Mission-Critical Mobile Broadband Communications in Open Pit Mines

Uzeda Garcia, Luis Guilherme; Portela Lopes de Almeida, Erika; Barbosa, Viviane S. B.; Caldwell, George; Rodriguez Larrad, Ignacio; Lima, Hernani; Sørensen, Troels Bundgaard; Mogensen, Preben Elgaard

Published in:
I E E E Communications Magazine

DOI (link to publication from Publisher):
10.1109/MCOM.2016.7452267

Publication date:
2016

Document Version
Peer reviewed version

Citation for published version (APA):
Uzeda Garcia, L. G., Portela Lopes de Almeida, E., Barbosa, V. S. B., Caldwell, G., Rodriguez, I., Lima, H., ... Mogensen, P. E. (2016). Mission-Critical Mobile Broadband Communications in Open Pit Mines. I E E E Communications Magazine, 54(4), 62-69. DOI: 10.1109/MCOM.2016.7452267

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

The authors 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.

ABSTRACT

The need for continuous safety improvements and increased operational efficiency is driving the mining industry through a transition toward automated operations. From a communications perspective, this transition introduces a new set of high-bandwidth business-critical 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 and 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.

INTRODUCTION

Extraction of minerals stretches back to pre-historic times and remains 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 percent 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, e.g. "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 large-scale mobile cyber-physical system (MCPS) [1], where operational and information technologies come together, the so-called "IT/OT convergence" [2]. Amid 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 radio frequency (RF) engineers are accustomed to. For example, the topography of a typical pit consists of benches and slopes with mineral-rich reflective surfaces that 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. We examine some of the environmental and operational characteristics that make the deployment of broadband mission-critical wireless networks in open-pit mines particularly challenging. We describe an integrated framework devised to address the difficulties in deploying and maintaining a wireless network that supports current and future automation initiatives. Then

---

Luis G. U. Garcia is with Vale Institute of Technology (ITV) and Massachusetts Institute of Technology (MIT); Erika P. L. Almeida is with Institute of Technological Development (INDT) and Aalborg University (AAU); Viviane S. B. Barbosa is with Vale Institute of Technology (ITV) and Universidade Federal de Ouro Preto (UFOP); George Caldwell is with Institute of Technological Development (INDT); Hernani Lima is with Universidade Federal de Ouro Preto (UFOP); Ignacio Rodriguez, Troels B. Sørensen, and Preben Mogensen are with Aalborg University (AAU).

0163-6804/16/$25.00 © 2016 IEEE

(a) (b)

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

we discuss a series of correlated topics suggested for future investigation. Finally, we wrap up the discussion.

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 article, is closer to traditional LTE-Advanced (LTE-A) use cases.

Despite those differences, communication is already essential and considered determinant. Miners work in 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.

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 and 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 out by heavy machinery that is 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 unique case due to the geological disposition of ore bodies.

Deployment Scenarios: Mines are typically located in remote areas, where little to no 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. In contrast to communications in underground mines, which has been subject of extensive research [5, 6], wireless communications in open-pit mines is 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.

First, 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 in jagged discontinuities [3]. In addition, electromagnetic properties of the mineral-rich surfaces also play a role. High concentrations of minerals such as hematite (Fe_2O_3) and magnetite (Fe_3O_4) can lead to very high reflectiveness [7] and severe multipath propagation. This could make radio interference containment and hence system-level planning a much more challenging task.

Another unique factor is the very nature of mining. For example, a large iron ore mine can move a total of one million tons of material per day. An ever changing topography leads to unpredictable coverage if the system is left unchecked. Consider the examples shown in Figs. 1(a) and 1(b), which give 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 an elevated position. However, as pits become deeper, line-of-sight (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, 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 wireless performance at later 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-critical and business-critical automated systems. Finally, in the operational technology (OT) world, Ethernet rather than IP is the prevailing connectivity mode. Hence, tunneling solutions may be required if LTE-A is employed.

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.

