as the one where the transmitter is placed in elevated positions, above the median altitude of the coverage area. The definition becomes clearer in Fig. A.5, in which the cumulative distributions of the altitude difference between the receiver and the transmitter, for each one of the transmitters, are presented. Positive altitudes are those in which the receiver is above the transmitter, and negative altitudes occur when the receiver is below the transmitter. In general, all small cells, but small cell number 3, have at least 60% of the measured locations above the transmitter height. Concerning the macro cells, all of them, but macro cell number 4, are located above the receiver, considering all the measurement routes. Small cell 3 is "on the border" of our definition of macro and small cells.

Using the model presented in Section III, we define path loss models for the transmitters. At first, a simple linear regression, using all the points measured for a given transmitter, is done. The path loss exponents, α, are shown in Table A.2 for all macro and small cell transmitters measured in the mines. This Table also shows the percentage of LOS and NLOS locations within each coverage area. Through a simple path loss exponent classification, three groups were observed.

The first group contains the macro cells deployed in the inverted pyramid mine, mine 1, described in Section II, which encompasses at least 3 large and deep pits, where most of the measurements were concentrated. The propagation in this group is characterized by path loss exponents between 1.5 and 2.1. Path loss exponents below the FSPL exponent have been found previously in the vast literature on radio propagation in underground mines, due to the waveguide effect caused by multiple reflections on tunnel walls, floor and ceiling [5,13]. Although the experiment presented here does not permit us to conclude that the same effect is present in the mine, we believe that this phenomenon should be further investigated also in the open-pit mine scenario. The second group contains the macro cells deployed in mine 2, the hillside mine. This mine, as previously mentioned, is in much earlier iron ore exploration, therefore the pit is not so deep as in mine 1. Although both scenarios consist of macro cells, the path loss exponents in mine 2, the inverted pyramid mine, are higher than those observed the hillside mine, mine 1: between 2.7 and 2.9. This is an indication that a simple path loss model cannot be generalized for macro cell deployments in open-pit mines. Finally, group 3 is composed of all small cells of both mines, and the path loss exponents are between 3 and 3.6. The larger exponent is expected considering that these transmitters are located below the median terrain altitude, placed just a few meters above the ground level when compared to the macro cells. Besides NLOS conditions caused by obstacles in the propagation path, small cells are also subject to NLOS caused by the geometry (in terms of distances and antenna heights) of transmitter and receiver: obstructions of the propagation path also occur when the first Fresnel zone touches the ground. In small cells, this location is closer to the transmitter than in macro cells, because they are placed closer to the ground level. However, due to terrain irregularities, the determination of the exact breakpoint distance is trickier in mine scenarios.

The LOS/NLOS percentage, also in Table A.2, was investigated with the

Table A.2: Path loss exponent and LOS and NLOS percentage.

Transmitter	**LOS [%]**	**NLOS [%]**	α
Macro Cell 1	43	57	2.1
Macro Cell 2	62	38	1.5
Macro Cell 3	78	22	2.1
Macro Cell 4	78	22	2.9
Macro Cell 5	65	35	2.7
Small Cell 1	22	78	3.3
Small Cell 2	19	81	3.6
Small Cell 3	54	45	3.6
Small Cell 4	39	61	3

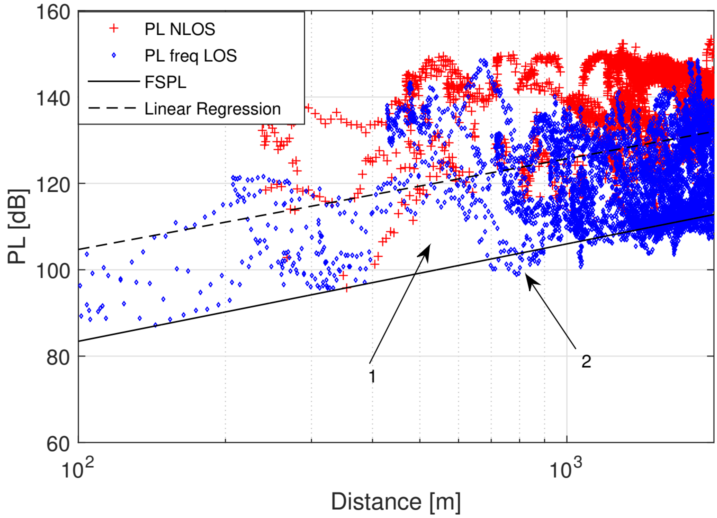


Fig. A.6: Path loss and linear regression for all Macro Cell transmitters in the inverted pyramid mine (1).

aid of DTM, with a 1 m resolution. In general, as in other scenarios, macro cells have a higher percentage of LOS samples, and small cells deployments present a higher percentage of NLOS samples. The exceptions are Macro cell 1 and Small cell 3. Macro cell 1 coverage area is mostly obstructed by at least one hill, as in Fig. A.3, which explains the higher percentage of NLOS locations. Small cell 3, on the other hand, is at the border of our definition of macro and small cells, and part of the measured points are below the transmitter altitude. LOS and NLOS percentages are strongly dependent on specific terrain characteristics. Based on the previous observations - path loss exponents and percentages of LOS/NLOS samples - we propose single slope models for macro cell deployments, one for each mine, and a dual slope model for small cell deployments in open-pit mines.

The macro cell path loss estimates and models are presented in Figures A.6 and A.7 for each mine. LOS samples are plotted in blue, and NLOS samples are plotted in red. In black, the dashed line represents the single slope model, and the solid line represents the FSPL model, for comparison. From the results, it is observed that in macro cells deployments, LOS and NLOS locations are mixed all along the distance between transmitter and receiver locations. This indicates that NLOS condition is caused by terrain obstructions, that affect specific measurement routes, rather than only by the transmitters and receivers geometries, in terms of antenna heights and distances. From the path loss results in those figures, it is also possible to notice the higher variability of the terrain in the inverted pyramid mine, mine 1, when compared to the hillside mine, mine 2. In Fig. A.6, the two arrows show how the obstacles in the terrain impact on the fluctuations over the path loss model.

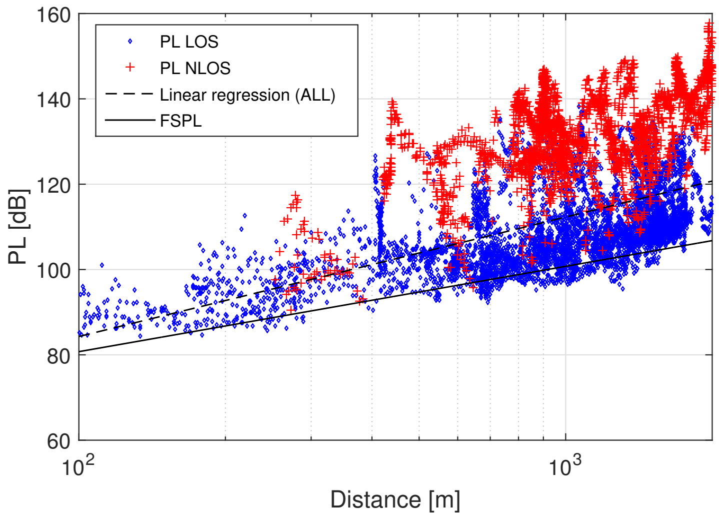


Fig. A.7: Path loss and linear regressions for all Macro Cell transmitters in the hillside mine (2).

The terrain variability in this mine also explains the difference of 20 dB considering the FSPL model. The results are further detailed in Tables A.3 and A.4. The last line of each table shows the aggregated models, fitted over all the collected data of transmitters in groups 1 and 2, respectively. The model is defined in terms of path loss exponent, α, intercept, β, shadowing σ_{SF} and RMSE. The results show a clear difference in propagation mechanisms between macro cell deployments in the inverted pyramid mine, mine 1, and in the hillside mine, mine 2, as discussed previously in Table A.2. The inverted pyramid mine aggregated results show an exponent of 2.1, in comparison to 2.8 measured in the hillside mine.

On small cell deployments, although there are distances with mixed LOS and NLOS samples, there is a clear transition distance between them where the propagation is mainly characterized by NLOS points. These cells are closer to the ground level, and the breakpoint distance, where the path loss exponent changes, occurs closer to the transmitter. For this reason, the re-

	α	β	σ_{SF}	RMSE
Macro Cell 1	2.1	59.9	11.1	12.4
Macro Cell 2	1.5	74.7	8.8	12.7
Macro Cell 3	2.1	64	9.1	10.5
All Cells	**2.1**	**62.7**	**12.3**	**12**

Table A.3: Summary of the parameters of the proposed macro cell path loss model, inverted pyramid mine (1).

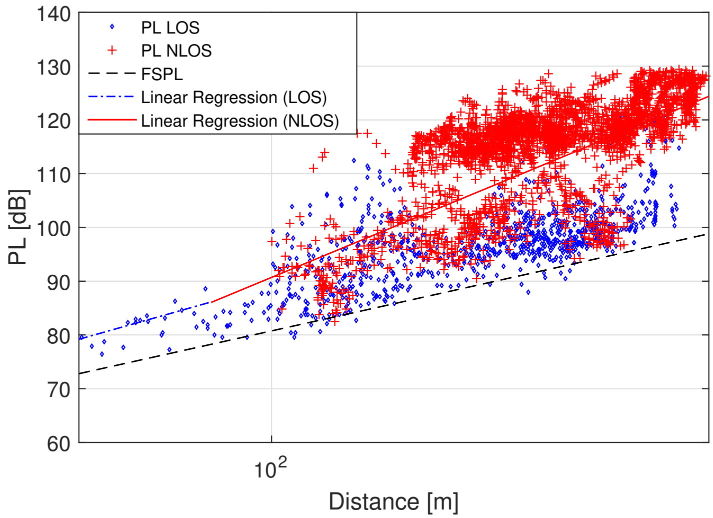


Fig. A.8: Path loss and linear regressions considering LOS and NLOS samples, for all Small Cell transmitters in mines 1 and 2.

sults are presented as a function of the obstruction, or not, of the LOS. Fig. A.8 shows the path loss estimates and models considering the aggregated samples of all transmitters in group 3 and Table A.5 summarizes the models for each one of the transmitters in the group, as well as the combined model. The results of the NLOS conditions of small cell 3 are omitted due to a limitation in our measurement setup: there was not enough measurement range to fit a model. The path loss exponent is 2.5 in LOS, and 3.7 in NLOS. Since we proposed a distinct model for LOS and NLOS, the RMSE, and shadowing values are reduced when compared to the macro cell cases.

V Conclusion

To the best of our knowledge, this paper presents the first empirical study of the large-scale radio propagation in iron ore open-pit mines at the 2.6 GHz frequency band. An extensive measurement campaign was carried out in

Table A.4: Summary of the parameters of the proposed macro cell path loss model, hillside mine (2).

	α	β	σ_{SF}	RMSE
Macro Cell 4	2.9	25.6	10.6	12
Macro Cell 5	2.7	33.9	9.9	12.5
All Cells	**2.8**	**29.8**	**11**	**12.4**

two large mining complexes located in the southeast of Brazil, where 9 transmitters were deployed in macro- and small-cell scenarios. Considering the topographic contrast between an open-pit environment and rural or urban scenarios, we rediscussed the notion of macro and small cells.We have also presented preliminary path loss models for both types of deployments.The results show that the geometry of the mines impacts the path loss exponent, implying that there are no two mines alike.

This work is part of ongoing research effort which will gradually cover other propagation characteristics in open-pit mines, such as shadowing, small-scale phenomena, and the extension to other frequency bands of interest. Our final objective is to characterize the mobile radio propagation channel in iron open-pit mines in order to support the operation of autonomous and tele-operated equipment in this challenging environment. In a broader sense, the results are of interest to those working on next radio technology and its industrial applications.

Acknowledgment

The authors would like to thank the automation, telecommunications, mineral exploration cartography, and IT teams from Vale S.A. for their valuable inputs and help.

References

[1] S. Vellingiri, D. Tandur, and M. Kande, "Energy efficient wireless infrastructure solution for open pit mine," in *Advances in Computing, Communications and Informatics (ICACCI), 2013 International Conference on*. IEEE, 2013, pp. 1463–1467.

Table A.5: Summary of the parameters of the proposed small cell path loss model.

		α	β	σ_{SF}	RMSE
Small	LOS	2.5	40.5	6.3	7.3
Cell 1	NLOS	3.9	10.8	7.3	7.6
Small	LOS	2.1	48.9	5	5.8
Cell 2	NLOS	3	41	5.3	4.9
Small	LOS	2.9	32	5.3	5.9
Cell 3	NLOS	-	-	-	-
Small	LOS	2.4	39.1	5.5	5.7
Cell 4	NLOS	3.5	15.9	5.5	7.8
All	**LOS**	**2.5**	**38.5**	**7.5**	**6**
Cells	**NLOS**	**3.7**	**15.9**	**7.2**	**7.9**

[2] L. G. U. Garcia, E. P. Almeida, V. S. Barbosa, G. Caldwell, I. Rodriguez, H. Lima, T. B. Sørensen, and P. Mogensen, "Mission-critical mobile broadband communications in open-pit mines," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 62–69, 2016.

[3] V. S. Barbosa, L. G. Garcia, G. Caldwell, and H. Lima, "The challenge of wireless connectivity to support intelligent mines," in *24th World Mining Conference (WMC)*, 2016.

[4] Z. Sun and I. F. Akyildiz, "Channel modeling and analysis for wireless networks in underground mines and road tunnels," *IEEE Transactions on communications*, vol. 58, no. 6, 2010.

[5] A. E. Forooshani, S. Bashir, D. G. Michelson, and S. Noghanian, "A survey of wireless communications and propagation modeling in underground mines," *IEEE Communications surveys & tutorials*, vol. 15, no. 4, pp. 1524–1545, 2013.

[6] J. Aitken, "Development of a radio propagation model for an open cut mine," in *20th International Electronics convention & exhibition*, 1985.

[7] R. Nilsson and J. van de Beek, "Channel measurements in an open-pit mine using usrps: 5g—expect the unexpected," in *Wireless Communications and Networking Conference (WCNC), 2016 IEEE*. IEEE, 2016, pp. 1–6.

[8] N. S. Adawi, "Coverage prediction for cellular mobile radio system operating in the 800/900 mhz frequency band," *IEEE Trans. on Vehicular Technology*, vol. 37, no. 1, pp. 3–72, 1988.

[9] W. C. Lee, *Mobile communications engineering*. McGraw-Hill Professional, 1982.

[10] J. D. Parsons and P. J. D. Parsons, "The mobile radio propagation channel," 1992.

[11] S. Sun, T. S. Rappaport, T. A. Thomas, A. Ghosh, H. C. Nguyen, I. Z. Kovács, I. Rodriguez, O. Koymen, and A. Partyka, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5g wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843–2860, 2016.

[12] I. Rodriguez, "An empirical study on radio propagation in heterogeneous networks: with focus on mobile broadband networks and small cell deployment," Ph.D. dissertation, Aalborg Universitetsforlag, 2016.

[13] M. Liénard and P. Degauque, "Natural wave propagation in mine environments," *IEEE Transactions on Antennas and Propagation*, vol. 48, no. 9, pp. 1326–1339, 2000.

Paper B

5G in Open-Pit Mines: Considerations on Large-Scale Propagation in Sub-6 GHz Bands

Erika P. L. Almeida, George Caldwell, Ignacio Rodriguez,
Robson D. Vieira, Troels B. Sørensen,
Preben Mogensen and Luis G. Uzeda Garcia

Published at the *IEEE Globecom Workshops (GC Wkshps)*

Abstract

5G will play a pivotal role in the digitization of the industrial sector and is expected to make the best use of every bit of spectrum available. In this light, this paper presents the results of an extensive measurement campaign in two iron-ore open-pit mining complexes, at the 700 MHz and 2.6 GHz bands, considering macro and small cell deployments. The study is further motivated by the rise of unmanned machinery in the mining industry. We present values of path loss exponents, shadow fading standard deviations, autocorrelation distances and inter-frequency cross-correlation, which are all useful for the future wireless network design, simulation and performance evaluation. The results show that, in order to comply with ultra-reliable communications (URC) availability requirements, larger shadowing margins will have to be considered in the network planning in open-pit mines, when compared to traditional industrial environments. Furthermore, large cross-correlation between the shadowing in both frequency bands limits the gains when using multi-connectivity in order to enhance overall network availability.

I Introduction

The mining industry has a long history of reliance on wireless communications; radio was initially introduced to support mission-critical voice services. Gradually, new applications such as fleet management, real-time telemetry and GPS-augmentation systems required those voice networks to be complemented by narrowband solutions, such as TETRA and TEDS. Lately, broadband technologies such as WiMAX, Wi-Fi and even LTE coexist with narrowband technologies, supporting applications such as video surveillance, real-time data acquisition and analytics [1,2].

The need for continuous safety improvements and increased operational efficiency is pushing this industry towards unmanned operations. In fact, large-scale automation initiatives are already a reality at mine sites around the world [3]. New applications such as autonomous haulage systems (AHS), teleoperated bulldozers and excavators pose much more strict requirements in terms of network availability, accessibility, reliability, capacity and latency when compared to previous applications [4,5]. In practice, the industrial networking requirements set by robotic mining are in line with those associated with URC in 5G wireless systems [5–7].

However, due to the peculiar scenario and nature of operation, surface mining sites differ from traditional indoor industrial environments. For example, open-pit mines are outdoor scenarios, usually kilometers wide, and hundreds of meters deep. Furthermore, due to the nature of the mining activity, the scenario changes on a daily basis, also modifying the propagation environment [3].

In order to achieve such stringent availability requirements in a wireless network, it is crucial to have a deep understanding of the radio propagation channel. Despite the mining industry reliance on wireless communications, radio propagation in surface mines has not been explored as extensively as in underground mines [8]. In the case of open-pit mines, only a limited set of references was found. In [9], a geometric model is proposed based on the complete knowledge of the environment, however no measurements were presented to testify the results. In [10] the authors present a study of the channel impulse response in the 2.4 GHz band, based on wideband channel sounding. The conclusion is that the increased delay spread limits the performance of orthogonal division multiplexing (OFDM) systems such as LTE and Wi-Fi, with standard values of cyclic prefix. In a previous work [11], we proposed three path loss models based on measurements in the 2.6 GHz band and showed that, also from the radio propagation perspective, there are no two mines alike.

While there is no doubt that millimeter wave bands will be important for future 5G solutions in industrial scenarios, sub-6GHz spectrum is also very attractive in terms of cost and usability. Therefore, the aim of this paper is to present and discuss recent measurement results at low- and mid-bands, namely the 700 MHz (sub-1GHz) and the 2.6 GHz spectrum bands in open-pit mining scenarios. Here, we investigate large scale propagation in terms of path loss, shadowing, shadowing correlation distance and inter-frequency shadowing correlation. Those values are important to standardization forums and for evaluating future URC technology in this environment.

The remainder of this paper is organized as follows. Section II describes the measurement scenario, setup and the data processing. Section III presents the results and discusses their implications on the design of reliable networks in open-pit mines. Finally, Section IV concludes the paper.

II Methodology

In this section, we describe the methodology used in the measurement campaign and further data processing. The measurement campaign was performed in two iron-ore open-pit mine complexes located in Brazil, between April and May 2017. Figures B.1 and B.2 show aerial views of these mines, as well as the measurement routes and transmitter locations. Their legends also show the antenna height (h) above ground level for each transmitter.

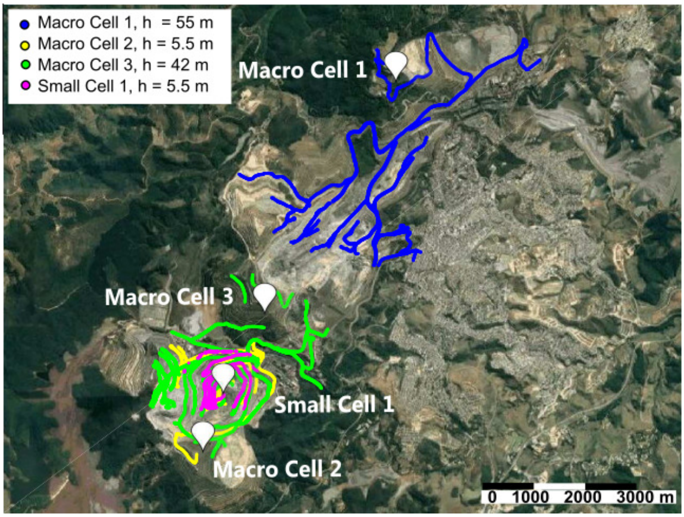


Fig. B.1: Measurement routes and transmitter positions in Mine 1. The height above ground level, h, is also displayed in the legend.

A. Measurement scenario and setup

Mining complex 1, Figure 1, has been in exploration since 1942 and comprises an area of approximately 60 km^2 (12 km $\times$ 5 km), with three main pits. The altitude of the highest transmitter, is 1300 meters above the sea level, while the lowest receiver position is located at an altitude of 810 meters. Anticipating the deployment of heterogeneous networks (HetNet), small cells have been incorporated, at this layer the absolute altitude difference is limited to 300 meters. Mine 2, Figure 2, a single-pit mine inaugurated in 2006 has an area of approximately 9.2 km^2 (4 km $\times$ 2.3 km). The altitude variation between transmitters and receiver positions in this mine ranges from 400 meters at the macro layer to 200 meters at the small cell layer.

Since open-pit mine terrain characteristics differ from those found in urban and suburban scenarios, it is important to redefine terms as macro and small cells. As done in [11], we define a small cell deployment as the one where the transmitter is placed closer to the ground level, below the median altitude of the covered area. A macro cell deployment, on the other hand, is defined as the one in which the transmitter is placed in an elevated position, above the median altitude of the covered area. The location of macro and small cells was chosen based on the available infrastructure (radio towers, cell-on-wheels (COW), power sources), accessibility, safety and also relevance to network coverage. Prior to the measurement campaign, a preliminary network coverage planning was done with a commercial software, to support the transmitters placement and ensure that relevant areas would be covered.

