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CERTIFICATE

We certify that **VIVIANE DA SILVA BORGES BARBOSA,** presented a paper titled **THE CHALLENGE OF WIRELESS CONNECTIVITY TO SUPPORT INTELLIGENT MINES,** in **ORAL** form, co-author(s) ERIKA PORTELA LOPES DE ALMEIDA, GEORGE CALDWELL, HERNANI MOTA DE LIMA, IGNACIO RODRIGUEZ LARRAD, LUIS GUILHERME UZEDA GARCIA, PREBEN MOGENSEN, TROELS BUNDGAARD SØRENSEN, at the **24th World Mining Congress**, held between 18th to 21st October 2016 at SulAmérica Convention Centre in the city of Rio de Janeiro.

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THE CHALLENGE OF WIRELLES CONNECTIVITY TO SUPPORT INTELLIGENT MINES

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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.

KEYWORDS

Mining automation, wireless communication, intelligent mines, communication requirements, mining application

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 & 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 & 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 Operational Control Center (OCC), for example a Mining 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 & Hall, 2015; Peterson & Dave, 2013).

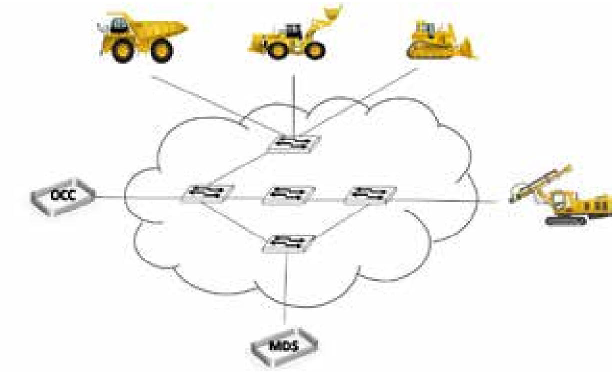


Figure 1 – Assets, OCC, MDS (hosts) are connected through links and nodes of a communication network

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 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.

WIRELESS COMMUNICATIONS FOR MINING ENGINEERS

In this Section, a brief overview of important communications concepts is presented. Interested readers are referred to Rappaport (2002) 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 Line-Of-Sight (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 interferences, indicating whether the original message can be decoded at the receiver side. Usually, this signal threshold is defined in terms of a minimal signal-to-noise ratio (SNR), or a minimal signal-to-noise-plus-interference ratio (SINR), and received signal strength indication (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 (Equation 1) defines the maximum data rate at which information can be sent over a communications channel:

$$C = B \times log_2(1 + SNR) \qquad (1)$$

In Equation (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 cell-on-wheels) 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.

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 Table 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 Table 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 & Davie, 2013).

Table 1 – Degrees of automation (Horberry & Lynas, 2012), with current examples

Degree of Autonomy	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} ("ToothMetrics^{TM} for loaders", 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.

CASE STUDY

Preliminaries

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 limited 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. Table 2 shows 2007 and 2014's fleet and their communication 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 degrees 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 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)		Data services enabling automation
			Conventional	Intelligent	
Bulldozer	3	5	32	3 500	Video, audio, commands, telemetry, dispatch, precision positioning. Teleoperated asset.
Drill rig	2	4	32	3 600	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 in 2007				1.2 Mbps	
Intelligent mine aggregated demand in 2014				52.9 Mbps	

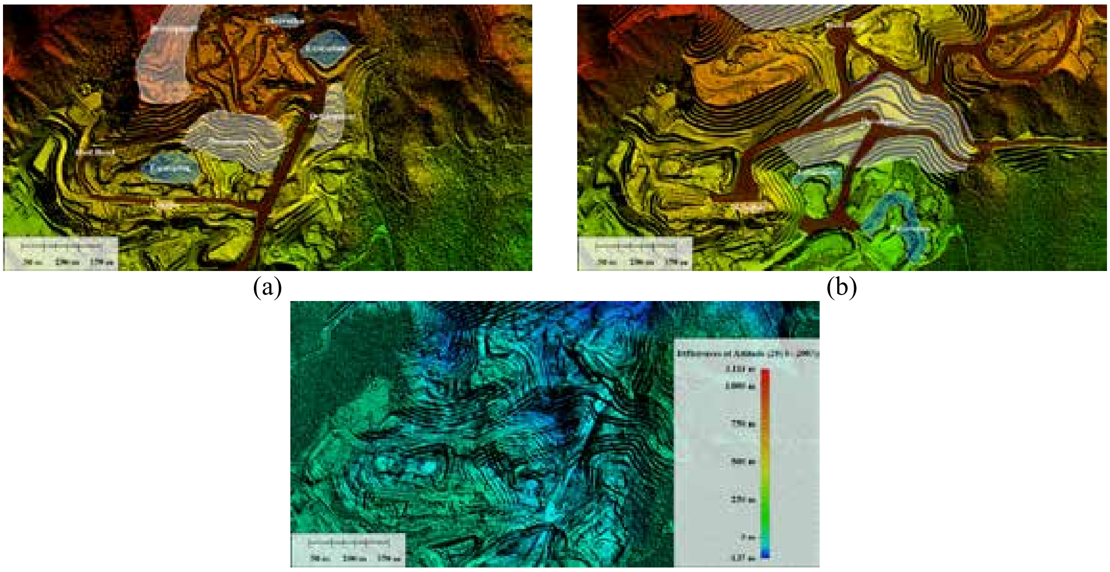
As a rule, the communications network is designed to fulfill the application requirements. Thus, it is necessary to ensure coverage and capacity for applications, but the latter is not necessarily uniform throughout entire the area of the mine, but at least within the area where the equipment is expected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

Table 3 – The fleet is allocated into specific polygons (regions)

Geometry's name	Total area (km^2)		Features of allocation
	2007	2014	
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).