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 quickly in case of emergency. Typically, these features are delivered by self-owned networks operating on the low-band UHF range of frequencies. As a result, systems like Terrestrial Trunked Radio (TETRA) and Project 25 (P25), usually designed for public safety applications [4], are still very common in mining sites.

In addition to mission-critical voice services, other important mining systems rely on narrowband data services, e.g. 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 (fuel is one of the major OPEX components).

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 range 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 impose severe limitations on emission levels. The reduced coverage radius leads to denser networks to cover the same area, increasing the total cost of ownership (TCO). Additionally, towns and cities may spring up around mines due to the economic activity, and the presence of additional users inevitably increases channel utilization; therefore, 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.

Technology Evolution and Regulatory Factors

The recent evolution of commercial cellular networks is turning these systems into viable options for critical communications [11]. For example, the Federal Communications Commission (FCC) explicitly recommended leveraging the advantages of LTE-A technologies and standards for the radio access network. Additionally, the 3rd Generation Partnership Project (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 [11]. 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 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.

BROADBAND CRITICAL COMMUNICATIONS AND INTELLIGENT MINING

The combination of robotics and information systems, in the form of autonomous and automated equipment, has emerged as a viable strategy to remove humans from hazardous areas and increase productivity in mines [8].

Automated equipment can be broadly classified into three categories [9]: *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. In all cases, wireless connectivity is the common denominator bringing together robotic equipment, information systems, and humans. 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.
- Uplink (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 use of the H.264 codec [10], high-definition (HD), at 15 frames per second (fps), and full-HD transmissions at 30 fps would require approximately 2.35 Mb/s and 7.75 Mb/s per equipment, respectively, in contrast to the 32 kb/s required by basic telemetry. Clearly, the high data rate video requirements are beyond what is achievable with narrowband PMR, which is in the order of a few hundreds of kb/s. Therefore, a single highly dependable converged broadband wireless network providing voice and data services would be simpler to manage and potentially more cost-effective.

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 digital terrain model (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 ground level, in an elevated area, and the standard propagation model (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. 2.

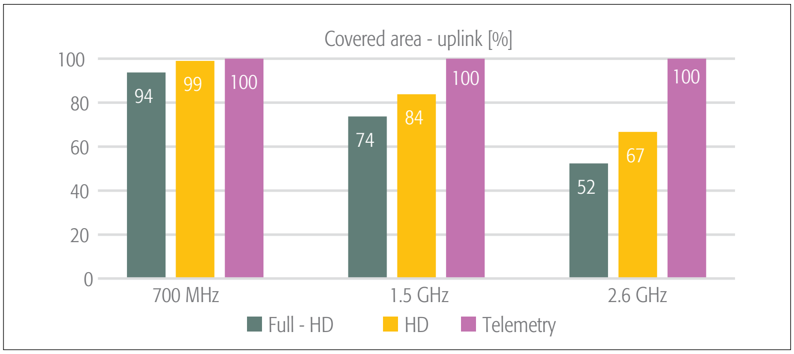


Figure 2. Percentage of locations where the throughput is sufficient to meet the requirements of telemetry applications, HD video and Full-HD video, with LTE-A deployments in 700 MHz, 1.5 GHz and 2.6 GHz, considering a single user.

In all bands, the required 99 percent 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 percent grade of service (GoS) at 700 MHz, considering 10 users and 30 users. The UL data rate per user would drop to 1 Mb/s and 32 kb/s, respectively; therefore, despite LTE-A, broadband services would not be supported.

This simplified planning exercise illustrates one important difference between narrowband 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 on 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.

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.