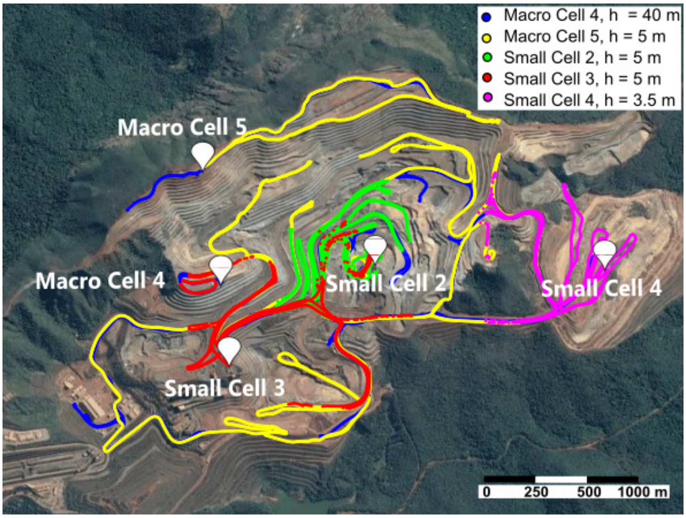


Fig. B.2: Measurement routes and transmitter positions in Mine 2. The height above ground level, h, is also displayed in the legend.

The measurements are taken in the 2.6 GHz and 700 MHz bands due to their importance to the mining industry. First, both of these bands are in the operational bands of LTE systems, which is a promising technology candidate for mission-critical communications [12]. Second, the usage of part of the 700 MHz spectrum band is under discussion in Brazil to support infrastructure and mission critical communications. Third, the 2.6 GHz band is also close to the 2.4 GHz ISM band, which is widely used in wireless networks deployments in open-pit mines in Brazil, and around the world [1]. Besides these three reasons, sub-6 GHz frequencies are already envisioned as a fundamental part of upcoming 5G technologies, specially in earlier implementation phases [7].

Two continuous wave (CW) signals were generated by a couple of Agilent signal generators (models E4438C and E4421B), combined, and transmitted on a single dual-band omni-directional antenna, with 60° elevation beamwidth. The transmitter antenna gain is 4 dBi for the 700 MHz band, and 6 dBi for the 2.6 GHz band. In all transmitters at the 700 MHz band, the EIRP was approximately 20 dBm. Small cell deployments in 2.6 GHz band EIRP was approximately 17 dBm. At the 2.6 GHz band macro cell deployments, the signal was amplified before combining in order to extend the measurement range. The final EIRP was around 50 dBm.

The receiver was mounted on a vehicle rooftop, at 1.8 m height, with two dual-band omni-directional antennas of gain equal to 1.1 dBi. The vehicle was driven at an average speed of 35 km/h and all the routes were repeated at least twice. The received signal strengths and GPS locations were collected simultaneously at both frequencies, using an R&S TSMW Universal Radio Network Analyzer at a rate of 150 samples/s.

B. Data Processing

From the measurements, the path loss per link (L) can be estimated by:

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

where P_{TX} represents the transmitted power, in dBm, P_{RX} represents the local mean received power, also in dBm, averaged over 40λ of the 700 MHz band signal in order to remove the fast fading [13,14], L_c represents the combined cable losses, in dB, at both Tx and Rx sides, $G_{TX}(\theta)$ and G_{RX} are the Tx and Rx antenna gains, in dB, respectively. It is important to mention that we have compensated the antenna pattern according to the elevation angle, θ, in degrees, between transmitter and receiver.

The analysis proceeds with the parametrization of a statistical large-scale path loss model. In this work, we chose to parametrize the alpha-beta (AB) model with floating intercept [15], in order to highlight the differences between the considered scenarios. Those differences will be further discussed in Section III. The interested reader can find the mathematical formulation of the AB model in the Appendix.

By removing the estimated mean path loss over segments of 50 meters, l_n, we create a local mean fading process representing the random variations on the local mean. Assuming that the path loss model in Eq. B.6 (Appendix) is able to predict the local mean, this random process corresponds to the shadow fading term that is usually considered in the multiplicative fading model [14]. The shadowing standard deviation can be calculated as:

$$\sigma_{SF} = \sqrt{\frac{\sum_{n=1}^{N} (L_n - l_n)^2}{N-1}} \tag{B.2}$$

where L_n represents n^{th} measured path-loss sample. Although there is no direct link between the predictions from Eq. B.1 and the local mean, it is still useful to characterize the correlation properties of the local mean fading process.

From the shadowing samples, $X_n = L_n - l_n$, we can also estimate the sample autocorrelation, $R_{XX}(d_k)$, as a function of discrete distances, d_k, as [16]:

$$R_{XX}(d_k) = \frac{\sum_{n=1}^{N-k} X_n X_{n+k}}{\sum_{n=1}^{N} X_n^2} \tag{B.3}$$

where X_n represents the shadow fading at n^{th} distance, and $d_k = k\Delta d$. In order to calculate, we have quantized the distances, d_k, with $\Delta d = 1$ meter.

Until now, all the processing was done considering one frequency at a time. However, since the measurements on both frequencies were taken simultaneously, and over the same routes, we can also calculate the inter-frequency shadowing correlation coefficient, ρ_{xy}:

$$\rho_{xy} = \frac{\sum_{n=1}^{N} X_n Y_n}{\sqrt{\sum_{n=1}^{N} X_n^2 \sum_{n=1}^{N} Y_n^2}} \tag{B.4}$$

where X represents the shadowing at the 700 MHz band, and Y denotes the shadowing at the 2.6 GHz band.

III Results and Discussion

In this section we discuss the results from the measurement campaign, presented in Table B.1. Path loss models are given in terms of the path loss exponent, α, the intercept, β, and root-mean-square error (RMSE). Table B.1 also shows the values of shadowing standard deviation, σ_{SF}, autocorrelation distances, d_{corr} and inter-frequency shadowing correlation. The results are summarized in Table B.1. Differences in the topography in mines 1 and 2 led to distinct path loss models for macro cell deployments. Mine complex 1 has at least three pits in an inverted-pyramid shape, where the measurements were located. Mine 2, on the other hand, is a hillside mine with no pits as deep as those in Mine 1. The same difference was not observed in the models for small cells. Therefore, we present two macro cell models, one for mine 1, and one for mine 2, and a single small cell model.

A. Path Loss Models

Path loss measurements and models for macro cell transmitters in mine 1 are shown in Figure B.3, considering both the 700 MHz band, in blue, and the 2.6 GHz band, in red. The path loss exponents are 2.3 and 2.1 respectively, and the intercept points are 36 and 62.7 dB. As in [11], we do not distinguish between LOS and NLOS propagation, because there is no clear breakpoint distance in case of macro cells in open-pit mines. The RMSE in each case is 10.7 and 12 dB. Results for the macro cells in Mine 2 are shown in Figure B.4, considering the two studied spectrum bands. Once again, similar path loss exponents were found for both frequencies: 3 and 2.8 for the 700 MHz and 2.6 GHz band respectively, ant β values are 8.9 and 29.8 in each case. The RMSE in each case is 10.7 and 12.4 dB.

The results of small cells are aggregated in Figure B.5. In the case of small cells, there is a clear breakpoint distance between LOS and NLOS data. We

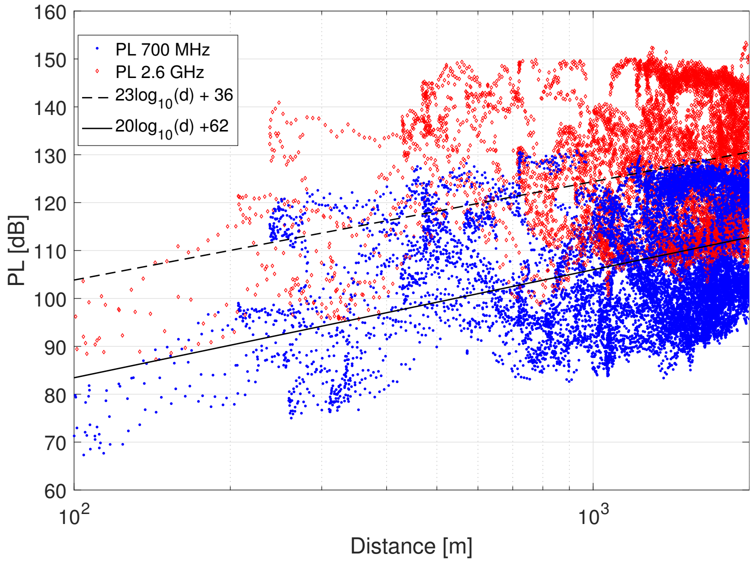


Fig. B.3: Path loss and linear regression for macro cell deployments in mine 1, at 2.6 GHz and 700 MHz band. Shadow fading standard deviation, σ_{SF}, equals 10 dB and 12.3 dB for the 700 MHz and 2.6 GHz bands respectively.

present the path loss model based on the LOS conditions, and the brekpoint distance is defined where the LOS model intersects the NLOS model. For the

Table B.1: 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} α_{NLOS}	2.3	2.1	3.0	2.8	2.4 3.7	2.5 3.7
β_{LOS} β_{NLOS}	36	62.7	8.9	29.8	30 4.9	38.5 15.9
$RMSE_{LOS}$ $RMSE_{NLOS}$	10.7	12	10.7	12.4	7 8.7	6 7.9
$\sigma_{SF_{LOS}}$ $\sigma_{SF_{NLOS}}$	10	12.3	9.5	11	8.4 7.5	7.5 7.2
$d_{corr,LOS}$ $d_{corr,NLOS}$	78.6	80.3	68.5	63.5	19.3 15	16.6 13.7
ρ_{xy}	0.87		0.92		0.81	

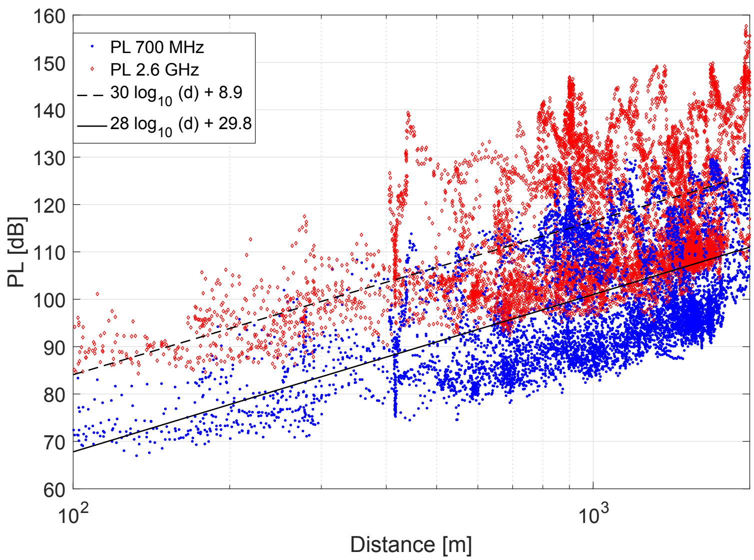


Fig. B.4: Path loss and linear regression for the macro cell deployments in mine 2, at 2.6 GHz and 700 MHz band. Shadow fading standard deviation, σ_{SF}, equals 9.5 dB and 11 dB for the 700 MHz and 2.6 GHz bands respectively.

LOS part, the path loss exponent is 2.3 for both frequencies, close to the free space path loss exponent, where α equals 2. This is aligned with the literature for small cells in urban deployments [17,18]. The frequency dependent offset between the path loss in each frequency is 8.5 dB, compared to the 10.2 dB expected from the free space path loss difference. Considering the NLOS measurements, we found path loss exponents of 3.7 considering both the 700 MHz and the 2.6 GHz band.

B. Shadowing

Shadowing standard deviations, σ_{SF}, (Table B.1) are similar at both frequencies in most deployments. The shadowing standard deviations in macro cells are between 9.5 and 12.3 dB, and in small cells they are in the range of 7.2 and 8.4 dB, depending of the line-of-sight conditions. Macro cell shadowing values are slightly higher than those recommended for the evaluation of urban macro and rural macro scenarios [19], which are 8 dB in NLOS conditions. These values will significantly impact the design of ultra-reliable networks in open-pit mines, since larger values of σ_{SF} imply larger shadow fading margins in order to obtain a certain network availability.

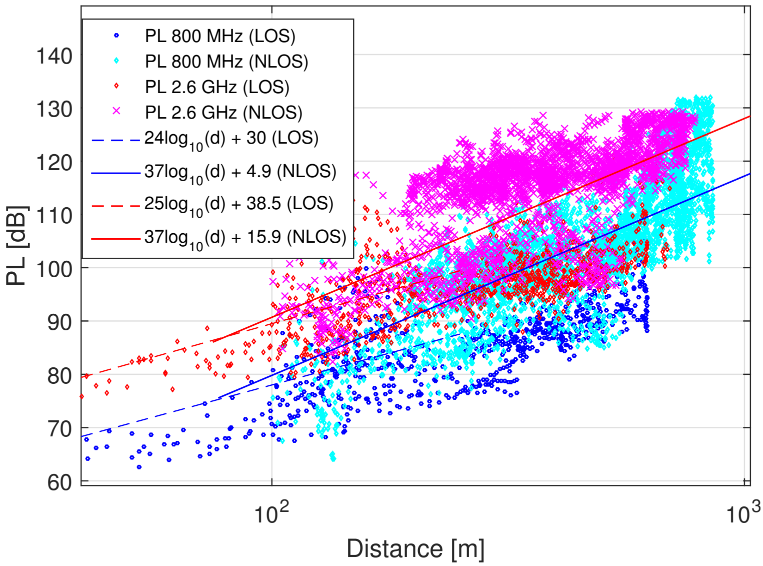


Fig. B.5: Path loss and linear regression for the small cells in mines 1 and 2, at 2.6 GHz and 700 MHz band. LOS Shadow fading standard deviation, $\sigma_{SF_{LOS}}$, equals 8.4 dB and 7.5 dB for the 700 MHz and 2.6 GHz bands respectively. $\sigma_{SF_{NLOS}}$ equals 7.5 and 7.2 dB.

C. Shadowing correlation distance

Besides the standard deviation of σ_{SF}, it is important to also investigate the spatial autocorrelation of the shadowing process, relevant to the parametrization of handover procedures. The correlation distance is calculated as the distance where the autocorrelation, Eq. B.3, reaches the value of $1/e$, and usually modeled as a first-order autoregressive process, implying an exponential decay [20]. For each transmitter, we calculated the autocorrelation considering contiguous drive-test routes of 1 km for macro cells, and 150 meters for small cells. We tested different route lengths and observed that the autocorrelation value does not change significantly for routes longer than 1 km in macro cell deployments. Small cell route lengths were chosen for the LOS and NLOS characteristics. In each case, we calculated the autocorrelation using lags within one third of the route distance. The final results are calculated as an average of each of the autocorrelation in each one of those routes. The results for three macro cell deployments in 700 MHz and 2.6 GHz bands are shown in Figure B.6 and detailed in Table B.1. Similar results were obtained for other macro and small cell deployments, but omitted from the figure due to lack of space.

Average correlation distances for macro cells deployed in mine 1 are 78.6 and 80.3 meters at 700 MHz and 2.6 GHz bands, respectively. For macro

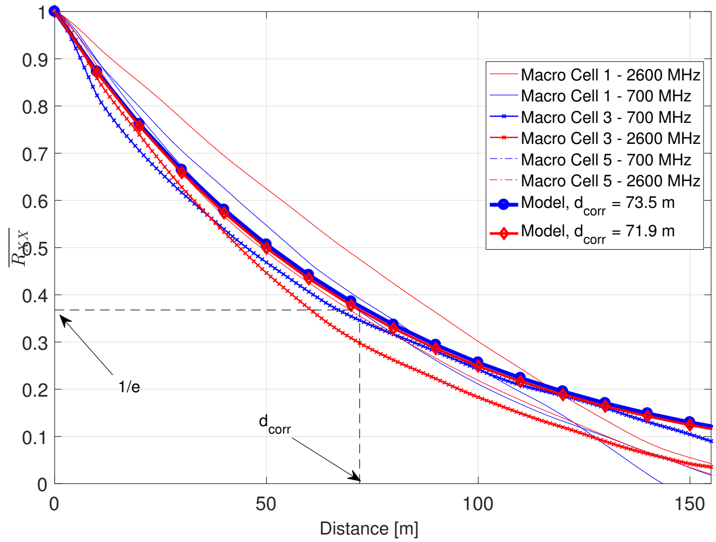


Fig. B.6: Shadow fading autocorrelation at both frequency bands, considering the deployments at mines 1 and 2

cells deployed in mine 2, these values are lower: 68.5 and 63.5 meters. These values fall within the range between urban deployments, 50 meters, and rural deployments, 120 meters [19]. These results are justified by considering that the mine topography is more rugged than a rural area, but there are not as many obstructions, such as buildings, as in a urban scenario. The model presented in [20] with the average values in each frequency band, 73.5 m and 71.9 m, is also shown in Figure B.6.

Considering small cells in LOS, average correlation distances are 19.3 and 16.6 meters, at 700 MHz and 2.6 GHz respectively. In NLOS conditions, these values are 15 and 13.7 meters. These values are slightly higher than those recommended for urban micro deployments in [19], which are respectively 10 and 13 meters.

D. Inter-frequency shadowing correlation

Finally, we investigate the inter-frequency shadow fading correlation ρ_{xy} in the 700 and 2600 MHz frequency bands. The shadow fading correlation is an important measure of the advantages of using inter-frequency multi-connectivity as a technique to enhance the availability of wireless systems, as presented in [21].

The results are shown in Table B.1. The macro cell results show values between 0.87 and 0.92, while small cell results show ρ_{xy} equal to 0.81. Highly correlated shadowing processes are expected at similar frequency bands, for example 1 or 2 GHz apart, since both experience the same shadowing effects. The results at the mine environment are in agreement with those observed in urban deployments, at the 955 MHz and 1.8 GHz bands [18].

E. Discussion

Knowledge about large-scale propagation is fundamental in the design and performance evaluation of wireless networks, especially when considering the strict availability requirements of URC networks. Here, we discuss the results in light of the impact they will have on the design of wireless networks in open-pit mines.

Path loss exponents and intercept values, for example, are very useful for quick link budget and system capacity estimation. The results show that, similar to urban deployments [18], the path loss exponents are comparable in the two frequency bands. Differences in the mines topographies led to distinct path loss models. In the first mine, path loss exponents in the order of 2 were found, and in the second mine, those exponents were in the order of 3. Considering small cells, the results are shown according to the LOS conditions. In the LOS part, exponents in the order of 2, and in the NLOS part, they are in the order of 4. Differences between macro and small layers can also be exploited on the design of ultra-reliable heterogeneous wireless networks in open-pit mines. For example, in co-channel deployments, high path loss exponents provide a natural isolation from interference [3].

Shadowing standard deviations for macro cells, are between 9.5 and 12.3 dB considering both frequency bands. For small cells, the shadowing standard deviation is between 7.2 and 8.4 dB, depending on the frequency and LOS conditions. Macro cell values are slightly higher than those found in urban, suburban and industrial environments. The direct implication is the increase in shadow fading margins in order to support URC, leading to denser networks. For example, considering a log-normal shadowing, the availability (probability that the received signal power x is higher than a threshold x^{URC}) is calculated as [22]:

$$P(x > x^{URC}) = 1 - Q\left(\frac{SF_{margin}}{\sigma_{SF}}\right) \tag{B.5}$$

where Q is the error function: $Q(x) = \frac{1}{2}\mathrm{erfc}\left(\frac{x}{\sqrt{2}}\right)$. An outage probability in the order of 10^{-5} considering the most restrictive σ_{SF} for macro cells, 12.3 dB, as a simple consideration, would require a shadow fading margin of 50 dB. For small cells, considering the highest σ_{SF} value, the necessary margin would be 35 dB. Considering the same outage probability, indoor industrial environments need, in contrast, a shadow fading margin of 28 dB according to [22].

Shadowing correlation distances were similar for macro cells in both frequency bands: approximately 72 meters. Considering small cells, the LOS correlation distance is between 16.6 and 19.3 meters, and the NLOS correlation distance is between 13.7 and 15 meters. These values are higher than those found in urban deployments, and smaller than the recommended for rural environments, and should be considered in the parametrization of handover procedures in open-pit mines. Parameters like time-to-trigger and hysteresis need to be set accordingly based on the scenario and cell-type, in order to balance the probability of handover and the probability of outage. Furthermore, the speed of the user-equipment (UE) need to be considered. In the mine, this is quite diverse: while as drillers and bulldozers are most of the time static or subject to very limited mobility, hauling trucks can drive up to 50 km/h within the main mine routes.

Finally, we presented the inter-frequency cross-correlation of shadowing for deployments at 700 MHz and 2.6 GHz. The correlation values are between 0.81 and 0.92 in macro and small cell deployments. In [21], the author investigates the availability gains when using simultaneously different carrier frequencies to send data through the network. Different combinations of frequencies were investigated, in the sub-6 GHz band (2 and 2.5 GHz) and in also in the mmWave spectrum (15, 28 and 73 GHz). In all cases, as the shadowing correlation between the frequencies increases, the availability gain obtained through multi-connectivity reduces, for there is no diversity with respect to shadowing. However, it is important to highlight that the network can still exploit macro diversity. Following the same analysis presented in [21], our results indicate that the availability gain of multi-connectivity in this combination of frequencies, 700 MHz and 2.6 GHz, can be rather limited in open-pit mines.

IV Conclusion

In this paper, we presented original results from an extensive measurement campaign in a industrial setting where sub-6GHz 5G wireless systems are expected to play an important role in the near future, namely open-pit mines. We have focused on large scale propagation at the 700 MHz and 2.6 GHz frequency bands. The results show that mine topography significantly impact the macro cell path loss models. Furthermore, shadow fading statistics (standard deviation, autocorrelation distances, inter-frequency shadowing correlation) have been diligently examined for both bands in HetNet scenarios. Observed shadow fading variances of up to 12.3 dB may imply network densification in order to achieve URC availability requirements. Furthermore, we have observed high inter-frequency shadowing correlation, which limits the availability gains of multi-connectivity in this combination of frequencies.

Our results will be useful for the design, modeling and evaluation of wireless networks supporting unmanned mining initiatives.