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. Table 3 also highlights in its last column the assets that were allocated into a specific geometry for the simulations.

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



(a) (b)

(c)

Figure 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

Network Planning

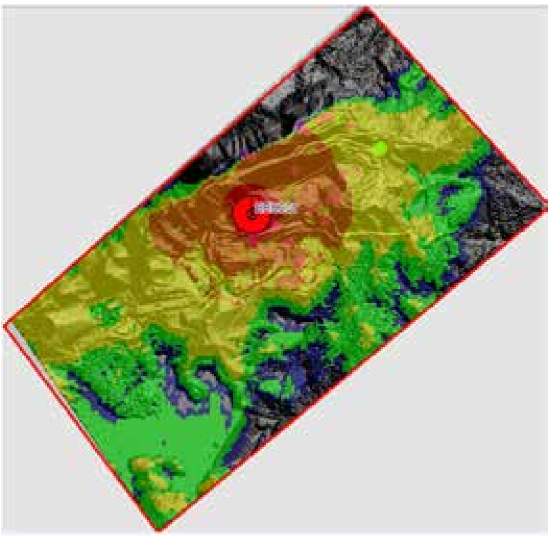
The next step in evaluating the impact of fleet increase and topographic variation on the quality of service provided by the wireless network is to simulate a given wireless network performance over time using a network planning software. The first simulation considered the deployment of a network infrastructure capable of providing the services shown in Table 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, transmission 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 Table 4.

Table 4 – Transmitter parameters for conventional mine

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

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, 2002). In the results presented below, the Standard Propagation Model, calibrated with real measurements results, was considered. Figure 3 (a) 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.



(a) (b)

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

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 Table 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 Table 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 Figure 3, 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 Table 2: conventional and intelligent mine traffic.

Table 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
Equipment type	Percentage of satisfied users (%)		
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

From the Monte Carlo simulations, considering the first case, we conclude that this deployment is capable of meeting the requirements of all the conventional mine applications and users, within the polygons defined in Table 3 and Figure 2(a), at the mine in the year of 2007, as shown in the second column in Table 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 Figure 3 (b), in comparison to Figure 3 (a). 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 Table 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 coordination, that coordinates the use of the spectrum in the frequency by different nodes, and the enhanced 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 Table 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 Table 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.

Table 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

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 Table 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 Table 5, it can be observed that the two equipment with the largest percentage of unsatisfied users are the bulldozers and the drill rigs, 92.8% and 94.3%. Combining this information with Table 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.

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 of coverage 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, D., & Pravica, L. (2011). Assessing the impact of driverless haul trucks in Australian surface mining. *Resources Policy, 36 (2),* 149-158.

Boulter, A., & 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, L. G. U., Almeida, E. P. L., Barbosa, V. B., Caldwell, G., Rodriguez, I., Lima, H., Sørensen, T. B., & Mogensen, P. (2016). Mission-Critical Mobile Broadband Communications in Open-Pit Mines. *IEEE Communications Magazine*.

Hargrave, C. O., Ralston, J. C., & Hainsworth, D. W. (2007). Optimizing wireless LAN for longwall coal mine automation. *Industry Applications, IEEE Transactions on, 43(1),* 111-117.

Horberry, T., & Lynas, D. (2012). Human interaction with automated mining equipment: The development of an emerging technologies database. *Ergon. Aust, 8,* 1-6.

McHattie, L. (2013, August). *Advances in mining engineering to enable information mobility for 'intelligent mining'.* Paper presented at the World Mining Congress, Montreal, Quebec, Canada.

Martins, A. G. (2013). *Simulação das operações de lavra da mina de Brucutu utilizando um modelo de programação linear para alocar equipamentos de carga.* (Master's thesis). Ouro Preto School of Mines, Ouro Preto, Brazil. Retrieved from http://www.repositorio.ufop.br/handle/123456789/3148.

Korane, K. J. (2013). Drones come down to Earth [Magazine article]. Retrieved from http://machinedesign.com/constructionoff-road/drones-come-down-earth-ugvs-and-driverless-vehicles-reality

Peterson, L. L., & Davie, B. S. (2013). *Computer networks: a systems approach.* Elsevier.

Rappaport, T. S. (2002). *Wireless communications: principles and practice*. New Jersey: Prentice Hall PTR.

ToothMetrics^{TM} for loaders installed on LeTourneau 2350 [Information on a page]. (2013, September 16). Retrieved from http://www.motionmetrics.com/installations/toothmetrics-for-loaders-installed-on-letourneau/.