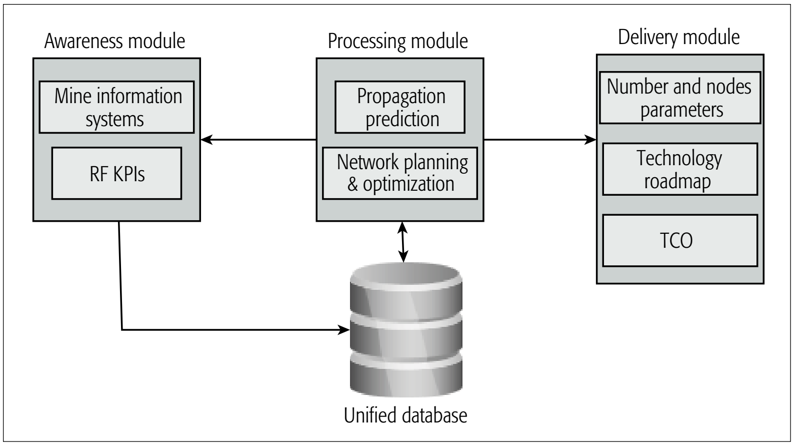


Figure 3. Self-organizing Wireless Infrastructure for the Next Generation (SWING) mines.

PLANNING AHEAD

While the landscapes 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 timeframes mandates 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 what 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 (SONs) [13]. The framework is shown in Fig. 3 and aims at simplifying the task of delivering and maintaining broadband connectivity in open-pit 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 key performance indicators (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: This 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. The unified database 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: This module analyzes the information received from the unified database, and makes decisions about network re-planning, RRM optimization, and 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 tests motivated by mine expansion.

Delivery Module: This module 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 cell-on-wheels (COW). In a more visionary scenario, such a 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 uplink capacity limitation of the deployment of a single 700 MHz LTE-A macrocell with 5 MHz bandwidth.

PROOF-OF-CONCEPT

To illustrate the operation of the proposed framework, we consider a simplified static optimization case, for the example shown earlier. 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 begins considering coverage predictions and restrictions.

Besides the previous simulations, the processing module also takes into account new updated propagation information, such as that presented in Fig. 4, the direct received signal strength indicator (RSSI) from new drive-tests.

The transmitters were a macrocell located in

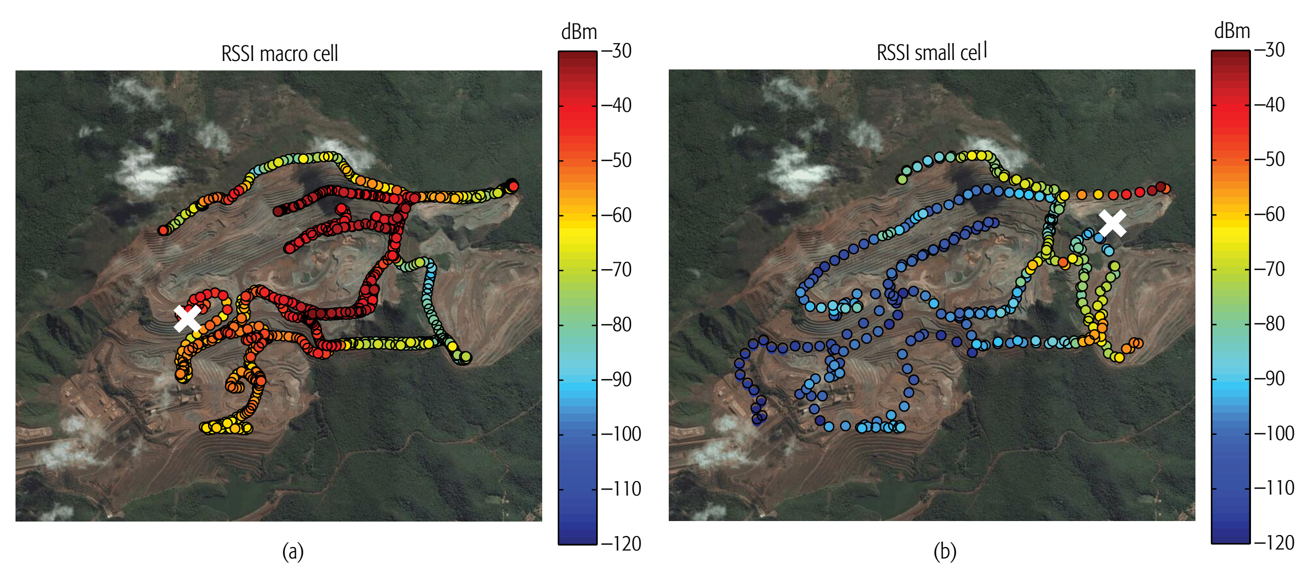


Figure 4. Drive-test RSSI values at 1500 MHz: a) macrocell deployment; b) small cell deployment.