V Appendix

The AB model consists in a linear regression of the L_{dB} estimates considering a floating intercept. The path loss ($PL_{[dB]}$) is modeled as:

$$PL(d)_{[dB]} = \alpha \cdot 10\log_{10}(d_{[m]}) + \beta \tag{B.6}$$

The path loss exponent α and the floating intercept β can be obtained by a least square linear regression of the path loss, L, estimates obtained in Eq. B.1:

$$\alpha = \frac{\sum_{n=1}^{N}(D_n - \overline{D})(L_n - \overline{L})}{\sum_{n=1}^{N}(D_n - \overline{D})^2} \tag{B.7}$$

$$\beta = \overline{L} - \alpha \times \overline{D} \tag{B.8}$$

where $D_n = 10\log_{10}(d_{n_{[m]}})$ is the 3D distance, in logarithmic scale, between the transmitter and the n^{th} average distance range, and $\overline{D}$ represents the average distance, also in logarithmic scale, over the considered data set. L_n represents the path loss estimate at the n^{th} average point, and $\overline{L}$ represents the average path loss over the considered data set. We also consider the root mean square error $RMSE = \sqrt{\frac{\sum_{n=1}^{N}(L_n - PL_n)^2}{N}}$.

Acknowledgment

The authors would like to thank the Operational Techonlogy and Information Technology teams from Vale S.A. for their valuable inputs and help during the measurement campaign.

References

[1] S. Vellingiri, D. Tandur, and M. Kande, "Energy efficient wireless infrastructure solution for open pit mine," in *Advances in Computing, Communications and Informatics (ICACCI), 2013 International Conference on*. IEEE, 2013, pp. 1463–1467.

[2] T. Sens. (2016) Private LTE a game changer for industries. [Online]. Available: https://www.nokia.com/blog/private-lte-game-changer-industries/

[3] L. G. U. Garcia, E. P. Almeida, V. S. Barbosa, G. Caldwell, I. Rodriguez, H. Lima, T. B. Sørensen, and P. Mogensen, "Mission-critical mobile broadband communications in open-pit mines," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 62–69, 2016.

[4] V. S. Barbosa, L. G. Garcia, G. Caldwell, and H. Lima, "The challenge of wireless connectivity to support intelligent mines," in *24th World Mining Conference (WMC)*, 2016.

[5] A. Boulter and R. Hall, "Wireless network requirements for the successful implementation of automation and other innovative technologies in open-pit mining," *International Journal of Mining, Reclamation and Environment*, vol. 29, no. 5, pp. 368–379, 2015.

[6] A. Frotzscher, U. Wetzker, M. Bauer, M. Rentschler, M. Beyer, S. Elspass, and H. Klessig, "Requirements and current solutions of wireless communication in industrial automation," in *Communications workshops (ICC), 2014 IEEE international conference on*. IEEE, 2014, pp. 67–72.

[7] M. Series, "Imt vision–framework and overall objectives of the future development of imt for 2020 and beyond," *Recommendation ITU*, pp. 2083–0, 2015.

[8] A. E. Forooshani, S. Bashir, D. G. Michelson, and S. Noghanian, "A survey of wireless communications and propagation modeling in underground mines," *IEEE Communications surveys & tutorials*, vol. 15, no. 4, pp. 1524–1545, 2013.

[9] J. Aitken, "Development of a radio propagation model for an open cut mine," in *20th International Electronics convention & exhibition*, 1985.

[10] R. Nilsson and J. van de Beek, "Channel measurements in an open-pit mine using usrps: 5g—expect the unexpected," in *Wireless Communications and Networking Conference (WCNC), 2016 IEEE*. IEEE, 2016, pp. 1–6.

[11] E. P. Almeida, G. Caldwell, I. Rodriguez, S. Abreu, R. D. Vieira, V. S. Barbosa, T. B. Sørensen, P. Mogensen, and L. G. U. Garcia, "Radio propagation in open-pit mines: a first look at measurements in the 2.6 ghz band," in *28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,(PIMRC)*, 2017.

[12] GSMA, "Network 2020: Mission critical communications," GSMA, Tech. Rep., 2017.

[13] N. S. A. et al, "Coverage prediction for mobile radio systems operating in the 800/900 mhz frequency-range," *IEEE Transactions on vehicular technology 37.1*, vol. 37, no. 1, 1988.

[14] W. C. Lee, *Mobile communications engineering*. McGraw-Hill Professional, 1982.

[15] S. Sun, T. S. Rappaport, T. A. Thomas, A. Ghosh, H. C. Nguyen, I. Z. Kovács, I. Rodriguez, O. Koymen, and A. Partyka, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5g wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843–2860, 2016.

[16] E. Tanghe, W. Joseph, L. Verloock, L. Martens, H. Capoen, K. Van Herwegen, and W. Vantomme, "The industrial indoor channel: large-scale and temporal fading at 900, 2400, and 5200 mhz," *IEEE Transactions on Wireless Communications*, vol. 7, no. 7, 2008.

[17] I. Rodriguez, "An empirical study on radio propagation in heterogeneous networks: with focus on mobile broadband networks and small cell deployment," Ph.D. dissertation, Aalborg Universitetsforlag, 2016.

[18] P. E. Mogensen, P. Eggers, C. Jensen, and J. B. Andersen, "Urban area radio propagation measurements at 955 and 1845 mhz for small and micro cells," in *Global Telecommunications Conference, 1991. GLOBECOM'91.'Countdown to the New Millennium. Featuring a Mini-Theme on: Personal Communications Services*. IEEE, 1991, pp. 1297–1302.

[19] I. M. Series, "Guidelines for evaluation of radio interface technologies for imt-advanced." ITU, Tech. Rep., 2009.

[20] M. Gudmundson, "Correlation model for shadow fading in mobile radio systems," *Electronics letters*, vol. 27, no. 23, pp. 2145–2146, 1991.

[21] D. Öhmann, A. Awada, I. Viering, M. Simsek, and G. P. Fettweis, "Achieving high availability in wireless networks by inter-frequency multi-connectivity," in *Communications (ICC), 2016 IEEE International Conference on*. IEEE, 2016, pp. 1–7.

[22] B. Singh, Z. Li, O. Tirkkonen, M. A. Uusitalo, and P. Mogensen, "Ultra-reliable communication in a factory environment for 5g wireless networks: link level and deployment study," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2016 IEEE 27th Annual International Symposium on*. IEEE, 2016, pp. 1–5.

Paper C

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

Erika P. L. Almeida, George Caldwell, Ignacio Rodriguez,
Robson D. Vieira, Troels B. Sørensen, Preben Mogensen
and Luis G. Uzeda Garcia

Published at the *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*

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.

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:

$$L = P_{TX} + G_{TX}(\theta) + G_{RX} - P_{RX} - L_c \tag{C.1}$$

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:

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

where free space loss is given by:

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

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:

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

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. (C.4) and it is calculated as:

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

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

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

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:

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

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

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

model that estimates the path loss, $PL_{\alpha\beta}$, based on the linear regression of the path loss estimates given by Eq. (C.1):

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

The path loss exponent, α, and the intercept, β, are obtained by means of a least squares linear regression of the L samples. The fitting procedure is detailed in [5]. For convenience, the values of α and β for each case are repeated in Table C.1. It is important to note that the Macro Cell models do not differentiate between LOS and NLOS samples.

Table C.1: 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:

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

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. (C.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 C.1.

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

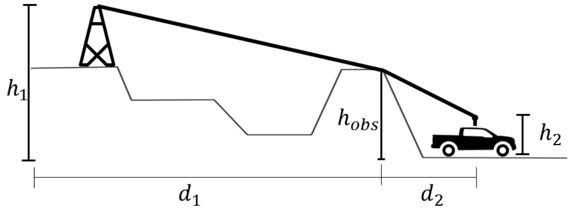


Fig. C.1: Illustration of the parameters used to calculate h and ν in Eq. C.10 and Eq. C.11.

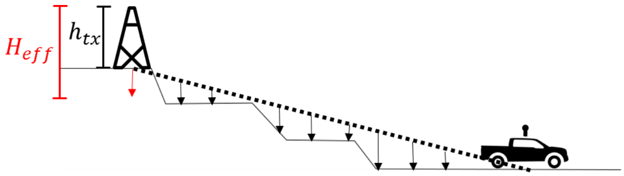


Fig. C.2: Example of the calculation of H_{eff} as proposed in [9]. The red arrow represents the average difference between the dashed line connecting the ground levels of Tx and Rx in respect to the terrain profile, which is subtracted from h_{tx}.

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

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

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

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

The last term in Eq. C.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 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 Fig. C.2.

IV Results

Table C.2 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 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.

Table C.2: 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

Table C.3: SPM Calibration

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

The *SPM* model, on the other hand, permits the adjustment of a group of calibration factors as discussed in Section A., which are shown in Table C.3. The results are shown considering two distinct types of calibration: one considering the individual calibration (row SPM in Table C.2), and another considering the data from all transmitters for calibration (row SPM All in Table C.2). 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.

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.

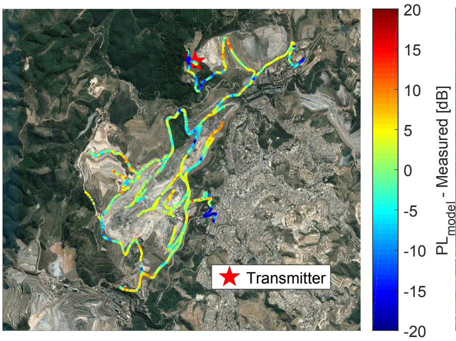
Therefore, in order to evaluate the model general applicability to the mining scenario, we also calibrated it considering all the data from the 8 transmitters. In this case, the RMSE values varied from 5.3 dB and 10.3 dB, and the median RMSE value is 6.7 dB. Still, it is better than the other models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

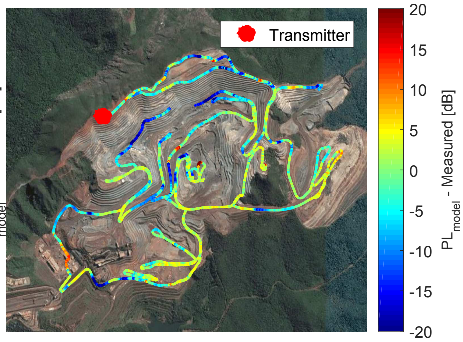
The empirical (*AB*) models had an intermediary fit between the ITU-526, Okumura Hata and Cost models, and the median RMSE value was 11.1 dB. The RMSE values considering the AB model fit in Table C.2 vary from 7.9 dB to 13.8 dB. These values are different from the ones in [5], where we used the entire 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 C.2), 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.

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





(a) **(b)**

Fig. C.3: Difference between the predicted path loss PL_{Vale} and the measured path loss, L. (a) Macro Cell 1, in Mine 1, at 700 MHz, (b) Macro Cell 4, in Mine 2, at 2600 MHz.

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 Fig. C.3a and Fig. C.3b, 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. 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 C.1.

Figure C.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

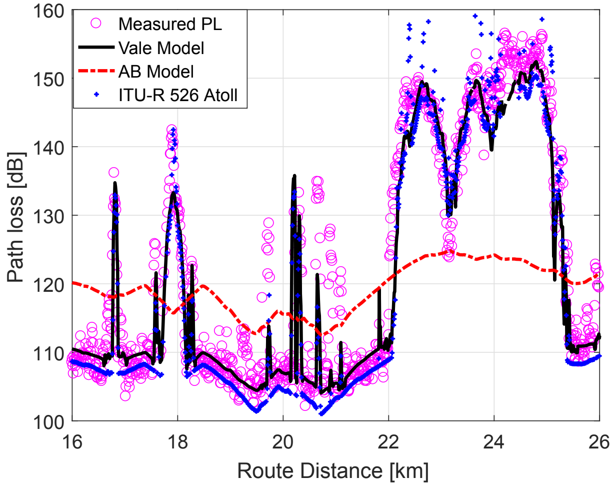


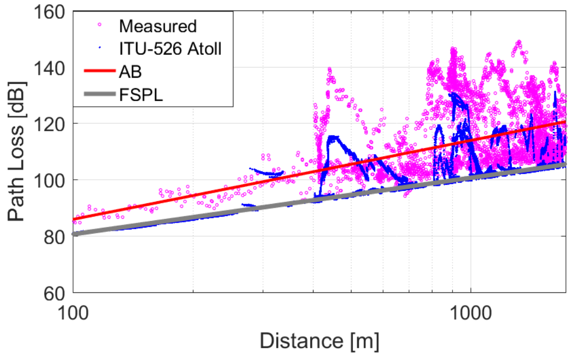
Fig. C.4: Measured L, PL_{Vale}, $P_{\alpha\beta}$ and $P_{ITU_{526}}$, as a function of the driven distance. Macro Cell 4 drive test, at 2.6 GHz.

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

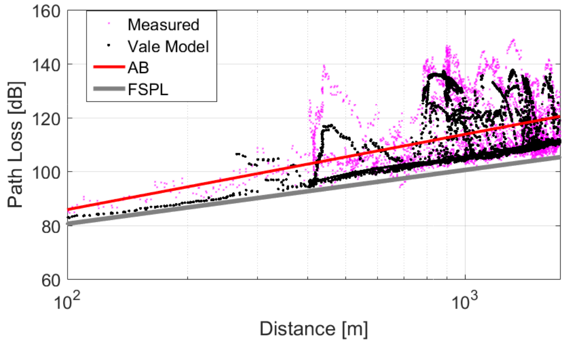
This observation becomes clearer in Fig. C.5. Fig. C.5a shows the comparison of the path loss results as a function of the distance between Tx and Rx. In blue, we see the results from ITU-526 model, and in pink the measured results. One can see that the ITU-526 model underestimates the PL for not considering the effect of the effective antenna height. On the other hand, Fig. C.5b 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 C.1, 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.



(a)



(b)

Fig. C.5: Path loss as a function of the distance between Tx and Rx for Macro Cell 4, in 2.6 GHz. (a)Measured data, AB, FSPL and ITU-R 526 as implemented in Atoll. (b) Measured data, AB, FSPL and proposed model, with $k = 3$.

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.

References

[1] L. G. U. Garcia, E. P. L. Almeida, V. S. Barbosa, G. Caldwell, I. Rodriguez, H. Lima, T. B. Sørensen, and P. Mogensen, "Mission-critical mobile broadband communications in open-pit mines," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 62–69, 2016.

[2] A. E. Forooshani, S. Bashir, D. G. Michelson, and S. Noghanian, "A survey of wireless communications and propagation modeling in underground mines," *IEEE Communications surveys & tutorials*, vol. 15, no. 4, pp. 1524–1545, 2013.

[3] J. Aitken, "Development of a radio propagation model for an open cut mine," in *20th International Electronics convention & exhibition*, 1985.

[4] E. P. L. Almeida, G. Caldwell, I. Rodriguez, S. Abreu, R. D. Vieira, V. S. Barbosa, T. B. Sørensen, P. Mogensen, and L. G. U. Garcia, "Radio Propagation in Open-pit mines: a first look at measurements in the 2.6 GHz band," in *28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,(PIMRC)*, 2017.

[5] E. P. L. Almeida, G. Caldwell, I. Rodriguez, R. D. Vieira, T. B. Soerensen, P. Mogensen, and L. G. U. Garcia, "5G in open-pit mines: Considerations on large-scale propagation in sub-6 GHz bands," in *Globecom Workshops (GC Wkshps), 2017 IEEE*. IEEE, 2017, pp. 1–6.

[6] Forsk, "Atoll: Technical reference guide for radio networks v3.2.2," 2015.

[7] ITU, "ITU–R P.526—13 propagation by diffraction," 2013.

[8] S. I. Popoola, A. A. Atayero, N. Faruk, C. T. Calafate, E. Adetiba, and V. O. Matthews, "Calibrating the standard path loss model for urban environments using field measurements and geospatial data," 2017.

[9] ITU, "ITU–R input document 3k/72-e - proposed modification to recommendation ITU–R P.1546-2," 2005.

[10] W. C. Lee, *Mobile communications engineering*. McGraw-Hill Professional, 1982.

[11] J. Parsons, "The mobile radio propagation channel," 2000.

[12] E. ÖstlinOstlin, H. Suzuki, and H.-J. Zepernick, "Evaluation of the propagation model recommendation itu-r p. 1546 for mobile services in rural australia," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 1, pp. 38–51, 2008.

[13] P. R. de Freitas and H. Tertuliano Filho, "Parameters fitting to standard propagation model (spm) for long term evolution (lte) using nonlinear regression method," in *Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA), 2017 IEEE International Conference on*. IEEE, 2017, pp. 84–88.

Paper D

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

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

Published at the *2019 IEEE 90th Vehicular Technology Conference (VTC Fall)*

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, to estimate the path loss. 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 D.1.

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 D.1.

Table D.1: Summary of the RX and TX configuration in the dedicated and automated site surveys.

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

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 the software QGIS [5] to pre-process the maps with a 1 m $\times$ 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:

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

  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 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}:

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

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:

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

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

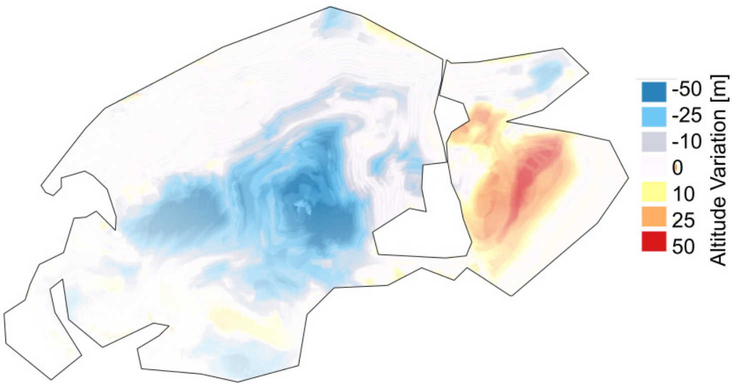
III Results and Discussion

Fig. D.1 shows the topographic change during this period. Fig. D.1a shows an aerial image of this mining complex during the first, dedicated, site survey. Fig. D.1b shows the aerial image during the second, automated, site survey, and Fig. D.1c 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. D.1) to the estimated path loss from the Vale model (Eq. D.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. D.2a, and the same result for the drive-test collected in December 2018 is shown in Fig. D.2b. In this figure, one can notice important differences between an automated and a dedicated drive test:

- 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

(a) Mine topography, May, 2017.

(b) Mine topography, December, 2018.



(c) Altitude variation between May, 2017 and December 2018.

Fig. D.1: Mine topographic variation between both measurement campaigns. The area of interest spans 3 by 4 km 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 D.2a, 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. D.1c.

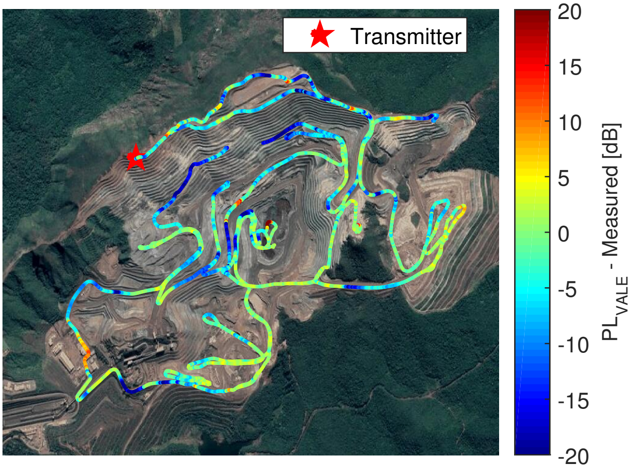
In these plots, cold colors represent locations in which the measured path loss is higher than the predicted (*underestimated*) path loss, and red colors represent locations in which the predicted (*overestimated*) path loss is higher than the measured. The adherence of the model is higher when the difference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

In the first case, in Fig D.2a, 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 D.2b, 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.

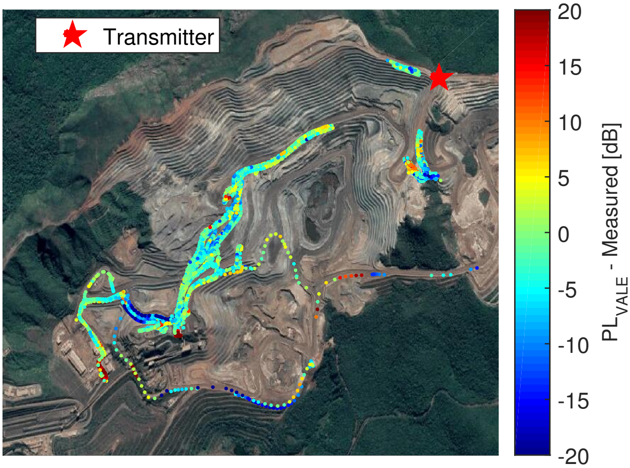
The results are also shown in a different perspective in Fig.D.3, in which the estimated and the predicted path loss are plotted as a function of the distance between the TX and the RX. In both figures, the black line represents the FSPL, the blue dots, the PL estimated from the measurements and the magenta dots, the PL predicted by the model. A summary of the results is given in Table D.2.

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 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

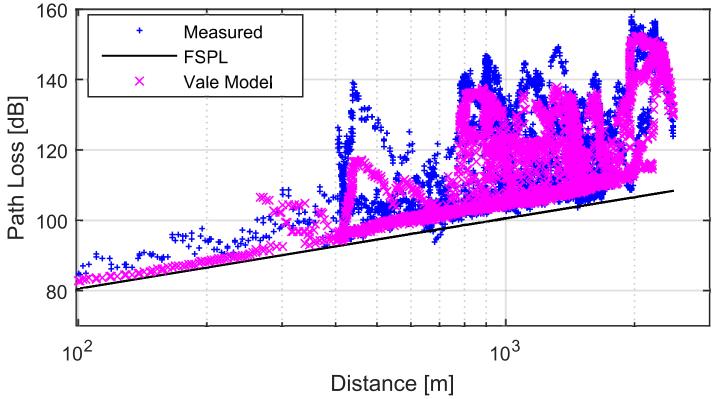


(a) Drive Test on May 2017.