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 shown in Fig. 4(a). 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 six small cells operating at 2600 MHz placed where most of the traffic is expected to be located. This band is chosen because it favors interference containment among small cells. Figure 5(a) 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 percent of the users are offloaded to small cells, resulting in four users per small cell and six users remaining in the macro layer. The throughput map is shown in Fig. 5(b); the UL data rate per user increases up to 2.35 Mb/s, 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.

RESEARCH DIRECTIONS

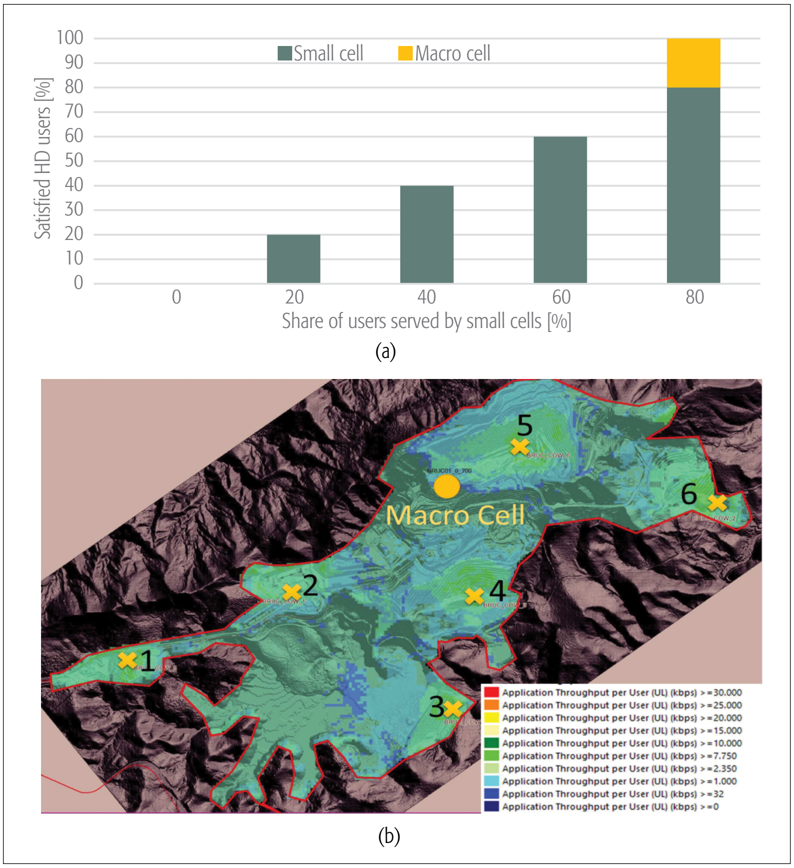
We summarize some of the topics addressed throughout the preceding discussions, and hint at related topics that fellow researchers might find worth investigating further.

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-scale 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 would provide 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 more productive. A large share of the interactions will rely upon the industrial broadband



(a)

(b)

Figure 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.

wireless network. As such, this network becomes equivalent to an invisible utility that must be protected from threats and attacks in order to 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.

CONCLUSIONS

This article has addressed the delivery of broadband critical communications in open-pit mines. Although such an 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 toward a safer, more productive and sustainable mining industry. This article 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 article 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. R. Rajkumar *et al.*, "Cyber-Physical Systems: The Next Computing Revolution," *Proc. 47th Design Automation Conf.*, ACM 2010, pp. 731–31.

[2] D. Dujovne *et al.*, "6TiSCH: Deterministic IP-Enabled Industrial Internet (of Things)," *IEEE Commun. Mag.*, vol. 52, no. 12, 2014, pp. 36–41.