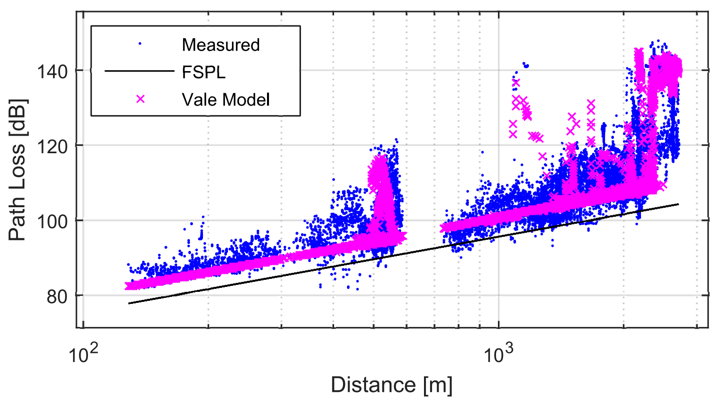


(b) Drive Test on December, 2018.

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



(a) Results from May, 2017.



(b) Results from December, 2018.

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

Table D.2: 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

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.

References

[1] M. N. Sishi and A. Telukdarie, "Implementation of industry 4.0 technologies in the mining industry: A case study," in *Industrial Engineering and Engineering Management (IEEM), 2017 IEEE International Conference on*. IEEE, 2017, pp. 201–205.

[2] ABI Research, "Private networks for the mining industry," https://www.abiresearch.com/press/us-29-billion-market-opportunities-lte-vendors-min/, accessed: 2019-06-18.

[3] E. P. L. Almeida *et al.*, "Radio Propagation in Open-pit mines: a first look at measurements in the 2.6 GHz band," in *28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2017.

[4] E. P. L. Almeida*et al.*, "An empirical study of propagation models for wireless communications in open-pit mines," in *IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018.

[5] QGIS, "A Free and Open Source Geographic Information System," https://qgis.org/en/site/, accessed: 2019-06-16.

[6] J. D. Parsons and P. J. D. Parsons, "The mobile radio propagation channel," 1992.

[7] P. H. O. Gomes *et al.*, "Evaluation of Shadowing caused by Mining machinery in V2I Communications," in *PIMRC 2018 International Workshop on V2X Communications and Channel Modeling*, 2018.

[8] E. P. L. Almeida *et al.*, "Deployment Strategies for the Industrial IoT: A Case Study based on Surface Mines," in *Submitted to: IEEE 90th Vehicular Technology Conference (VTC Fall)*, 2019.

Paper E

Mission-Critical Mobile Broadband Communications in Open-Pit Mines

Luis G. Uzeda Garcia, Erika P. L. Almeida,
Viviane S. B. Barbosa, George Caldwell, Ignacio Rodriguez,
Hernani Lima, Troels B. Sørensen, and Preben Mogensen

This paper has been published at the
IEEE Communications Magazine, Vol. 54, No. 4

Abstract

The need for continuous safety improvements and increased operational efficiency is driving the mining industry through a transition towards automated operations. From a communications perspective, this transition introduces a new set of high-bandwidth business- and mission-critical applications that need to be met by the wireless network. This article introduces fundamental concepts behind open-pit mining and discusses why this ever changing environment coupled with strict industrial reliability requirements pose unique challenges to traditional broadband network planning and optimization techniques. On the other hand, unlike unpredictable disaster scenarios, mining is a carefully planned activity. Taking advantage of this predictability element, we propose a framework that integrates mine and radio network planning so that continuous and automated adaptation of the radio network becomes possible. The potential benefits of this framework are evaluated by means of an illustrative example.

I Introduction

Extraction of minerals stretches back to pre-historic times and remains as one of the most essential industrial activities bringing forth the conveniences of modern lifestyle. As a maxim, if it cannot be grown, it needs to be mined. However, mining frequently involves people working in distant areas under potentially dangerous conditions. With the end of the so-called mining boom, (iron) ore prices have now fallen nearly 80% since 2011, forcing mining companies to do more with much less.

In this challenging economic scenario, mining giants such as Vale (Brazil) and others have several ongoing large-scale automation initiatives. Known by different names, such as "Autonomous Mine", these initiatives involve the proliferation of large unmanned machines doing the harsh and risky work in remote locations connected via fiber and broadband radios to conveniently placed information and control centers where humans and computers plan, supervise and/or control their operation. One can think of this mine-wide network of interacting yet physically distributed machines as a Mobile Cyber-Physical System (MCPS) [1], where Operational Technology (OT) and Information Technology (IT), the so-called "IT/OT convergence" [2]. Amidst the countless challenges related to the development, implementation and management of a MCPS, securing highly reliable tether-free broadband connectivity is paramount. Consider that endless streams of mission-critical data from all sorts of sensors, actuators, and supervisory systems will be traversing the network with stringent latency and packet error rate (PER) requirements.

This automation revolution is taking place gradually and connectivity is shifting from existing narrowband Professional Mobile Radio (PMR) systems to broadband systems due to the unabating demand to transfer large volumes of information to feed decision-support systems in real time. However, open-pit mines are not exactly the kind of environment RF engineers are accustomed to. For example, the topography of a typical pit consists of benches and slopes with mineral-rich reflective surfaces, which are always changing thus altering the propagation conditions used to plan the radio network. Conversely, a deep understanding of wireless connectivity is not part of the traditional skill set of mining engineers, which hampers conversations and might lead to false expectations from both sides. Finally and similarly to public safety networks, wireless connectivity is not a source of revenue for mining companies, but rather a key enabler of automated operations, whose own feasibility hinges on a cost-effectiveness analysis. Therefore, the ability to predict the associated investment, years in advance, is critical.

In what follows, the role that broadband wireless networks (will) play in mine automation is discussed. Section II examines some of the environmental and operational characteristics that make the deployment of broadband mission-critical wireless networks in open-pit mines particularly challenging. Section III describes an integrated framework devised to address the difficulties in deploying and maintaining a wireless network that supports current and future automation initiatives. The last part of the section is devoted to a series of correlated topics suggested for future investigation. Finally, Section IV wraps up the discussion.

II Wireless Conectivity in Open-Pit Mines

Wireless networks have been widely used by the mining industry for their mobility support, rapid deployment and scalability within dynamic environments. However, mining comprises a set of industrial domains with different needs and expectations about radio solutions. For example, the automation of processing plants is conceptually closer to Industrial Internet of Things (IoT) [2] scenarios, while automation of heavy machinery employed in open pits, discussed in this paper, is closer to traditional LTE-Advanced (LTE-A) use cases.

Despite those differences, communication is already essential and considered determinant: miners live day-to-day situations that may cost lives because the environment naturally presents a number of risks, requiring constant safety precautions and staff training. Critical business, safety and production systems also rely on wireless connectivity.

A. Operational Context

Mining for Non-miners

Mining includes the processes and activities whose purpose is the extraction of minerals from unevenly distributed natural deposits. Such activities can be roughly divided into four large groups: Prospecting & Exploration, Extraction, Processing and Mine Reclamation [3]. In this work, we pay special attention to the extraction activity, the part that is generally taken for the whole by laymen. Extraction usually follows rock blasting and is carried by heavy machinery, able to load and haul tons of material at once.

Open-pit mines are characterized by the transit of gargantuan machinery, uneven roads, potentially unstable terrain, taxing weather and environmental conditions. And akin to wireless networks, where each deployment is unique due to the propagation conditions, each mine is a particular case due to the geological disposition of ore bodies.

Deployment Scenarios

Mines are typically located in remote areas, where little to none previous communication infrastructure exists. The provision of ubiquitous and reliable wireless connectivity in mines resembles disaster scenarios where communication is vital, but very little can be taken for granted. Opposed to communications in underground mines, that have been subject of extensive research [4,5], wireless communications in open-pit mines are relatively unexplored.

Dependable wireless networks must be planned and optimized according to the specific scenarios where they operate. In this respect, open-pit mines bring a few interesting elements to the table that set them apart from well researched environments, such as cities, rural areas and even hilly terrains.

Firstly, an open-pit mine differs from natural surfaces and most man-made structures. The terrain is sprinkled with deep troughs whose sides are cut into benches resulting into jagged discontinuities [3]. In addition, electromagnetic properties of the mineral-rich surfaces play a role too. High concentrations of minerals such as hematite (Fe_2O_3) and magnetite (Fe_3O_4) can lead to very high reflectiveness [6] and severe multipath propagation. This could make radio interference containment and hence system-level planning a much more challenging task.

Another particularity stems from the very nature of mining. For example, a large iron ore mine can move a total of 1 million tons of material per day. An ever changing topography leads to unpredictable coverage if the system is left unchecked. Consider the example shown in Fig. E.1a and Fig. E.1b, which gives a sense of the scale change over the course of one year. A typical narrowband network deployment in open-pit mines consists of a single macrocell, providing coverage from on an elevated position. However, as pits become deeper, LOS conditions may be lost. Areas initially covered by forest and later by waste rock or ore would present different RF propagation conditions. In addition to that, the location of the rock faces being mined also vary during the mine life-cycle. When combined, these factors imply that initial radio measurement data, calibrated models and deployment plans will not be able to characterize the wireless performance at later different stages. Thus requiring expensive and time-consuming planning processes to be continuously repeated over time, requiring frequent re-positioning of nomadic access nodes. As long as broadband connectivity provided on a best-effort basis is sufficient, mining teams can grapple with network outages. This certainly is not the case for mission- and business-critical automated systems.

Finally, in the OT world, Ethernet rather than IP is the prevailing connectivity mode, hence tunneling solutions may be required if LTE-A is employed.

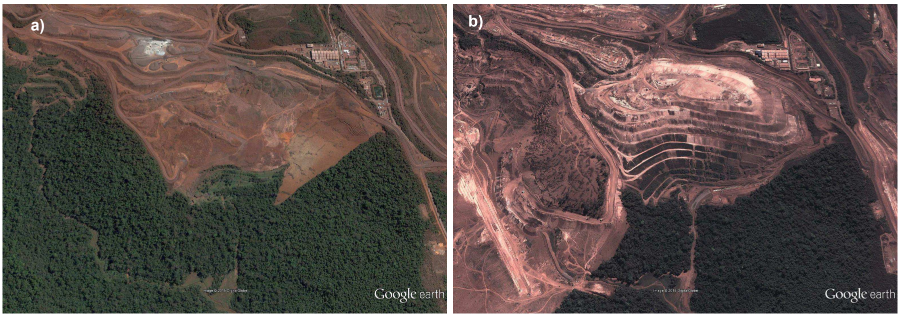


Fig. E.1: Carajas iron ore mine in Brazil in (a) August, 2011 and (b) July, 2012 ©2016 Google.

B. Essential Applications

Although strongly regulated by international authorities, mines are still very hazardous environments that need constant safety monitoring and reliable communications. Not surprisingly, the first and foremost driver behind the introduction of wireless communication in mines was safety. Professional voice services such as group and individual calls, dynamic grouping, fast call set-up, and ambiance listening are necessary to ensure that first responders will be able to exchange information reliably and timely in case of emergency. Typically, these features are delivered by self-owned networks operating on the low-band Ultra High Frequency (UHF) range of frequencies. As a result, systems like TETRA and Project 25 (P25), usually designed for Public Safety applications [7], are still very common in mining sites.

In addition to mission-critical voice services, other important mining systems rely on narrowband data services, for example: fleet management, real-time telemetry, and GPS-augmentation systems. Particularly, dispatch systems play a fundamental operational role, scheduling haul trucks and optimizing routes to increase productivity and reduce running expenses, e.g. fuel is one of the major OPEX components.

C. Initial Broadband Deployments

With the gradual introduction of new applications in mines, such as video surveillance, real-time data acquisition and analytics, broadband technologies are being deployed to complement narrowband systems. A wide gamut of IEEE 802.11 based solutions are in widespread use. Initial offerings consisted of ruggedized WiFi access points and repeaters. Lately, multi-hopping and self-organizing mesh networks led to overall performance improvements without investments in wired infrastructure.

However, some well-known technical issues can impact the performance of contention based wireless networks, such as the use of Industrial, Scientific and Medical (ISM) bands that eliminates licensing fees but imposes severe limitations on the emission levels. The reduced coverage radius leads to denser networks to cover the same area, increasing the TCO. Additionally, towns and cities may spring around mines due to the economic activity, and the presence of additional users inevitably increases the channel utilization; therefore, the service quality become less predictable.

To overcome most of these problems, vendors provide multi-band radios and implement proprietary Radio Resource Management (RRM) and layer-2 routing algorithms. Unfortunately, these radios are more expensive and proprietary solutions tend to be incompatible leading to customer lock-in

D. Technology Evolution and Regulatory Aspects

The recent evolution of commercial cellular networks are turning these systems into viable options for critical communications [8]. The Federal Communications Commission (FCC) for example, explicitly recommended leveraging the advantage of LTE-A technologies and standards for the radio access network. Additionally, the 3GPP and TETRA and Critical Communications Association (TCCA) joined efforts to include critical mission functionalities into LTE-A standards after TCCA adopted LTE-A as the technology for mission critical mobile broadband communications.

However, the deployment of an LTE-A network presupposes the availability of at least 1.4 MHz per carrier, in contrast to the 12.5 - 25 kHz required by legacy systems [8]. Understanding that bidding in an auction and competing with carriers was not an option for certain strategic sectors of the state and economy, Anatel, the spectrum regulator in Brazil, approved a resolution dedicating a 2×5 MHz slice of the Evolved Universal Terrestrial Radio Access (E-UTRA) operating band, for public safety, national defense and infrastructure LTE networks. In Australia, Rio Tinto and BHP Billiton have both filed submissions with the Australian Communications and Media Authority (ACMA), which proposed to issue apparatus licenses in the 1800 MHz band.

Involving carriers, two other paths are possible: using services provided by carriers and subleasing the spectrum from current incumbents. The first is unlikely because of the little interest, from a business perspective, in providing mobile services in remote areas. The second, however more probable, is not trivial from business and regulatory perspectives.

Finally, regarding standardization efforts, the features being introduced in LTE-A that are relevant for public safety networks are equally important to the mining sector. Group communications and Mission Critical Push To Talk (MCPTT) over LTE-A would eliminate the need for separate voice and data networks. High-power user equipment, Isolated LTE-A Radio Access Network (RAN) and Proximity-based Services (ProSe) are all important to make the network more resilient against backhaul connectivity losses and cell coverage dead zones. ProSe could also find application in collision awareness and avoidance solutions. Finally, RAN Sharing Enhancements (RSEs) might facilitate the adoption of sharing practices among critical users. In that respect, LTE-A in Unlicensed Spectrum (LTE-U), and the deployment of Heterogeneous Networks (HetNets), combining macrocells already deployed in open-pit mines and small cells, might also play an important role in circumventing the relatively small capacity offered by 5 MHz LTE-A deployments.

E. Broadband Critical Communications and Intelligent Mining

The combination of robotic and information systems, in the form of autonomous and automated equipment, has emerged as a viable strategy to remove humans from hazardous areas and to increase productivity in mines [9].

Automated equipment can be broadly classified into three categories [10]: *remotely controlled*, *teleoperated* and *fully automated*. In the first two, the human operator is still in control of the machines; the main difference relies on the need of a line-of-sight between the operator and the machine, while the teleoperator can be, in theory, anywhere in the world. In turn, fully automated machines rely on onboard intelligence and communications capabilities. Wireless connectivity is the common denominator bringing together robotic equipment, information systems and humans in all cases. A fully connected robotic mine simply cannot be bought off-the-shelf and implemented even though some components are commercially available today. From available Quality-of-Service (QoS) requirements, the common characteristics seem to be:

- Small payload sizes
- High-packet rates

- High-delay and jitter sensitivity
- Modest bandwidth requirements
- UL dominated traffic

Another absolutely critical requirement for teleoperated systems is the transmission of live video and (ideally) audio feeds so that the operator has sufficient and *timely* information about the environment and the equipment being controlled. Assuming the usage of the H.264 codec [11], High Definition (HD), at 15 frames per second (fps) and Full-HD transmissions at 30 fps would require approximately 2.35 Mbps and 7.75 Mbps per equipment, respectively, in contrast to the 32 kbps required by basic telemetry. Clearly, the high data rate video requirements are beyond the achievable with narrowband PMR, which is in the order of a few hundreds of kbps. Therefore, a single highly dependable converged broadband wireless network providing voice and data services would be simpler to manage and potentially more cost-effective.

F. Initial Coverage and Capacity Evaluation

To gain further insight into the issues related to the deployment of a cellular infrastructure in a mine site, a simple uplink analysis of a single macrocell, single user LTE-A deployment, with 5 MHz bandwidth, serving an area of approximately 11 km^2 was performed considering a single user in three bands: 700 MHz, 1.5 GHz and 2.6 GHz. A 1 meter/pixel resolution DTM obtained from Vale's geographic information system (GIS) database was used as input to a commercial planning tool software (Atoll). The macrocell antenna was placed at 60 m above the ground level, in an elevated area, and the SPM was calibrated with drive-test measurements. Open-loop power control is assumed and the scheduler selects proper Modulation and Coding Scheme (MCS), according to the UL received power, to calculate the achievable throughput for each location. The percentage of locations that would achieve the minimum data rate for basic telemetry applications, HD and Full-HD video for the different bands is shown in Fig. E.2.

In all bands, the required 99% coverage probability for basic telemetry applications is achieved. However if we consider a single Full-HD or HD transmission, covered locations would drop. In fact, the results show that even HD transmission can be challenging for a single macrocell LTE-A deployment, depending on the available spectrum.

To evaluate the results in a more realistic scenario, the simulation was repeated for a 99% GoS at 700 MHz, considering 10 and 30 users. The UL data rate per user would drop to 1 Mbps and 32 kbps respectively; therefore, despite LTE-A, broadband services would not be supported.

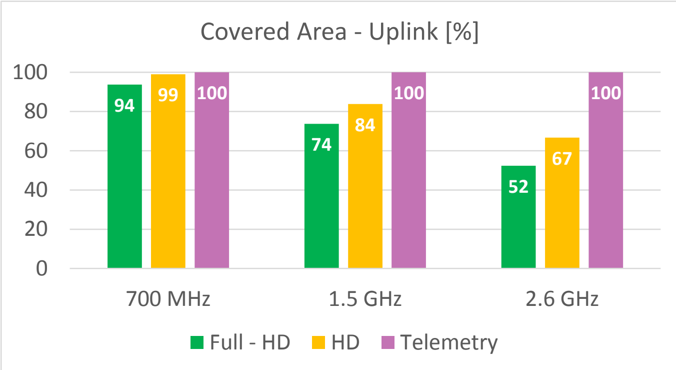


Fig. E.2: Percentage of locations where the throughput is sufficient to meet the requirements of telemetry applications, HD video and Full-HD video, with LTE-A deployments in 700 MHz, 1.5 GHz and 2.6 GHz, considering a single user.

This simplified planning exercise illustrates one important difference between narrow- and broadband deployments. Coverage zones for each service level are sensitive to the bands and amount of spectrum allocated to the system. This simple observation is not a surprise for RF engineers, but goes against conventional wisdom in the mining industry. Since spectrum is a scarce resource and mines impose practical restrictions to the installation of network infrastructure, coverage, capacity, and above all, network resilience must be the object of careful considerations during network planning and continuous optimization in mines.

III An Integrated Planning and Optimization Framework

Constant terrain profile and clutter variations coupled with stringent OT requirements entail continuous efforts to achieve stable and highly predictable connectivity in open-pit mines. Although stand-alone RF planning tools can still be used, repeating the process is laborious, error-prone, and likely to use outdated information, leading to unsatisfactory results. Furthermore, there are key pieces of information that the mining industry may offer to network planners, which make the proposition of delivering highly dependable wireless broadband connectivity more credible and sustainable.

A. Planning Ahead

While the landscape of mine sites are truly mutant, such changes are not fortuitous. Although several decades elapse between the initial exploration and land reclamation, stakeholders expect returns on investment as quickly as possible. This gulf between short-term pressures and long operational time frames mandate a careful exercise in economics, constrained by certain geological and mining engineering aspects, namely mine planning. At this stage, using data acquired during the exploration phase, engineers select appropriate physical (geometric) design parameters and define the short, medium and long term schedules for the extraction of marketable material (ore) and waste rocks that need removal to expose the ore. The goal is to optimize the costs of mineral exploitation, respecting the constraints imposed by topography, safety, equipment capacity and operating costs [3]. Mine planning essentially determines where, when, and to which extent the terrain profile will be modified, also providing estimates of fleet sizes and their communications requirements, translating into quasi-determinist traffic dimensioning information in the wireless world. Acknowledging the value of this data coming from the mining domain, we present an integrated framework inspired by the concepts of Radio Environment Maps (REMs) [12] and Self-Organizing Networks (SON) [13]. The framework is shown in Fig. E.3 and aims at simplifying the task of delivering and maintaining broadband connectivity in open-pit mines.

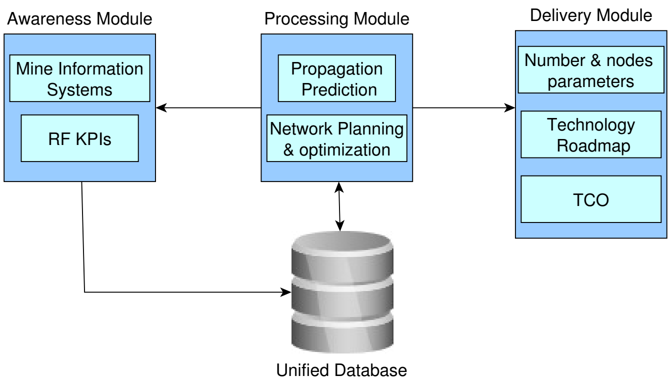


Fig. E.3: Self-organizing Infrastructure for the Next Generation (SWING) Mines.

- **Awareness module**: this is the sensing (input) interface between the real-world mine environment and the integrated framework. It fetches and combines data from several mine information systems (dispatch, mine planning, GIS, etc) as well as other sources of relevant information on the radio access interface obtained from monitoring the network and gathering KPIs. Coverage information can be provided by drive-tests, which can be automatized using the Minimization of Drive Tests (MDT) LTE-A feature. The framework also takes advantage of periodic aerial topographic surveys carried out in order to update mine maps. In this respect, drones are a cost-effective solution to update these maps and could, at least in theory, be used to perform drive tests.

- **Unified database**: it can be understood as a REM, dynamically storing the environmental information extracted and post-processed by the awareness module from mine systems, i.e. current and future topographic data, location of users with augmented GPS (DGPS or RTK) precision, as well as network conditions, parameters and requirements. Constantly exchanges data with the processing module, providing information gathered by the awareness module and receiving information about physical and logical parameters to be optimized in the network.

- **Processing module**: it analyzes the information received from the unified database, makes decisions about network re-planning, RRM optimization as well as physical parameters, such as optimal antenna elevation and azimuth. It can perform short-term and long-term information analysis: combining network requirements and current infrastructure to check the need for local optimization, or considering long-term mine planning to predict when network infrastructure updates will be needed. It can also trigger the collection of new sensor data, such as a new drive test motivated by mine expansion.

- **Delivery module**: it is the output interface. In its simplest form, it might provide a report and/or actionable information to humans who will then carry out a task. Alternatively, it may interface with other software and hardware to achieve a certain goal. For example, it may reconfigure an antenna azimuth position control system, deliver a flight plan to an Unmanned Aerial Vehicle (UAV) or provide mine staff with a set of new coordinates for a mobile small cell, a CoW. In a more visionary scenario, such CoW would be able to reposition itself autonomously.

In short, the goal of the proposed framework is to move away from reactive network planning and optimization by turning these tasks into a continuous and proactive procedure that should lead to a broadband wireless network that will safely accommodate the needs of automated mines. As an example of the framework in action, the next subsection will tackle the UL capacity limitation of the deployment of a single 700 MHz LTE-A macrocell with 5 MHz bandwidth.

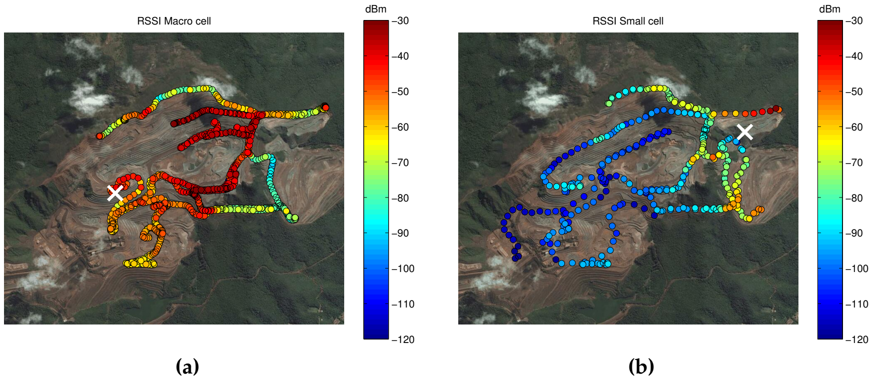


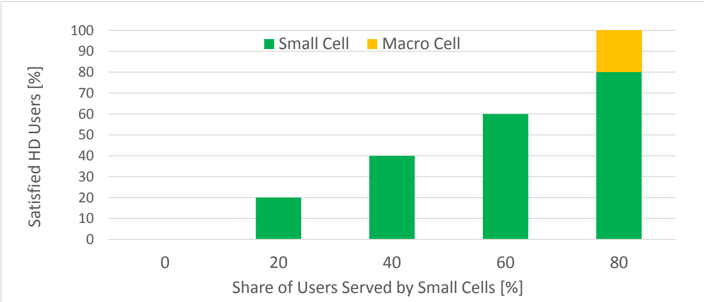
Fig. E.4: Drive-test RSSI values at 1500 MHz (a) Macrocell deployment (b) Small cell deployment.

B. Proof-of-Concept

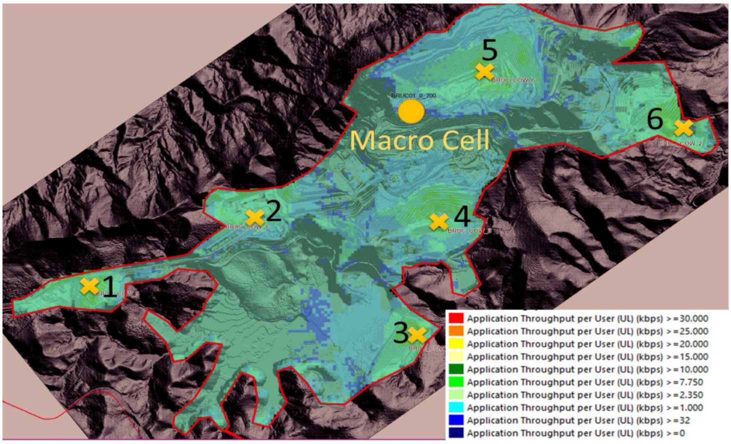
To illustrate the operation of the proposed framework, we consider a simplified static optimization case, for the example shown in Section F.. From the awareness module, the terrain profile, the location, number and requirements of the active users are known, as well as the deployed network infrastructure, a single 700 MHz LTE-A macrocell. It is identified that the UL requirements for 30 users are not met, due to insufficient cell capacity. This information is sent to the processing module, and the optimization begin considering coverage predictions and restrictions.

Besides the previous simulations, the processing module also takes into account new updated propagation information, such as the one presented in Fig. E.4, RSSI from new drive-tests. The transmitters were a macrocell, located in an elevated position and a small cell with antenna closer to the ground level. Macrocells favor the LOS conditions over a larger area of the mine, and combined with the reflective behavior of the scenario, lead to a very high RSSI in most of the area covered, as in Fig. E.4a. On the other hand, the RSSI measured from the small cell is in the order of 30-40 dB lower. By placing the antennas closer to the ground, NLOS conditions are more likely to occur, increasing the probability of blockage and reducing the potential area covered. Reduced coverage may be beneficial in co-channel small cell deployments, providing good signal levels in their LOS vicinity and taking advantage of the terrain profile for creating physical isolation between cells.

These observations are inputs to the processing module, motivating the desired solution: to provide reliable HD transmission to 30 users distributed across the entire mine. The output of the optimization framework considers a combined deployment of a macrocell at 700 MHz and 6 small cells operating at 2600 MHz placed where most of the traffic is expected to be located.



(a)



(b)

Fig. E.5: Example of an Heterogeneous Network deployment in open-pit mines. (a) Percentage of satisfied HD users as a function of the share of users served by small cells and (b) Throughput plot in the scenario where 80% of the users are served by small cells. The yellow crosses represent the location of small cells at the final setup.

This band is chosen for it favors the interference containment among small cells. Fig. E.4b shows the percentage of satisfied HD users, according to the percentage of users offloaded to small cells. Depending on the position of the small cells, more or less users are offloaded from the macro layer. The requirements are only met when 80% of the users are offloaded to small cells, resulting in 4 users per small cell and 6 users remaining in the macro layer. The throughput map is shown in Fig. E.5b; the UL data rate per user increases up to 2.35 Mbps, sufficient to meet the HD requirements, but still insufficient for Full-HD.

While a significant amount of effort remains until the integrated framework is fully developed, the preliminary results illustrate the potential gains of this platform.

C. Research Directions

We summarize some of the topics addressed throughout the preceding discussions and hint at correlated topics that fellow researchers might find worth investigating further.

- **Radio Propagation:** The quality of radio network planning depends on the accuracy of RF propagation models, and there is very little material available in the literature dealing with propagation in open-pit mines. More data is needed, in terms of measurement campaigns, in order to develop and validate large- and small-scale wideband channel characterization considering macrocell and small cell deployments, as well as mobile backhaul (MBH) links. Furthermore, ray-tracing techniques could also play an important role in characterization and optimization of smaller areas, taking advantage of the mineralogy information contained in databases.

- **Integrated Mine and RF Planning Systems:** Development of a GIS platform providing tight integration of RF and Mine Planning tools that could act as a common ground where mining and RF experts would come together and discuss the implications of their design decisions, thus facilitating the exchange of ideas and observations leading to new problem formulations, algorithms and technical solutions. Since waste rock needs to be moved anyway, it might be used to create physical isolation between cells, providing favorable low interference conditions.

- **Field Robotics:** Mobile infrastructure delivering wireless connectivity that is able to navigate through the mine site either autonomously or teleoperated would make the repositioning of nomadic nodes much more rapid and safer as humans would hardly ever be physically present. Similarly, drones could be used as drive-test tools that are able to access hard to reach areas in the mines and detect potential connectivity issues before mobile mining equipment becomes affected.

- **Cyber-physical Security:** An autonomous mine is a layered construct where physical and computational components interact in order to make mining activities safer, more sustainable and productive. A large share of the interactions will rely upon the industrial broadband wireless network. As such, this network becomes equivalent to an invisible utility that must be protected from threats and attacks in order ensure the integrity of the entire cyber-physical system. The emerging field of ultra-reliable communications (URC) [14] is expected to play an important role in the area of cyber-physical security.

- **Return on Information:** Developing a framework that accurately quantifies the total economic value of an investment in information and communication technologies upon which upper management can make decisions is just as critical as delivering a reliable network. Tight cross-disciplinary collaboration between mining and wireless networking and automation experts is needed to develop models that will allow pertinent sensitivity analyses to be performed in order to provide a clear-cut picture of the TCO and the estimated benefits in terms of mining productivity.

IV Conclusions

This paper has addressed the delivery of broadband critical communications in open-pit mines. Although such environment is alien to the vast majority of RF engineers and wireless system designers, wireless connectivity plays a vital role in current and future large-scale mine automation plans. Therefore, it is not an overstatement to claim that the future of both industries is intertwined as the wireless world turns its attention to industrial automation and intelligent, connected mines loom on the horizon as a path towards a safer, more productive and sustainable mining industry. This paper attempted to bring these two dissimilar industries a bit closer by highlighting the specific challenges, e.g. high-reflectivity of mineral rich surfaces and mutant topographic profiles, and by proposing a network planning and optimization framework that makes use of the important information pieces offered by mine planning systems. As a final contribution, the paper also outlined a few complementary research directions that may lead to a self-planning and self-deployable communications infrastructure, a key enabler of future unmanned mining activities in remote and extreme environments.

Acknowledgment

The authors would like to thank the automation, telecommunications, mineral exploration cartography and IT teams from Vale for their valuable inputs and acknowledge the support granted by MCTI/CTInfo/CNPq, process 440880/2013-0.

References

[1] R. Rajkumar, I. Lee, L. Sha, and J. Stankovic, "Cyber-physical systems: the next computing revolution," in *Design Automation Conference (DAC), 2010 47th ACM/IEEE*. IEEE, 2010, pp. 731–736.

[2] D. Dujovne, T. Watteyne, X. Vilajosana, and P. Thubert, "6tisch: deterministic ip-enabled industrial internet (of things)," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 36–41, 2014.

[3] W. A. Hustrulid, M. Kuchta, and R. K. Martin, *Open pit mine planning and design, two volume set & CD-ROM pack*. CRC Press, 2013.

[4] A. E. Forooshani, S. Bashir, D. G. Michelson, and S. Noghanian, "A survey of wireless communications and propagation modeling in underground mines," *IEEE Communications surveys & tutorials*, vol. 15, no. 4, pp. 1524–1545, 2013.

[5] L. Bandyopadhyay, S. Chaulya, and P. Mishra, *Wireless communication in underground mines: RFID-based sensor networking*. Springer Science & Business Media, 2009.

[6] J. Garvin, J. Head, and S. Zisk, "On the origin of high radar reflectivity surfaces on venus," in *Lunar and Planetary Science Conference*, vol. 16, 1985, pp. 266–267.

[7] G. Baldini, S. Karanasios, D. Allen, and F. Vergari, "Survey of wireless communication technologies for public safety," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 619–641, 2014.

[8] R. Ferrus and O. Sallent, "Extending the lte\lte-a business case: Mission-and business-critical mobile broadband communications," *IEEE Vehicular Technology Magazine*, vol. 9, no. 3, pp. 47–55, 2014.

[9] D. Kumar, "Emerging tools and techniques for mine safety and disaster management," in *Natural and Anthropogenic Disasters*. Springer, 2010, pp. 332–365.

[10] D. Lynas and T. Horberry, "Exploring the human factors challenges of automated mining equipment," in *46th Annual Human Factors and Ergonomics Society of Australia Conference 2010, HFESA 2010*. HFESA (Human Factors and Ergonomics Society of Australia), 2010, pp. 115–122.

[11] J. Ostermann, J. Bormans, P. List, D. Marpe, M. Narroschke, F. Pereira, T. Stockhammer, and T. Wedi, "Video coding with h. 264/avc: tools, performance, and complexity," *IEEE Circuits and Systems magazine*, vol. 4, no. 1, pp. 7–28, 2004.

[12] Y. Zhao, L. Morales, J. Gaeddert, K. K. Bae, J.-S. Um, and J. H. Reed, "Applying radio environment maps to cognitive wireless regional area networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on*. IEEE, 2007, pp. 115–118.

[13] L. Jorguseski, A. Pais, F. Gunnarsson, A. Centonza, and C. Willcock, "Self-organizing networks in 3gpp: standardization and future trends," *IEEE Communications Magazine*, vol. 52, no. 12, pp. 28–34, 2014.

[14] P. Popovski, "Ultra-reliable communication in 5g wireless systems," in *5G for Ubiquitous Connectivity (5GU), 2014 1st International Conference on*. IEEE, 2014, pp. 146–151.

Paper F

The Challenge of Wireless Connectivity to Support Intelligent Mines

Viviane S. B. Barbosa, Luis G. Uzeda Garcia, George Caldwell,
Erika P. L. Almeida, Ignacio Rodriguez, Troels B. Sørensen,
Preben Mogensen, Hernani Lima

Published at the *24th World Mining Congress, Mining in a World of Innovation.*

Abstract

The need for continuous safety improvements and increased operational efficiency is driving the mining industry through a transition towards large-scale automation of operations, i.e., "intelligent mines". The technology promises to remove human operators from harsh or dangerous conditions and increase productivity, from extraction all the way to the delivery of a processed product to the customer. In this context, one of the key enablers is wireless connectivity since it allows mining equipment to be remotely monitored and controlled. Simply put, dependable wireless connectivity is essential for unmanned mine operations. Although voice and narrowband data radios have been used for years to support several types of mining activities, such as fleet management (dispatch) and telemetry, the use of automated equipment introduces a new set of connectivity requirements and poses a set of challenges in terms of network planning, management and optimization. For example, the data rates required to support unmanned equipment, e.g. a teleoperated bulldozer, shift from a few kilobits/second to megabits/second due to live video feeds. This traffic volume is well beyond the capabilities of Professional Mobile Radio narrowband systems and mandates the deployment of broadband systems. Furthermore, the (data) traffic requirements of a mine also vary in time as the fleet expands. Additionally, wireless networks are planned according to the characteristics of the scenario in which they will be deployed, but mines change by definition on a daily-basis. Therefore, a careful and continuous effort must be made to ensure the wireless network keeps up with the topographic and operational changes in order to provide the necessary network availability, reliability, capacity and coverage needed to support a new mining paradigm. By means of simulations, we analyze the effects on the wireless network along 7 years of constant topographic changes in an open-pit mine coupled with much higher data requirements. The authors also present a new network topology that is able to partially meet the requirements posed by mining automation and discuss the consequences of not providing connectivity for all applications. The work also discusses how the careful positioning of the heavy communications infrastructure (tall towers) from the early stages of the mine site project can make the provision of incremental capacity and coverage simpler.

I Introduction

The replacement of human labor by mechanical and electronic devices is not new in the industrial world. Specifically in the mining industry, which encompasses higher operational risks, process automation has the potential to ensure exploitation with higher levels of safety and efficiency. Autonomous equipment has been adopted to a greater or lesser degree in underground and surfaces mines. Although automated processes are well established in underground mines (such as the use of longwall shearers at coal mines), open-pit mines are still employing initiatives through pilot-projects for testing automation of loading and haulage equipment, as those working in mines like Gabriela Mistral (Codelco), Pilbara (Rio Tinto) and Brucutu (Vale). Collaboration between equipment suppliers and mining companies are common to the development of these systems, often customized for the project in terms of volume and capacity [Bellamy and Pravica, 2011,Hargrave et al., 2007,Korane, 2013].

Monotonous and repetitive activities are immediate candidates for the automation process. There are natural candidates in open-pit mines, i.e., operations whose automation is less challenging than others, such as the work of trucks (hauling the material from excavators sites to the dump area), drill rigs (drilling according to a previous mesh for loading explosives), bulldozers (working on haul roads and stripping areas), and water trucks (spraying water to reduce dust). On the other hand, the excavators are still far from being 100% automated, because there is a complex set of tasks that cannot be classified as monotonous and repetitive, currently requiring greater intervention of a human operator [Bellamy and Pravica, 2011,Garcia et al., 2016,Hargrave et al., 2007,Korane, 2013].

The common denominator of all applications that require connection of mobile field equipment to an Operation Control Center (OCC), for example a Mine Dispatch System (MDS)), is wireless communications, as shown in Figure 1. The automation project will only be successful if the communications requirements are met by the wireless network. Depending on the task and the desired level of automation, these requirements will be more or less restrictive: for example, sending the mesh to the drill rig may be delay tolerant whilst teleguided operation may be intolerant to network delays. A larger amount of delay and error-intolerant data leads to the need to increase the transmission capacity, without compromising the reliability and responsiveness of the system. Therefore, mapping the requirements is essential for proper network planning [Boulter and Hall, 2015,Peterson and Davie, 2007].

In the mining industry, variabilities in topographic and geological domains compound the challenge of making the quality of service provided by the wireless network manageable. Radio waves are sensitive to morphological changes, which can lead to either favorable or unfavorable conditions for telecommunications systems, and the impacts of these changes in the wireless network are still poorly studied in open-pit mine environments. Furthermore, the introduction of foreseen industrial applications requiring connectivity, e.g. the Industrial Internet of Things, will further increase the burden on the mission-critical wireless network. Simply put, the mining environment needs a continuous wireless network planning, monitoring and optimization

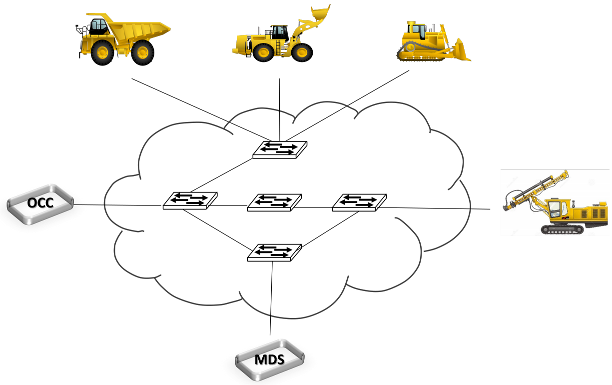


Fig. F.1: Assets, OCC, MDS (hosts) are connected through links and nodes of a communication network.

due to ever changing morphology and automation needs [Garcia et al., 2016].

In this context, we present and discuss the challenges of providing reliable wireless networks to support intelligent mines. First, a brief overview of fundamental communications concepts, necessary to understand the paper discussions, is given. In section "Mining Applications", the communication requirements of conventional mine applications are presented and compared with the requirements posed by intelligent mine applications. Section "Case Study" presents and discusses network simulations over a real mine deployment considering two different moments in time, 7 years apart, and also the fleet and communications requirements changes. Finally, Section "Conclusions" wraps up this present work.

II Wireless Communications for Mining Engineers

In this Section, a brief overview of important communications concepts is presented. Interested readers are referred to [Rappaport et al., 1996] for more information.

Wireless communications comprise the task of transmitting information among devices that are not electrically connected. The transmitted signal is, therefore, propagated through the air by different mechanisms such as reflection, diffraction and scattering, which allow the signal to be received even in locations where there is no LOS between transmitters and receivers. The dispersion of the transmitted signal over the wireless medium, aligned with the losses associated to these different propagation mechanisms, cause fluctuations in the received power as a function of distance, frequency, receiver's speed and the environment over which the signal is propagated. Another relevant source of random fluctuations over the received signal is the noise inherent of electronic circuits. It is important to mention that noise increases with the bandwidth of the transmitted signal.

Although many types of communication links exist, in this work focus will be given to point-to-multipoint systems, where a central transmitter is responsible for providing connectivity over a given area. The communication range, or coverage probability, is defined as the area within which the received power is above a given power threshold with a certain probability. This threshold also considers the receivers noise and other sources of interference, indicating whether the original message can be decoded at the receiver side. Usually, this signal threshold is defined in terms of a minimal SNR, or a minimal SINR, and RSSI. Additionally, the definition of the coverage area also considers signal fluctuations caused by the different propagation mechanisms.

Although it is a fundamental concept, coverage itself does not guarantee that a given transmission will be successful. There are different types of data, for example, that are time sensitive. Real-time monitoring, for instance, lose its value if the video frames are not sent with a minimum data rate, for it causes delays in the transmitted data. The Shannon-Hartley theorem F.1 defines the maximum data rate at which information can be sent over a communications channel:

$$C = B \times \log_2(1 + SNR) \tag{F.1}$$

In Eq. F.1, C represents the channel capacity, in bits per second, B is the channel bandwidth in hertz (Hz) and the SNR is given in linear power ratio. A direct conclusion from the Shannon-Hartley theorem is that it is possible to increase the capacity of a communication channel by increasing the system bandwidth, or by enhancing the SNR. However, it is important to remember that there are limits for the increase in capacity, since spectrum is a scarce and expensive resource, transmit power levels are strongly controlled by regulatory authorities and that the received power decreases with the distance between transmitter and receiver.

The last two fundamental concepts to be mentioned in this brief overview are the latency and jitter in a communication system. Latency considers not only the delay caused by the channel insufficient capacity but the end-to-end delay in a transmission. Other sources of delay are, for example: collisions in multiple access techniques, insufficient processing power at the nodes or congestion in upper layers. Depending on the application, upper layer protocols, or even the users can deal with latency if it is constant. For example, if the latency of a video transmission is constant but small, in a remote control application, the perception of it by the end user will be minimized, since the flow of information is continuous. Variable latency, or jitter, on the other hand, can damage severely the quality of experience of a user over the network.

It is also worth mentioning that a typical system comprises a base station (a tall tower usually located in a high place to have a better LOS) and a number of nodes and relay stations (for example CoWs) to extend the radio coverage and/or capacity. Finally, the choice between commercial carrier services and a private infrastructure hinges on service availability, costs, digital security policies, quality of service requirements and the foreseen mining applications.

III Mining Applications

Mines are characterized by dynamism and intense topographical changes, as a result of mining excavations. Nonetheless, there are also some communications “hot spots” in a mine, namely, places that will always have equipment around to transmit or receive data. Excluding excavation areas, development areas and haul roads, all being itinerant, ore dump points (crusher area) and waste rock dump (dump area) can be considered fixed. The primary crusher is the interface between the mine and the processing plant: the infrastructure for it, such as conveyor belts and stockpiles areas, is planned to be there for all over life of the mine. Waste rock sites are permanent until they reach their designed capacity with a maximum volume of material. When that happens, a new site needs to be prepared.

Although autonomous systems are still restricted to large enterprises, MDS are common in the mining sector and rely on wireless communications. The average throughput per node for MDS are usually around few tens of kilobits per second (kbps) in the uplink, the link between the host and the network node (the base station, for example), or downlink, defined as the link between the network node and the host. The haulage of Run-Of-Mine (ROM), waste rock and the geographical position of the trucks are monitored from inputs that operators report to the interfaces located in the cabins which, among other options, can inform the MDS if the truck is "full and going to dump" or "empty and waiting to load" or "hauling material" or "maneuvering". Each asset has a roll of typical options to their tasks that are sent periodically to MDS. The system is defined as passive if only monitoring is possible, for example to generate reports containing the Key Performance Indicators at the end of a period. On the other hand, the system is defined as active if it allows for dynamic allocation. In the latter, after dumping the hauled material, a target is given to the trucks by the MDS, to reduce queues sizes at excavations areas, thus increasing individual assets' productivity [Martins, 2013]. Optionally, embedded sensors to measure tire pressure, engine temperature, and fuel levels can be installed in the equipment to enable monitoring the machine's performance from the MDS. With these tools, the team of technicians and engineers are able to determine more accurately the best time for preventive maintenance or refueling, reducing the unproductive time and increasing the machine's lifetime – justifying the saying "what gets measured gets managed".

[Horberry and Lynas, 2012] describe three levels of automation associated with the mining industry, as shown in Tab. F.1. They differ mainly by the need for remote connection to an OCC that, in the first instance, aims to monitor or teleoperate the equipment. Note that the link that provides the remote connection between the OCC and equipment in the open pit environment cannot be achieved through coaxial cables or optical fibers, due to intense movement and ever changing topography. One alternative solution to stablish the remote connection is the use of electromagnetic waves in radio frequency channels that enable the transmission and reception data.

In an intelligent mine, the communication requirements, linked to those applications with a higher autonomy degree levels as listed in Tab. F.1, are not limited to dispatch and telemetry systems: they are integrated to all autonomous tasks to control remotely the whole production. The wireless communications, therefore, will become robust to support all new applications and the merge of OCC and MDS. It is important to note that control applications require higher data rates and are less tolerant to latency and jitter, resulting in strict capacity, reliability and coverage requirements from the network. Video applications, a staple for teleoperated machinery, may consume an average throughput from 2.25 to 7.75 Megabits per second (Mbps) depending on the desired resolution and frame rate. They are very sensitive to the network quality, in terms of bandwidth and latency, i.e., interruptions or delays in real time audio or video are unacceptable. The satisfactory transmission of videos from several machine mounted cameras, the downlink of operational command, and in some cases, the transmission of engine noise enable the operator to run the equipment from a OCC, as if he were running it on the site [Garcia et al., 2016,McHattie, 2013,Peterson and Davie, 2007].

IV Case Study

In order to evaluate the impact of the mine topography variation and the fleet variation over the time on the quality of the service provided by the wireless network infrastructure, we now present this case of study. It considers the mine topography, fleet (bulldozers, haul trucks, drill rigs and loaders) and wireless network infrastructure in two distinct points in time: 2007 and 2014. The following terminology is adopted for the coverage and capacity's simulations of the wireless communication in an open-pit mine:

- *Conventional mine:* the communication network requirements are lim-

Table F.1: Degrees of automation with current examples [Horberry and Lynas, 2012].

Automation degree level	Description	Example
Low	This category includes perception systems, usually installed in vehicles. The operator has full control of the equipment at all times, handle with alerts and information about system health. The devices are simpler compared to automation systems in large scale. The connection to a OCC is unnecessary.	ToothMetrics^{TM} [Motion Metrics, 2013]: constant bucket monitoring through videos and automatic identification of missing teeth. The operator received an alert on a screen into the excavator's cabin.
Mid	Most of the time, the operator has control of the equipment, but some functions are controlled by a system and only supervised. It includes semi-autonomous and remote operations. The connection to the OCC is optional or may be necessary depending on the application.	Leica Geosystems Mining® [Korane, 2013]: the unmanned (track or wheel) dozers can clear and prepare a particular area.
Full	Most of the tasks are controlled by software. Human-element issues here might include ongoing supervision of operation. The connection to the OCC is required.	Komatsu's FrontRunner® [Korane, 2013]: the trucks are monitored from the OCC and run on the hauling road under the supervision of remote operators.

ited to telemetry and dispatch (narrowband) applications;

- *Intelligent mine:* the communication network requirements includes (wideband) applications of video, audio, commands and high-precision positioning, in addition to telemetry and dispatch applications, due to the higher automation degree associated with machinery operation.

By means of two digital surface models corresponding to 2007 and 2014's surfaces, it was possible to simulate the behavior of a given wireless communication network infrastructure using a network planning toll, such as Atoll®, considering a number of assets with their respective geographical positions and average throughputs. Tab. F.2 shows 2007 and 2014's fleet and their communications requirements for applications of a conventional and intelligent mine.

An increase of 38% in the quantity of assets in 2014 is justified by the increasing average hauling distance, increasing stripping ratio and reduced physical availability of initial fleet. Therefore, for the ROM production not to decay along time, the fleet needed to become bigger. If the mine continues to operate conventionally in 2014, traffic on the communication network increases proportionally. Also, if a mine plans to employ equipment with medium or high degree of automation in its operation, it should prepare the wireless network to support new applications. In this study case, the aggregated demand (offered data traffic) for an intelligent mine in 2014 is more than 44 times greater than the total of a conventional mine in 2007. Briefly, more capacity is required for autonomous applications.

Table F.2: Number of hosts, data requirement and total rate (uplink) in an iron ore open-pit mine

Assets	Number in 2007	Number in 2014	Average throughput (kbps) Conventional	Intelligent	Data services enabling automation
Bulldozer	3	5	32	3500	Video, audio, commands, telemetry, dispatch, precision positioning. Teleoperated asset.
Drill rig	2	4	32	3600	Video, telemetry, dispatch, precision positioning. Operated asset by software.
Haul Truck	26	32	32	500	Telemetry, dispatch, precision positioning. Operated asset by software.
Loader	6	10	32	500	Video, telemetry, dispatch, precision positioning. Operated traditionally
Conventional mine aggregated demand, 2007				1.2 Mbps	
Conventional mine aggregated demand, 2014				1.6 Mbps	
Intelligent mine aggregated demand, 2014				52.9 Mbps	

As a rule, the communications network is designed to fulfill the application requirements. Thus, it is necessary to ensure coverage and capacity for applications, but the latter is not necessarily uniform throughout entire the area of the mine, but at least within the area where the equipment is expected to be located. Each asset is located within a specific polygon, according to mine scheduling, as shown in Tab. F.3.

In this simulation, 5 types of polygons were considered to allocate equipment in. Figure 2 shows a part of the mine where some polygons are enclosed at (a) 2007 and (b) 2014. The development area corresponds to the future area that will be mined, and those places depend upon the orientation (dip and direction) of the geological body, so, drill rigs and bulldozers should be located in these areas. The excavation areas are characterized by loader tasks and these areas are connected to the crusher and waste dump through hauling roads. Bulldozers are found in all the created polygon geometries due to its flexibility and mobility inherent to its work, while trucks can only run in roads previously prepared. Tab. F.3 also highlights in its last column the assets that were allocated into a specific geometry for the simulations.

Fig. F.2 shows the same enclosed mining area (1.163 m x 2.314 m = 2.691 km^2) from 2007 and 2014 and the position of some polygons, as well as a

Table F.3: The fleet is allocated into specific polygons (regions)

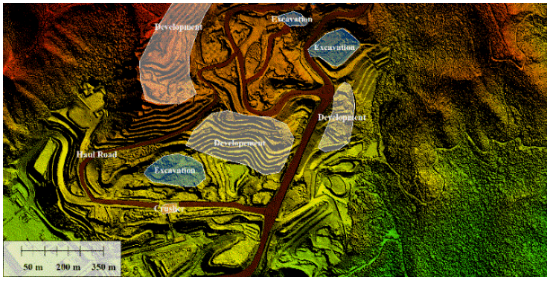
Geometry's name	Total area (km2) 2007	2014	Features of allocation
Development	0.2364 11.2%	0.6197 15.4%	These areas are prepared for future exploitation by **drills** and **dozers**.
Excavation	0.0713 3.4%	0.1124 2.8%	Extraction areas where the **excavator** loads the **truck**. **Dozers** are also common here.
Hauling road	0.1528 7.2%	0.3446 8.6%	Areas linking the excavation areas to dump points (crusher and waste pile). Roads for **trucks** and **dozers**.
Crusher	0.0022 0.1%	0.0056 0.1%	Areas for dumping ROM. It is common **trucks** and **dozers**.
Dump	0.0890 4.2%	0.5040 12.6%	Areas for dumping waste rock. It is common **trucks** and **dozers**.
Area total of operational mine	2.1180 100%	4.0150 100%	Area of entire mine (including the ones witch there isn't any equipment allocated in).

comparative figure showing the variation in height within the mine area. Fig. F.2c shows the areas that have become deeper in blue, and the areas that had their heights increased in red.

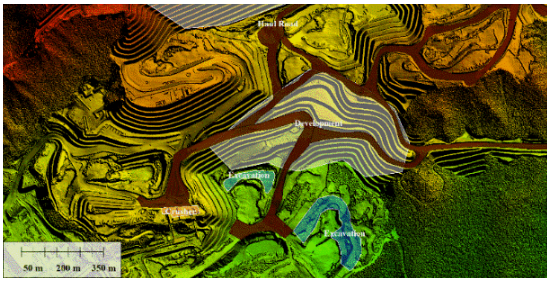
A. Network Planning

The next step in evaluating the impact of fleet increase and topographic variation on the quality of service provided by the wireless network is to simulate a given wireless network performance over time using a network planning software. The first simulation considered the deployment of a network infrastructure capable of providing the services shown in Tab. F.2, for the conventional mine scenario. In order to design such a network, it is important to consider the traffic constraints, the local topography as well as practical issues such as the optimal (and feasible) location to place base stations (macro and small cells of communication). The deployment of macro-cell base stations (tall tower) is expensive and, ideally, their location should not change over time. Consequently, it is interesting that network-planning engineers are in contact with mine-planning engineers to evaluate candidate points, desirably on the border of the mine that will not be mined. However, this is not always the case; the macro cell location is chosen considering the topography at the time of the initial deployment.

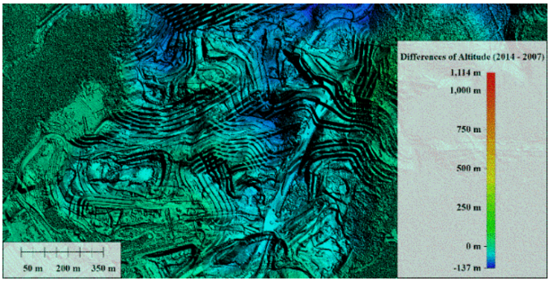
Considering the contour of the mine, the task of the network-planning engineer is to select locations to place the transmitter such that the coverage, capacity and latency requirements are met as cost-effectively as possible. In order to do that, the engineer should perform a set of simulations selecting the transmitter parameters, such as location, height, bandwidth, transmis-



(a)



(b)



(c)

Fig. F.2: Mining evolution. Dark brown regions refer to haul roads, white ones to development areas, the blue ones to excavator areas and the pink one to the crusher area: (a) 2007; (b) 2014; (c) Mine topography change between 2007 and 2014

Table F.4: Transmitter parameters for conventional mine

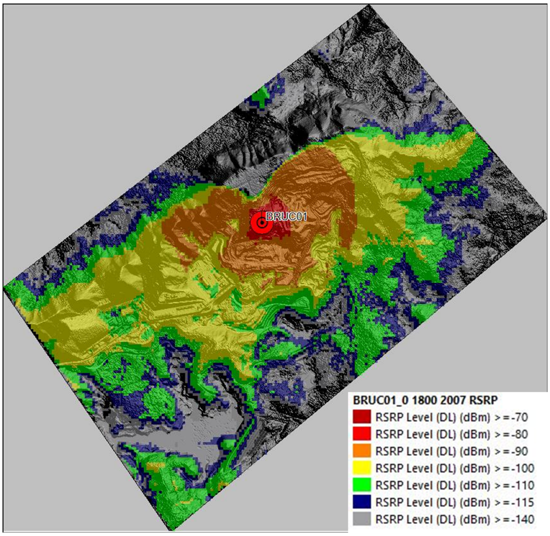
Transmitter	Parameter
Height [m]	40
Transmit power [dBm]	36
Downtilt [°]	0
Bandwidth [MHz]	5
Frequency [MHz]	1800
Antenna [type]	Omni
Antenna gain [dBi]	11

sion power, antenna types, tilt (inclination of the antenna) and the desired communication system. In these simulations, the authors considered a Long-Term Evolution (LTE) network, with the parameters presented in Tab. F.4.

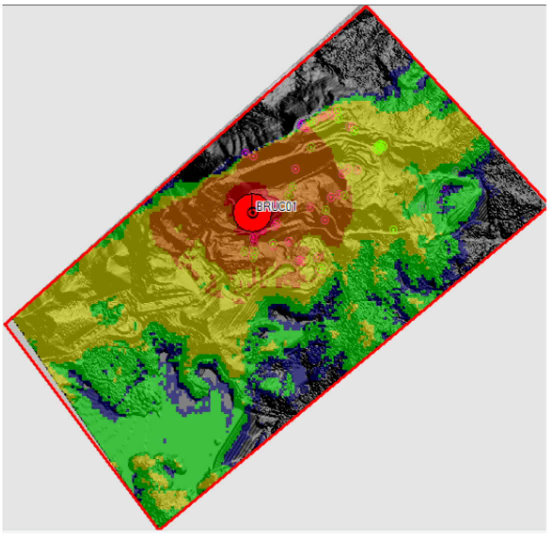
The network planning software employs propagation models that, in summary, relate the variation of signal level with the distance, frequency and type of scenario to predict the signal level in all points within the desired area [Rappaport et al., 1996]. In the results presented below, the Standard Propagation Model, calibrated with real measurements results, was considered. Fig. F.3a shows the Reference Signal Received Power (RSRP) levels in this simulation. As explained in Section "Wireless Communications for Mining Engineers", the received power levels are related to the achievable data rates applications running over the wireless network will experience.

In order to capture the effects of the statistical variation on the channel realizations, and also the impact of the change in position of the network clients over the zones defined in Tab. F.3, a Monte Carlo simulation was performed. In Monte Carlo simulations, the users are randomly positioned within the regions of interest and the results are collected in a "snapshot" of the network performance for a given set of parameters. The results are stored, and then new simulations are repeated, with new users' positions and channel realizations. After several snapshots, the resulting statistical distributions are analyzed and the mean values and standard deviations of the desired metrics are calculated. In Tab. F.5, we summarize the percentage of satisfied users as a function of the network deployment and user requirements. We present two network deployments: the macro deployment, and the heterogeneous deployment, a combination of macro and small cells. As detailed in Fig. F.3a, although the network deployment is the same in 2007 and 2014, there was a topographic change between the two years, causing impact on the coverage. Concerning the traffic requirements, we follow the description detailed in Tab. F.2: conventional and intelligent mine traffic.

From the Monte Carlo simulations, considering the first case, we conclude



(a)



(b)

Fig. F.3: RSRP levels for: (a) 2007 Macro deployment and (b) 2014 Macro deployment. The red circle represents the cellular tower.

Table F.5: Percentage of connected users in different moments in time, and distinct traffic conditions.

Network Deployment / Traffic Requirements	2007 Macro deployment Conventional Mine	2014 Macro deployment Intelligent Mine	2014 Heterogeneous deployment Intelligent Mine
Haul Truck	100.0	40.0	99.2
Bulldozer	100.0	26.6	92.8
Drill rig	100.0	28.9	94.3
Excavator	100.0	36.7	100.0
Total of connected users	100.0	37.8	98.3

that this deployment is capable of meeting the requirements of all the conventional mine applications and users, within the polygons defined in Tab. F.3 and Fig. F.2a, at the mine in the year of 2007, as shown in the second column in Tab. F.5.

Moving now in time, and taking into account the fleet growth observed from 2007 to 2014, and the topographic variation, we repeated the aforementioned network predictions, considering the same network infrastructure as in the first simulation. Since there was a topographic change between 2007 and 2014 the observed RSRP levels also varied, as shown in Fig. F.3b, in comparison to Fig. F.3a. Actually, in terms of coverage, the results of the year of 2014 are better than the results of year 2007. The reason for that comes from the particular features of this mine that extract ore and waste mainly from the hill, improving the LOS. The extraction of the material, between these years, created valleys and removed obstacles for the wireless signal, extending the coverage of the LTE transmitter.

However, when we look at the applications that need to be served by the initial network infrastructure at 2014, we see that there was a drop in the percentage of connected users (third column of Tab. F.5). The main reason for that is that the infrastructure deployed in 2007 does not provide enough capacity to serve the traffic demand of an intelligent mine. The practical consequence of the lack of capacity, and resultant increased delay, is that the autonomous equipment may not receive adequate (and timely) control information, halting its operation to avoid malfunctions. In the long term, frequent operational downtimes may bring substantial production losses.

In order to meet the demand of an intelligent mine, it is necessary to increase the system's capacity. There are many alternatives to achieve that goal. The first one is to increase the bandwidth of the system. For example, if we had considered 20 MHz instead of only 5 MHz, the capacity of the LTE macro cell would increase. However, spectrum is an expensive and tightly regulated resource. For example, Brazilian government got R$ 5.85 billion in the auction for the use of 4G spectrum among telecom operators. Therefore, one common approach is the use of Industrial, Scientific and Medical (ISM) band for increasing the total available bandwidth. However, the ISM band is unlicensed and prone to high interference levels, which may not be suitable for reliable applications. A successful approach to increase a system's capacity is to increase the number of networks nodes, or base stations, and reuse the available spectrum by sharing the available set of frequencies among the new transmitters. In this approach, it is very important to ensure that the interference between the network nodes is properly managed.

In LTE networks, the capacity can be increased by adding small cells to the network, which are defined as low power network nodes, placed closer to the ground level when compared to the macro-base station. The combination of small cells and macro cells is usually referred to as a heterogeneous deployment. However, if the small cells share the same spectrum with the macro-cell, it is very important to mitigate the interference between macro and small cells. Several techniques are available, such as inter-cell interference inter-cell interference coordination, that coordinates the use of the resources in time. Each small cell, placed at strategic locations – following the mining face equipment – such as the polygons defined in Tab. F.3, is capable of providing a fraction of the system capacity, according to the fraction of the spectrum (or time) it was allocated with. However, for the frequency reuse to be beneficial, it is important to ensure that the increase in SINR compensates the loss of spectrum and time.

In order to fulfill the requirements of intelligent mining, in the 2014 scenario, there is a need to modify the network deployment. The alternative chosen in this work was to include small cells, at the same frequency of the macro base station. This path was chosen because it reduces the costs associated to acquiring new spectrum; furthermore, in terms of network planning, this is one of the most challenging scenarios. Four small cells were included, with the parameters shown in Tab. F.6. Moreover, the original was moved to an optimized and future-proof location, i.e. no further relocations due to mining activities. The macro cell increases the reliability of the network, for its coverage overlaps with the small cells coverages, working as a backup link in case of failure, or as the main link in areas outside the coverage of small cells.

This setup is able to cover the entire mine area, and not only the focus polygons, and also provide much better connectivity, as shown in Tab. F.5, where more 98.3% of the total number of users are satisfied. However, even with the significant improvement and the concern of providing a backup link, the percentage of satisfied users is still far from what is required for automated applications, usually 99.999%. Automated systems are expected to operate seamlessly, and network outages lead to efficiency losses, exposing large equipment and operators to risks, and also exposing the mining industry to significant costs. From Tab. F.5, it can be observed that the two

Table F.6: Small cell transmitter parameters for Intelligent mine

Transmitter	Parameter
Height [m]	20
Transmit power [dBm]	36
Bandwidth [MHz]	5
Frequency [MHz]	1800
Antenna [type]	65° horizontal beamwidth
Antenna gain [dBi]	17

equipment with the largest percentage of unsatisfied users are the bulldozers and the drill rigs, 92.8% and 94.3%. Combining this information with Tab. F.3, that describes the area of each polygon, one can see that the service outage occurs specially in the Development Zone, suggesting that the network plan should still enhance the capacity within that area.

V Conclusion

The incorporation of new technologies in open-pit mines is a natural consequence of the computing evolution and workforce reorganizations. Communications systems that suit conventional narrowband applications (dispatch and telemetry) become overwhelmed by the inclusion of wideband applications required to support large-scale automation initiatives, e.g. tele-immersive operations.

The case study simulated the behavior of an LTE (4G) wireless communications network deployed in 2007 that successfully supported dispatch and telemetry applications, but fell short when data traffic increased from 1.2 Mbps to 52.9 Mbps in 2014. The initial infrastructure satisfied only an average of 37.8% of users in 2014. Furthermore, the mine became bigger and more areas needed to be connected by wireless communications.

To solve the problem without acquiring more expensive spectrum, four small cells were included in specific areas following the mining face equipment and the macro cell position was replaced, resulting in 98.3% of connected users. Despite the undeniable improvement, the solution is not, however, a permanent one: the topography and fleet changes require continuous wireless network planning to avoid lack ofcoverage or capacity for operations. The integration of radiofrequency (RF) and mine planning processes is the subject of ongoing research. Integration will provide the required knowledge to design an adequate infrastructure, which can ensure quality of service appropriate for the customized mining operation. Moreover, such tight collaboration will lead to a predictable and successfully positioning of the communications infrastructure from the early stages of the mining project, enabling greater scalability, besides having the potential to reduce capital and operational expenditure costs.

References

[Bellamy and Pravica, 2011] Bellamy, D. and Pravica, L. (2011). Assessing the impact of driverless haul trucks in australian surface mining. *Resources Policy*, 36(2):149–158.

[Boulter and Hall, 2015] Boulter, A. and Hall, R. (2015). Wireless network requirements for the successful implementation of automation and other innovative technologies in open-pit mining. *International Journal of Mining, Reclamation and Environment*, 29(5):368–379.

[Garcia et al., 2016] Garcia, L. G. U., Almeida, E. P. L., Barbosa, V. S., Caldwell, G., Rodriguez, I., Lima, H., Sørensen, T. B., and Mogensen, P. (2016). Mission-critical mobile broadband communications in open-pit mines. *IEEE Communications Magazine*, 54(4):62–69.

[Hargrave et al., 2007] Hargrave, C. O., Ralston, J. C., and Hainsworth, D. W. (2007). Optimizing wireless lan for longwall coal mine automation. *IEEE transactions on industry applications*, 43(1):111–117.

[Horberry and Lynas, 2012] Horberry, T. and Lynas, D. (2012). Human interaction with automated mining equipment: The development of an emerging technologies database. *Ergonomics Australia*, 8(1):1–6.

[Korane, 2013] Korane, K. J. (2013). Drones come down to earth.

[Martins, 2013] Martins, A. G. (2013). Simulação das operações de lavra da mina de brucutu utilizando um modelo de programação linear para alocar os equipamentos de carga. Master's thesis, Departamento de Engenharia de Minas, Universidade Federal de Ouro Preto.

[McHattie, 2013] McHattie, L. (2013). Advances in mining engineering to enable information mobility for 'intelligent mining'. In *World Mining Congress, Montreal, Quebec, Canada*.

[Motion Metrics, 2013] Motion Metrics (2013). Toothmetrics™ for loaders installed on letourneau 2350.

[Peterson and Davie, 2007] Peterson, L. L. and Davie, B. S. (2007). *Computer networks: a systems approach*. Elsevier.

[Rappaport et al., 1996] Rappaport, T. S. et al. (1996). *Wireless communications: principles and practice*, volume 2. prentice hall PTR New Jersey.

Paper G

Deployment Strategies for the Industrial IoT: A Case Study based on Surface Mines

Erika P. L. Almeida, Robson D. Vieira, Gabriel Guieiro,
Ignacio Rodriguez, Troels B. Sørensen, Preben Mogensen,
and Luis G. Uzeda Garcia

Published at *IEEE 90th Vehicular Technology Conference: VTC2019-Fall*

Abstract

The mining industry is on a transition towards unmanned operations. This implies a step change in wireless infrastructure expansion to support autonomous and teleoperated machinery. This paper investigates how the topographic changes over the course of 10 years of continuous mining affect the propagation conditions, and impacts the performance associated with different deployment strategies for wireless networks in a large open-pit mining complex in Brazil. Through a series of system-level simulations, using detailed terrain models, realistic traffic volumes and a dedicated propagation model, we compare the ability of different deployment strategies, and network features, to meet given performance targets with existing technology. The results show that heterogeneous deployments can be exploited to continuously guarantee coverage in this ever-changing topography, while interference mitigation techniques, such as enhanced inter-cell interference coordination (eICIC) and beamforming, can be used to reduce the system outage without need to increase the spectrum.

I Introduction

Being essentially an outdoor factory, surface mines are part of the Industrial Internet of Things (IoT) landscape. Wireless networking in surface mines has not been as intensively explored as in underground mines. This gap might be explained by two reasons. The first one is that a surface mine, or an open-pit mine, is essentially an enormous hole in the ground, an open space, where line-of-sight (LOS) conditions are abundant especially for macro cell communications [1]. The second reason stems from the communication requirements of early wireless applications: fleet management, vehicle monitoring, reporting and logging are fault-tolerant and not data-hungry services, consuming just a few kilobits per second, which could be accommodated by narrowband, or broadband, technologies, such as WiFi and WiMAX [2].

Although, at first sight, this environment might not be as challenging for wireless networks as underground mining, it is important to consider that substantial topographic change is inherent to surface mining activities. Every day, due to excavation, blasting, and disposal of waste material, the terrain is modified. These topographic variations have an impact on the experienced path losses, signal-to-noise ratios (SINR) and, ultimately, on the overall performance as well as the ideal topology of the network. Additionally, the position of the users is also affected due to the mining activity.

Another difficulty arises when we consider that akin to other verticals, mining is transitioning to digital and robotic operations, requiring lower latency, higher data rates and availability, in a uplink(UL)-dominated traffic [3–6].

The wireless network, that was previously used for monitoring, telemetry, safety and management activities, becomes now crucial for the entire business. Network planning and optimization will be fundamental to guarantee that the communication requirements will be met during the entire life cycle of each mining complex, ensuring a seamless mine operation. However, even though the necessity to consider the temporal evolution of the mine topography and automation traffic requirements in network planning has been identified in the past [6]; very few studies have been published regarding this matter to this day.

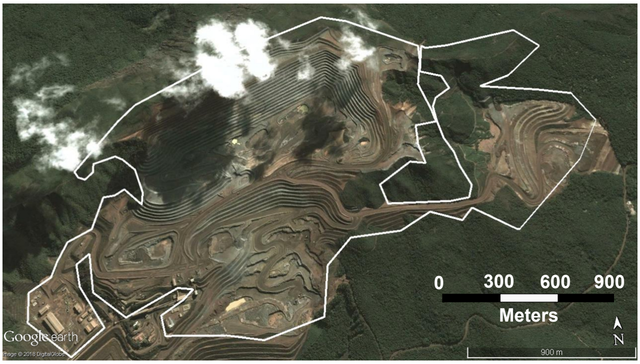
In 2013, the authors of [2] presented a survey of the distribution of wireless technologies in 20 open-pit mines, and discussed the challenges in planning a network for this environment. The identified challenges were: (i) topology, (ii) scalability and re-deployment, (iii) simultaneous coverage of active regions, (iv) mine instability and dynamic network reconfiguration, and (v) vehicle mobility, localization and safety. In that paper, the authors also proposed a set of solutions, ranging from Mesh networks, WiMAX and satellite communication systems. However, no performance evaluation was presented.

Our contribution in this paper is the detailed performance comparison of LTE based technologies in an evolutionary setting of realistic mine topography variation, propagation and traffic conditions over a 10 year time frame. Our choice of LTE is motivated by the mining's industry deployment of private LTE networks to accommodate new services [7]. In Section II, we discuss the impact of topographic variation in the performance of the wireless network over 10 years. The simulation assumptions are discussed in Section III, and include a dedicated propagation model [8] derived from extensive in situ measurement campaigns. Section IV presents the performance evaluation of well-known urban wireless network deployment strategies for urban scenarios, and discusses their suitability to the mining environment and their implications in terms of performance outage. We also include comparison between different approaches to enhance the system performance, such as increasing the available spectrum, and including interference mitigation techniques, such as eICIC and beamforming. The evaluation is done by means of semi-static system-level simulations. The current evaluation focuses on LTE TDD systems, and ongoing efforts consider the performance benefits yielded by more complex schemes introduced by later releases of LTE and 5G NR. The work is concluded in Section VI.

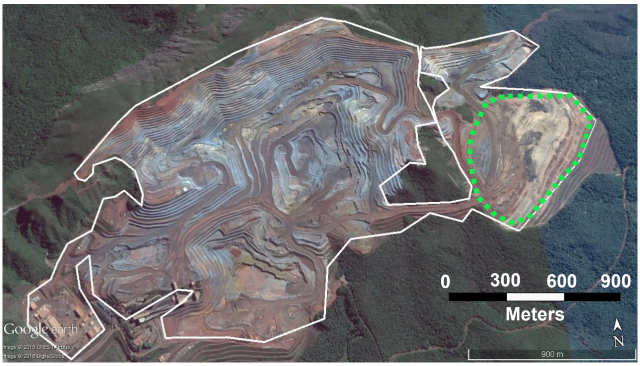
II Scenario Description and Topographic Variation

An example of the topographic variation in an open-pit mine is given in Fig. G.1, which shows aerial images of an operational iron-ore mine – located

(a)

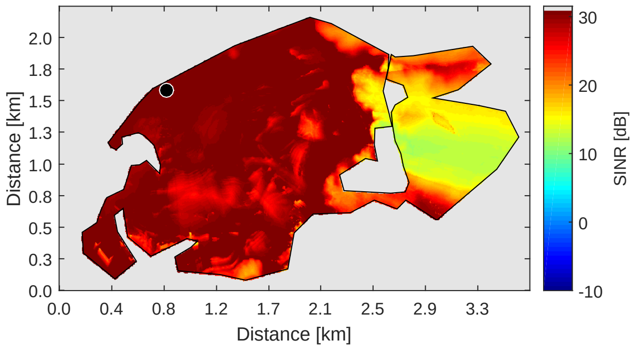


(b)

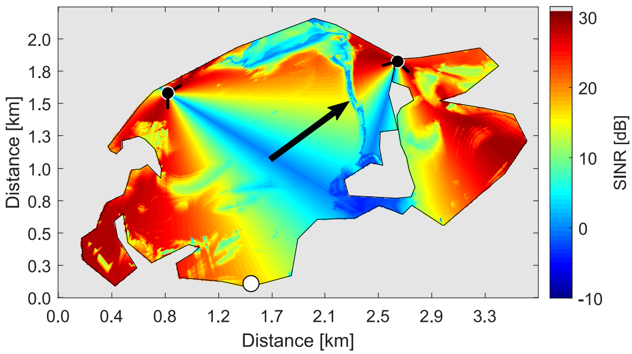


(c)

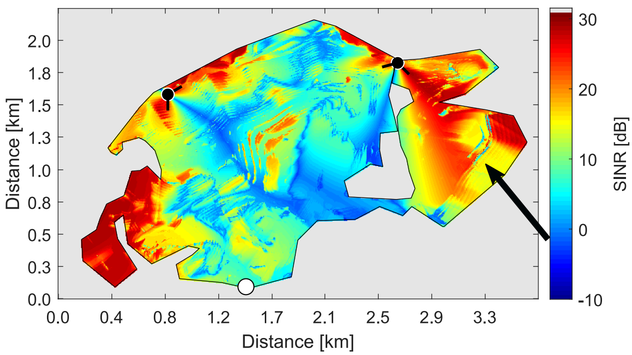
Fig. G.1: Aerial images of the mine area over the course of 10 years. Source: Google Earth. August 16, 2018. (a)Aerial Image, year 1. December 12, 2007. (b)Aerial Image, year 5. February 8, 2012. (c)Aerial Image, year 10. July 16, 2017.



(a)



(b)



(c)

Fig. G.2: Downlink (DL) Best Server SINR, LTE TDD, 10 MHz. (a)Year 1, one macro cell, omnidirectional. (b)Year 5, two macro cells, with 2 sectors each. (c)Year 10, two macro cells, with 2 sectors each.

in Minas Gerais, Brazil – over the course of 10 years. Fig G.1a shows the mine site one year after operations started. The expansion of the mining area is remarkable over the course of the first five years, leading to the scenario seen in Fig. G.1b. In this period, approximately 99 million cubic meters (i.e. 40 times the volume of the Great Giza pyramid) of material are removed from the mine, considering iron-ore and waste material, which is re-positioned inside of the mining site. In the next five years, although the surface area expansion is not as intense, the volume of removed material is similar: over a 100 million cubic meters of ore and waste were removed. The evolution of the mine between years 5 and 10 can be seen from the comparison between Figs. G.1b and G.1c. Besides the deepening and widening of the pit, the waste pile, highlighted in green in Fig. G.1c, rose up by 60 m due to the deposit of material.

Understanding how this topographic change impacts the wireless network performance, can help designing more reliable networks. A good starting point is the analysis of the SINR values over these 10 years of mine development depicted in Fig. G.2. In this example, we assumed an LTE TDD network, at the 700 MHz frequency band, with 10 MHz bandwidth, and considered the path-loss model from [8]. The transmitter (with 43 dBm tx power) locations are represented by the black dots in the pictures. The results were obtained based on a 5×5 m resolution DTM of the designated area. In this example, the network topology was selected based on the coverage and capacity requirements in each year.

A. Initial Insights

In year 1, Fig. G.2a, a single omni-directional transmitter was sufficient to provide the resources for the requested traffic, since the mining activity was concentrated at the vicinity of that transmitter. This case denotes the reality of mine deployments in the past, where initial wireless applications required low data rates, i.e., planning the network to achieve a target coverage also meant that the capacity was sufficient. In the absence of interference, the SINR values are extremely high. In year 5 and 10, due to the expansion of the mine and stricter communication requirements, the infrastructure consisted of two macro-cells, with two sectors each, placed on the border of the mine, where the mining activity would not force the relocation of 40 m tall towers over time. As expected, with the channel reuse the SINR levels decreased. However, In year 5 (Fig. G.2b), the interference from one transmitter to the other is contained by the hill highlighted by the black arrow. Finally, in year 10, Fig. G.2c, when this hill was mined, the overall SINR levels decreased. Additionally, in this figure, the black arrow highlights the extra diffraction loss caused by the elevation of the waste pile, which consequently degrades the SINR in that area.

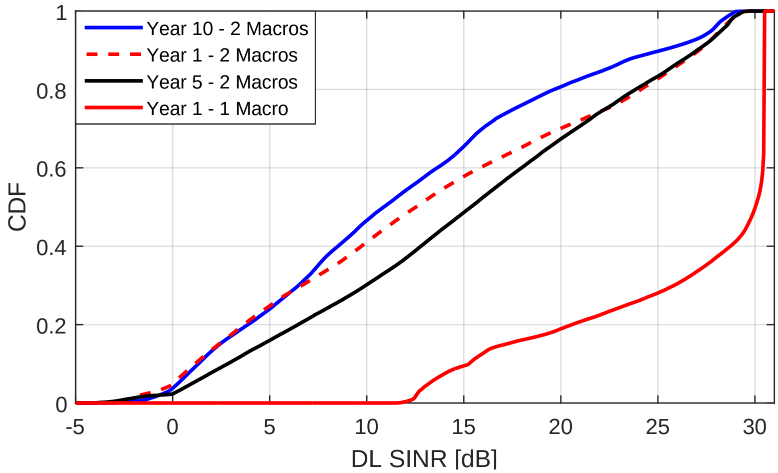


Fig. G.3: CDF of the DL SINR considering ten years of mine development.

The cumulative distribution function, CDF, of the SINR values for each year is depicted in Fig. G.3. In red, we have the curve from Year 1 with an omnidirectional transmitter, in black, the curve from year 5, and in blue, the curve from year 10. An extra curve, the red dashed line, was included in this figure to compare the SINR in year 1 to those in years 5 and 10 assuming the same infrastructure, i.e. 2 macro cells with 2 sectors each.

Considering only the cases with the same network topology, we observe that the effects of the mining activity on the SINR were not constant. Although the volume of material removed was similar in both periods, the effects on the SINR were opposite. From year 1 to 5, there was a general improvement of 3 dB in the SINR, while from year 5 to 10, there was an overall degradation of approximately 5 dB in the SINR. In year 1, the altitude of the terrain on the right and left sides of the hill highlighted in Fig. G.2b were comparable. In year 5, the intense mining activity in the left side of the mine deepened the terrain, increasing the diffraction loss between both transmitters consequently enhancing the SINR. The removal of the hill between year 5 and 10, explains the SINR degradation, as stated above.

The temporal topographic and SINR variations discussed above cannot be easily generalized to all surface mines, because the evolution of each mine site as well as its morphology and lithology are unique. However, the evaluation of this single case can provide important insights to network planning in open-pit mines. Some characteristics of this scenario are common to all surface mines: localized removal of material and growing waste piles resulting in significant variation of the line-of-sight conditions over short and long time scales.

III Simulation Assumptions

he simulations presented in this paper consider a LTE TDD system, operating on the 700 MHz and 2600 MHz band. The simulations consider the mining complex introduced in Section II. The high resolution DTMs were loaded in a MATLAB-based, semi-static network simulator detailed in [9]. The performance in each year was obtained independently. The main parameters of the simulation can be found in Table G.1. The association between a given UE and the serving cell is done based on strongest received signal level in DL.

The simulation considers the model proposed in [8], where the path loss is defined as a function of the free space path loss, a diffraction loss component, an effective height component and a calibration constant, k. In these simulations, this constant was adjusted based on the measurements collected in the same mine used as an example in Section II.

In HetNet scenarios, a cell range extension (CRE) is used to offload the traffic to small cells [10]. In the scenarios in which both macro and small cells are deployed in the same frequency band (2.6 GHz), the considered CRE bias is 3 dB. In scenarios with macro cells in the 700 MHz, and small cells in the 2.6 GHz, the considered RE is 6 dB to compensate for difference in path loss between the two frequency bands.

A. User location and traffic assumptions

We considered a realistic scenario in terms of number of users and communication requirements to capture the impact of the transition to autonomous operation in this mine. Not only the topography, but the communication requirements have also changed in open-pit mines in the few past decades, as summarized in Table G.2. In year 1, no autonomous equipment was present; therefore, we assume that the requirements for each one of the 46 users are: 32 kbps in the DL and UL.

Year 5 and Year 10 present a transition to autonomous mining. Depending on the degree of automation, the communication requirements vary. For example, fully-autonomous, driverless equipment, such as the autonomous hauling trucks (A) in Table G.2, rely on a virtualization of the operation area, a set of sensors to detect unmapped obstacles and on precise localization techniques. Tele-operated equipment, such as the bulldozer and drill in the same table, also require live video and audio transmission, so that the remote operator can control it, requiring significantly higher data rates. One specificity of this industrial environment, is the DL/UL traffic asymmetry [3], where the data rates are higher on the uplink (UL). In a transitional mine, conventional equipment, (C) in the table, which coexists with autonomous

Table G.1: Summary of simulation parameters.

LTE System	LTE TDD 60% UL and 40 % DL- 2x2 MIMO
Traffic Assumptions	Full-Buffer, with required data rates as in Table G.2
Tx Power	Macro cells: 43 dBm Small cells: 30 dBm
Antenna Configuration	Macro: 65° horizontal beamwidth, with 12° downtilt, placed at 40 m above ground level (agl). Gain: 17 dBi. Small: 10 dBi omni-antennas, placed at 5 m agl. UEs: 8 dBi omni-antennas, placed at 5 m agl.
Beamforming	Macro: Only at 2.6 GHz 5×4 8 dBi elements as in [11].
Path Loss Model	Vale model [8], with $k = 3$ for macro cells, and $k = 7$ for small cells
Resource Allocation	Priority to high SINR users, guaranteeing first the minimum required data rate
Frequencies	Macro cells: 700 MHz band or 2.6 GHz band Small cells: 2.6 GHz band

equipment, should also be visible to the controlling system. Therefore, even non autonomous equipment requires data rates between 80 kbps in the DL and 190 kbps in the UL. Another interesting point is that the number of users in the network might actually decrease, as the operation becomes totally autonomous: autonomous equipment tend to be more efficient than manually operated [5]. We assume full-buffer traffic throughout these simulations, which is a worst-case scenario.

The location of users is also realistic. For each year, we considered polygons that represent hauling roads, development and excavation areas, waste dump and crusher to model correctly the density of users in the region. The drill, for example, is in operation in the development area of the mine. Trucks transit between all regions, carrying waste and ore from the development, or excavation areas to the crusher or waste dump. For path loss calculations, we considered that the UE-side antennas are placed at 5 m above ground level (agl.): which is an average height value of hauling trucks, in which the antennas are placed at 7 m, and other vehicles in the mine, whose heights can be as low as 2 m [12].

Table G.2: Communication Requirements

Equipment	Quantity Year 5	Quantity Year 10	Required Data Rate DL [kbps]	Required Data Rate UL [kbps]
Trucks	10C+7A	13A	80	190
Drill	2C+1A	2C+1A	1140	2260
Loader	5C	7C	80	190
Bulldozer	3C+2A	3C+2A	1350	3150
Others	74	89	80	190
Total	104	117		

B. Resource Allocation and Interference Mitigation

he resource allocation is performed by each cell on a guaranteed-bit-rate basis, in which the minimum required data rate of users in high SINR is prioritized. If the minimum data rate of the users attached to that cell is guaranteed, the remaining resources are shared among the other users, in a round-robin fashion, just as in [9]. This applies to the DL and UL resources. In the DL, the SINR of the n^{th} user, served by the l^{th} cell, is calculated as:

$$SINR_{DL_n} = \frac{P_{RX_{l,n}}}{\sum_{c \neq l} I_{c,n} + N} \tag{G.1}$$

where N is the noise power, $I_{c,n}$ is the interference power received from the c^{th} cell. In Eq. G.2, $P_{RX_{l,n}}$ is given by:

$$P_{RX_{l,n}} = \frac{P_{TX_l} G_{TX_{l,n}} G_{RX}}{PL_{l,n}} \tag{G.2}$$

where P_{TX_l} is the transmit power of the serving cell, $G_{TX_{l,n}}$ is the antenna gain in the direction of the n^{th} user, G_{RX} is the receiving antenna gain and $PL_{l,n}$ is the path loss [8]. The power of interference is calculated in a similar way:

$$I_{c,n} = \frac{P_{TX_c} G_{TX_{c,n}} G_{RX}}{PL_{c,n}} \tag{G.3}$$

where P_{TX_c} is the transmit power of the interfering cell, $G_{TX_{c,n}}$ is the interfering antenna gain in the direction of the n^{th} user, and $PL_{c,n}$ is the path loss between the two nodes.

In the uplink, the SINR of the n^{th} user is calculated as:

$$SINR_{UL_l} = \frac{P_{RX_{n,l}}}{\frac{1}{K} \sum_k \sum_{c \neq l} I_{u_{ck},l} + N} \tag{G.4}$$

where $P_{RX_{n,l}}$ is the received power from the n^{th} user, considered at the serving cell l. The power of the interference is averaged in a Monte-Carlo simulation with K realizations. In each realization, users associated with different cells, $u_{c \neq l}$, are selected as interfering nodes. This selection occurs based on scheduling probabilities, taking into account the load and available resources at the c^{th} interfering cell.

We use SINR-to-throughput mapping curves, considering adaptive modulation and coding, as well as HARQ and 2×2 MIMO [9]. LTE fractional power control is considered. The main performance indicator is the *outage*, which, in this study, is defined as the percentage of users whose experienced data rates are below the required values in Table G.2.

Part of the results to be presented in the next section consider the use of eICIC [10] and beamforming features [11]. In the case of eICIC, or almost blank subframes, 40% of the downlink subframes from the macro cell are empty in the simulation. The objective is to reduce the interference with the small cells deployed in the same frequency band. Beamforming, on the other hand, was only considered in the macro cells at 2.6 GHz frequency band. In this study, we consider an antenna array with 5×4 elements in the BS side, for RX and TX beamforming, generated by the weighting and superposition vectors specified in [11]. For the purpose of beam steering, in this work, it is assumed perfect angle-of-arrival (AoA) estimation, therefore, when steering each beam we consider the position of the target UE. Then, considering this specific steering, the interference is calculated in the direction of all other UEs in the simulation, and considered in the SINR calculation afterwards.

C. Macro and Small Cell Deployment Strategies

The simulations consider different deployment strategies, such as small-cells only, macro cells as well as heterogeneous networks (HetNets). The placement strategy of macro and small cells takes into account some specifics of this environment, for example: macro cells are deployed on locations along the optimum ultimate pit, i.e. the contour of the mine at the end of its life, to preclude frequent and costly re-locations of cell towers. On mine sites, small cells tend to be nomadic in nature. They can and may need to be frequently re-positioned due to blasting, excavation, and mine development, which changes not only the vehicles routes, but also the traffic density. Such sites are usually deployed in the form of cell-on-wheels (CoWs) with antenna poles typically limited to 20 m. Small cells are still the predominant solution due to their flexibility, lower upfront costs and ease of installation. In large mines, the number of CoWs can be greater than 20 when the wireless access is based on WLAN and/or mesh networking technologies.

IV Outage Evaluation

A. Macro Cells

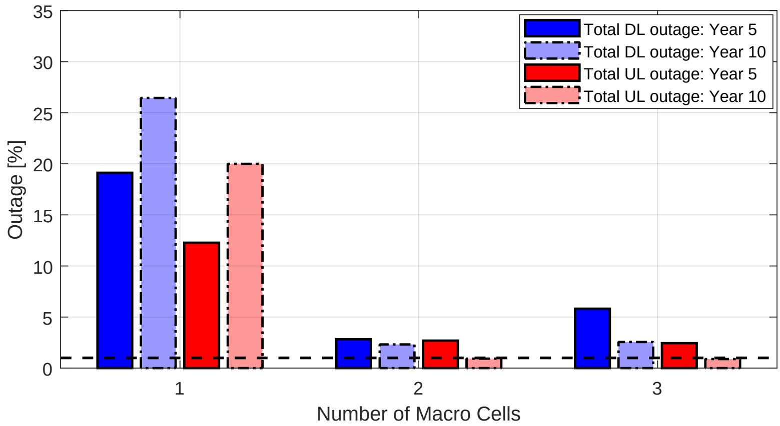
This simulation considers a TDD LTE network, with macro cells in the 700 MHz frequency band in a co-channel deployment with 10 MHz bandwidth. The first and second macro cells are the ones represented by the black dots in Fig. G.2. The third macro cell was placed in the white dot in Figs. G.2b and G.2c. In this work, we selected locations at the border of the mine, to guarantee that the positions of the macro cells remained unchanged over the last 5 years of mining exploration.

Fig. G.4a shows the variation of the DL and UL outage as a function of the number of two-sectors macro cells, in years 5 and 10. The results for the first year are not shown, because the desired performance is obtained with 1 omni-directional macro cell and a 10 MHz bandwidth. With 12° degrees downtilt, coverage is achieved in 99% of the cases, even with a single macro cell deployment. Therefore, the main cause of outage is the lack of resources in the network. The total increase of the traffic between Year 5 and Year 10 is about 9%, which explains partially the total degradation of 15% (7.3% in the DL and 7.7% in the UL) observed in Fig. G.4a, for one macro cell. The variation of the terrain still plays an important role, since it causes a degradation in the SINR. If the traffic was kept constant between year 5 and 10, the total outage would still be degraded by 10%, instead of 15%.

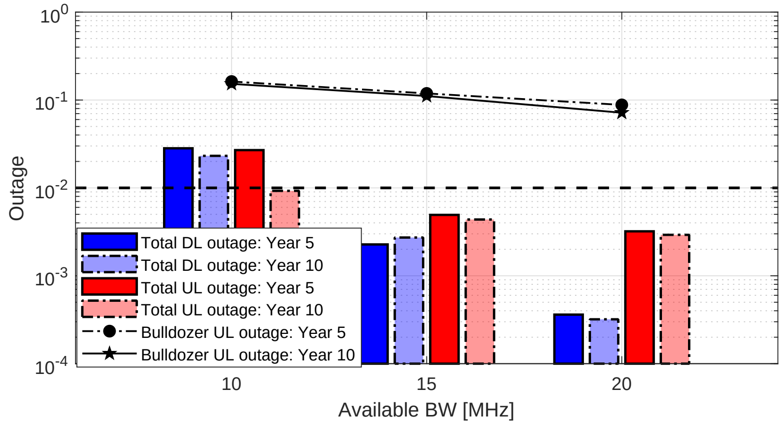
If sufficient coverage is provided, the network performance tends to be similar in different moments of time. In Fig. G.4a, this case is represented by the cases with 2 and 3 macro cells. Generally, the addition of new macro cells is capable of reducing both the UL and the DL outage, however, with a limited gain due to the degradation of SINR. This case can be seen in the DL outage in year 5, which actually increases with the addition of the 3^{rd} macro cell. In this case, the inclusion of resources in the network, by reusing the channel spatially, does not compensate the decrease of the SINR from the addition of a new cell. It is also worth mentioning that with more macro cells, the outage in year 10 is actually smaller than in year 5, despite the increase of the number of users, due to the variation of the terrain.

One strategy that can be used to increase the capacity of the network is increasing the available bandwidth, as in Fig. G.4b. In this example, the deployment with two macro cells was selected. The results show that increasing the bandwidth reduces dramatically the total outage in the DL and UL to values lower than 1%, with the best deployment being the one with 2 macro cells with 20 MHz bandwidth. This figure also shows, however, that the outage considering specific equipment, for example the bulldozer, is not below 1% in all cases. We will return to this matter in Section V.

Finally, it is important to stress that mining companies do not derive direct



(a) Percentage of outage considering a network with 10 MHz bandwidth, as a function of the number of macro cells.



(b) Outage considering a network with 2 macro cells, as a function of the available bandwidth.

Fig. G.4: Outage in a macro cell deployment.

revenue from wireless networks and that sub-1 GHz spectrum is a scarce and expensive resource. As a result, increasing the amount of dedicated spectrum may be unfeasible in real deployments.

B. Heterogeneous

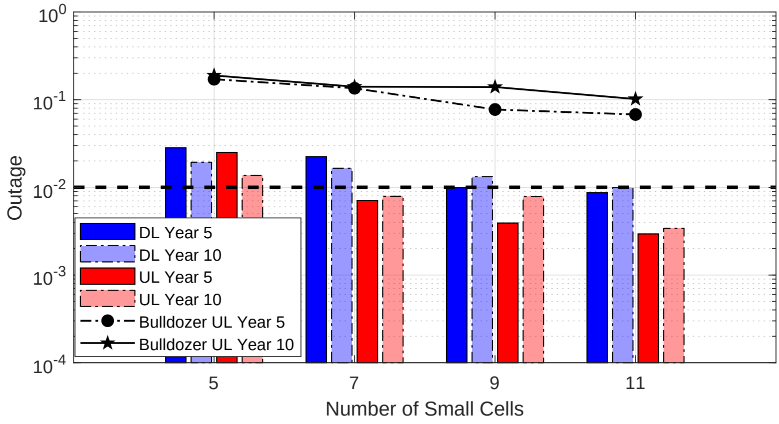
In this subsection, we investigate the results in a heterogeneous deployment.The macro cell layer is used to provide coverage, while the small cell layer provides capacity in high traffic areas. We assume a microwave backhaul connection between the small cells layer, and the macro cell layer. Although different combinations of spectrum in each layer are possible, we chose to evaluate three cases:

- In-band deployment: both the Macro cell, and the small cell layers are deployed in a 10 MHz channel in the 2.6GHz band.
- Out-of-band deployment: the Macro cells are deployed in a 10 MHz channel in the 700 MHz band, and the small cells are deployed in a 10 MHz in the 2.6 GHz band.
- In-band deployment, with interference mitigation techniques, in which macro and small cells share a 10 MHz channel in the 2.6GHz band.

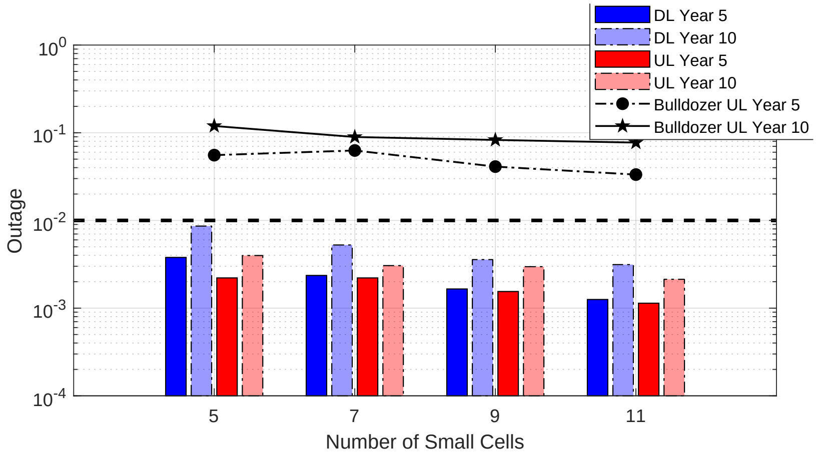
In-band deployment

The in-band deployment results are shown in Fig. G.5a, as a function of the number of small cells: 5, 7, 9 and 11. When compared to the equivalent macro cells only case (first column in Figure G.4b), the outage in the heterogeneous deployment with 5 small cells is decreased in the DL, due to the extra capacity added to the network by the small cells, which was sufficient to compensate for the decreased SINR. In the UL, on the other hand, the outage is slightly increased when compared to the macro cell case. In the macro cells case, the UL interference was limited by the number of simultaneous transmissions in this network, which depends on the total number of sectors in the network. When small cells are introduced, more transmissions can occur simultaneously, which decreased the UL SINR given by Eq. G.4. However, in general, adding more small cells to the network decreased the outage in both UL and DL, which reached levels close to 1% in the case with 11 small cells. The outage of the bulldozer in the UL, on the other hand, is 6.7% and 10% respectively for years 5 and 10.

Additionally, and in general, the difference in outage values between years 5 and 10 are smaller than those found in the equivalent macro cells case. This indicates that the system performance becomes less sensitive to the variation of the terrain (provided that small cells are properly re-positioned) from an interference point of view. The most significant difference between the outage of year 5 and 10 is less than 1%. This is due to the fact that the interference in small cells, even in this open scenario, is contained due to lower antenna heights, transmit power and the radio-propagation characteristics at the 2.6 GHz band.



(a) 10 MHz (2.6 GHz)



(b) 10 MHz (700 MHz) + 10 MHz (2.6 GHz)

Fig. G.5: Outage in a heterogeneous deployment, with two macro cells, as a function of the number of small cells.

Out-of-band deployment

Following what was done for the macro cell, in Section A., the next step is to increase the available spectrum, by adding a 10 MHz channel to the heterogeneous deployment. In this case, the small cells continued in the 2.6GHz band, while the macro cells are deployed in the 700 MHz band. A CRE bias of 6dB was added to aid in the load balancing between the macro layer and the small cell layer. The results are shown in Fig. G.5b.

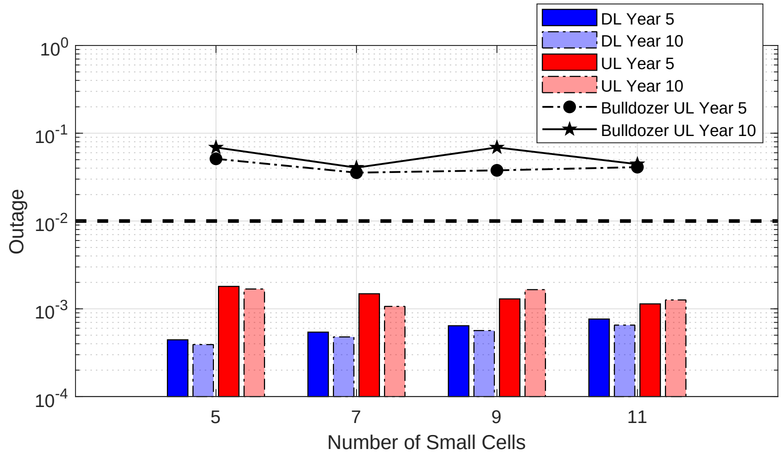


Fig. G.6: Outage in HetNet deployments combined with eICIC and beamforming, as a function of the number of small cells.

As expected, adding more spectrum to this network improved the overall system performance, as well as adding more small cells to the network, as observed in Fig. G.5a, However, the outage levels achieved with 5 small cells, in the out-of-band deployment, are comparable to the ones obtained in the in-band case with 11 small cells. For example, the bulldozer outage is increased from 3.9% in the first case, year 5, to 5.5% in the second case, with twice as much spectrum. The drill outage, on the other hand, is reduced from 6.7% to 5%. Considering the elevated costs for using these spectrum bands, and considering that the total load of the system is not that high, adding more spectrum in this scenario might not be the best option to achieve better network performance. Therefore, in the next subsection, we investigate the use of two interference mitigation techniques: beamforming and eICIC.

Interference mitigation techniques

Initially, both techniques were evaluated separately. eICIC is implemented through the concept of almost-blank subframes, in which the macro cells reduce the transmitted power in order to cause less interference in the small cells deployed in the same band. Though the technique is able to enhance the system's SINR, it is important to notice that blanking these subframes decrease the number of available resources for transmission. In these simulations, in which the bandwidth is limited to 10 MHz, this effect cannot be compensated by the increase in the SINR. The use of eICIC actually caused a decrease in the throughput, even when the percentage of blanked subframes was varied.

Macro cell beamforming, on the other hand, faced a different challenge in this environment, due to the irregularity of the terrain and small cells characteristics. Omni directional small cells, deployed in elevated positions, can actually cover (or interfere on) a large area even considering the reduced power. Additionally, the simulation assumption is that there is no coordination between the scheduling of macro and small cells due the independent (solar-powered) operation of small cells. These two factors, when combined, caused the situation that UEs attached to small cells suffer high interference from macro cell beams, and therefore a limited reduction in the outage when compared to the results in Fig. G.5a.

Taking this into consideration, we investigated the performance when combining the two techniques, and the results are in Fig G.6. The power concentration of the macro cell beams during the available DL frames, combined with the interference-free DL transmissions from small cells, were capable of reducing the DL outage to 10^{-3}, even less of what was achieved with the deployment with 20 MHz. The UL outage is also the minimum of the investigated deployments, in the order of 0.002. On the contrary of what was showed in the other cases, increasing the number of small cells, in this case, can actually slightly increase the outage of traffic hungry bulldozer in year 5 and 10. Potential solutions to decrease the outage in bulldozers and drills, that were not explored in this work, adding small cells to these areas (which are likely to be high traffic areas, since the materials moved by drills and bulldozers need to be transported by trucks), and using directive antennas in these UEs. Both bulldozers and drills stay in a constrained area during long periods, therefore, using directive antennas, or grid of beams is not unfeasible.

V Discussions

Considering the surface mine scenario, the deployment of macro cells have a clear advantage of guaranteeing a wide-area coverage. Furthermore, it can be expected that mine sites have pre-existent macro cell infrastructure. The results, however, point out a disadvantage to this deployment: increasing the bandwidth and the number of cells may reduce the total outage of the network, but the outage of individual equipment still remain quite high. The outage requirements of loaders, trucks and other vehicles are satisfied in all selected deployments. In the case of macro cells, the outage levels of the bulldozer are still between 7.5% and 11%. A practical issue comes from the fact that the location might need to change over the exploration time of the mine. Construction costs for new macro cells are certainly higher than the deployment of small cells. Therefore, macro cells location variability should be avoided in the network planning phase, to minimize the overall costs.

Heterogeneous networks, on the other hand, have the advantage of flexible deployment, providing coverage and capacity where it is needed. The flexibility, however, does not come without costs: re-deploying a small cell is still a manual procedure. It depends on the availability of employees and vehicles, and it is usually triggered by blasting, or by the performance degradation of the network, instead of being a predictive action. Recently, a relocatable platform has been proposed as a solution to reduce human interaction in the process of moving small cells around the mine [13]. In terms of performance, when compared to the macro cells case, these deployments were able to achieve lower outage levels for bulldozers and drills, even in the in-band deployments with no interference mitigation.

Small cells have an increased probability of suffering from severe shadowing in vehicle-to-infrastructure (V2I) links as discussed in [12]. In this work, it shown that the excess loss in the vicinity of a loaded truck can vary from 3.1 dB (10 m poles) to 24.7 dB (5 m poles).Though this excess loss is not included in this work, we investigated the system performance when the antenna height is changed, and the results showed that the outage variation in the worst case, 5 small cells in an in-band deployment, is always less than 1%. Therefore, we conclude that increasing the small cells antenna height can be beneficial for reducing blockage effects without degrading the performance.

Increasing the available bandwidth from 10 to 20 MHz was able to improve the performance of the network, in both macro and heterogeneous deployments. However, as mentioned, it might not always be feasible to have access to additional spectrum. Therefore we also investigated the outage when applying interference mitigation techniques. One technique that seems very promising in this environment is beamforming. First, due to the dynamic of the scenario, the percentage of LOS tends to increase with time. In this mine, between year 5 and 10, and considering 2 macro cells, the percentage of LOS varied from 61.8% to 82%, which potentially aids in the AoA estimation. Second, in an autonomous mine, the position of the nodes needs to be known to the system at any given moment in time. If this information is integrated to the communication network, as proposed in [3], it can aid the beamforming. This can be particularly beneficial in deployments in higher frequency bands, as the ones in the upcoming 5G systems.

VI Conclusion

In this paper, we presented a study about the effects of topographic change in open-pit mines on the performance of a wireless network under different deployments: macro and heterogeneous networks with in-band and out-of-band deployments. The simulation considered a realistic model of a mining complex in terms of terrain maps, propagation model, number of users, routes and traffic load. The results show that the terrain variability does impact to the performance of the network, especially in macro cell only deployments. Heterogeneous deployments, on the other hand, were less impacted by the terrain variability due to the flexibility of the nodes. Increasing the number of nodes in the network also increased the interference, motivating us to investigate the performance of interference mitigation techniques: beamforming and eICIC. When the techniques are combined, an outage level in the order of 10^{-3} can be achieved in both DL and UL.

References

[1] E. P. L. Almeida, G. Caldwell, I. Rodriguez, S. Abreu, R. D. Vieira, V. S. Barbosa, T. B. Sørensen, P. Mogensen, and L. G. U. Garcia, "Radio Propagation in Open-pit mines: a first look at measurements in the 2.6 GHz band," in *28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,(PIMRC)*, 2017.

[2] S. Vellingiri, D. Tandur, and M. Kande, "Communication architecture for remote monitoring and diagnostics in open pit mine." in *ETFA*, 2013, pp. 1–6.

[3] L. G. U. Garcia, E. P. L. Almeida, V. S. Barbosa, G. Caldwell, I. Rodriguez, H. Lima, T. B. Sørensen, and P. Mogensen, "Mission-critical mobile broadband communications in open-pit mines," *IEEE Communications Magazine*, vol. 54, no. 4, pp. 62–69, 2016.

[4] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0," *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 17–27, 2017.

[5] O. Gölbaşı and K. Dagdelen, "Equipment replacement analysis of manual trucks with autonomous truck technology in open pit mines," in *Proceedings of the 38th International Symposium on the Application of Computers and Operations Research (APCOM 2017)in the Mineral Industry*, 2017.

[6] A. Boulter and R. Hall, "Wireless network requirements for the successful implementation of automation and other innovative technologies in open-pit mining," *International Journal of Mining, Reclamation and Environment*, vol. 29, no. 5, pp. 368–379, 2015.

[7] D. Bushell-Embling. (2017) Mining sector driving private lte network adoption. [Online]. Available: https://www.nokia.com/blog/private-lte-game-changer-industries/

[8] E. P. L. Almeida, G. Caldwell, I. Rodriguez, R. D. Vieira, T. B. Sørensen, P. Mogensen, and L. G. U. Garcia, "An empirical study of propagation models for wireless communications in open-pit mines," in *IEEE 87th Vehicular Technology Conference (VTC Spring)*, 2018.

[9] C. Coletti, "Heterogeneous deployment analysis for cost-effective mobile network evolution:-an lte operator case study," Ph.D. dissertation, Aalborg Universitetsforlag, 2013.

[10] 3GPP, ""Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN), Overall description"," *TS 36.300 v11.3.0*, 2012.

[11] ITU, "Modelling and simulation of IMT networks and systems for use in sharing and compatibility studies," *Recommendation ITU-R M.2101-0*, 2017.

[12] P. H. O. Gomes, G. Guieiro, E. P. L. de Almeida, and L. G. U. Garcia, "Evaluation of shadowing caused by mining machinery in v2i communications," in *IEEE 29th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), 2018*. IEEE, 2018.

[13] S. Knutsson and D. Larmark, "Modular communications relay for autonomous quarry operation," Master's thesis, Faculty of Mechanical Engineering, Blekinge Institute of Technology, 2018.

ISSN (online): 2446-1628
ISBN (online): 978-87-7210-504-8

AALBORG UNIVERSITY PRESS