[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] G. Baldini *et al.*, "Survey of Wireless Communication Technologies for Public Safety," *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 2, 2014, pp. 619–41.

[5] A. E. Forooshani *et al.*, "A Survey of Wireless Communications and Propagation Modeling in Underground Mines," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 4, 2013, pp. 1524–45.

[6] L. Bandyopadhyay, S. Chaulya, and P. Mishra, *Wireless Communication in Underground Mines*, Springer, 2010.

[7] J. Garvin, J. Head, and S. Zisk, "On the Origin of High Radar Reflectivity Surfaces on Venus," *Lunar and Planetary Science Conf.*, vol. 16, 1985, pp. 266–67.

[8] D. Kumar, "Emerging Tools and Techniques for Mine Safety and Disaster Management," *Natural and Anthropogenic Disasters: Vulnerability Preparedness and Mitigation*, Springer Netherlands, 2010, pp. 332–65.

[9] D. Lynas and T. Horberry, "Exploring the Human Factors Challenges of Automated Mining Equipment," *46th Annual Human Factors and Ergonomics Society of Australia Conf. 2010, HFESA 2010*, 2010, pp. 115–22.

[10] J. Ostermann *et al.*, "Video Coding with H.264/AVC: Tools, Performance, and Complexity," *IEEE Circuits and Systems Mag.*, vol. 4, no. 1, 2004, pp. 7–28.

[11] R. Ferrus and O. Sallent, "Extending the LTE/LTE-A Business Case: Mission- and Business-Critical Mobile Broadband Communications," *IEEE Vehic. Tech. Mag.*, vol. 9, no. 3, 2014, pp. 47–55.

[12] Y. Zhao *et al.*, "Applying Radio Environment Maps to Cognitive Wireless Regional Area Networks," *2nd IEEE Int'l. Symp. New Frontiers in Dynamic Spectrum Access Networks*, 2007, pp. 115–18.

[13] L. Jorguseski *et al.*, "Self-Organizing Networks in 3GPP: Standardization and Future Trends," *IEEE Commun. Mag.*, vol. 52, no. 12, 2014, pp. 28–34.

[14] P. Popovski, "Ultra-Reliable Communication in 5G Wireless Systems," *2014 1st Int'l. Conf. 5G for Ubiquitous Connectivity (5GU)*, 2014, pp. 146–51.

BIOGRAPHIES

LUIS GUILHERME UZEDA GARCIA is currently an International Faculty Fellow at the Massachusetts Institute of Technology (MIT) and has been working at the Vale Institute of Technology (ITV) since 2013. He holds a Ph.D. degree in wireless communications from Aalborg University (AAU), and M.Sc. E.E. and B.Sc. degrees in electronics and computer engineering from the Federal University of Rio de Janeiro (UFRJ/COPPE). Besides wireless systems and industrial automation, his current research interests include through-the-earth communications, cyberphysical security, and machine learning.

ERIKA PORTELA LOPES DE ALMEIDA (erika.almeida@indt.org.br) received her B.Sc. in telecommunications engineering and M.Sc. E.E. degrees from the University of Brasília (UnB), Brazil, in 2007 and 2010, respectively. Since 2011 she has been a researcher at the Institute of Technology Development (INdT), where she has worked on Wi-Fi evolution and coexistence in TV white spaces. She is currently a Ph.D. student at Aalborg University, Denmark. Her research interests include Wi-Fi, radio propagation, future radio access technologies, and coexistence.

Viviane da Silva Borges Barbosa graduated in mathematics and mining engineering from the Federal University of Minas Gerais (UFMG). Since April 2014 she has been working in the research of exploration, mine planning, and wireless communications for surface mines at the Vale Institute of Technology. She is a CNPq researcher in information and communication technologies, and she is conducting a master of science at the School of Mines at the Federal University of Ouro Preto (UFOP).

George Caldwell received a B.Sc. in electrical engineering from the University of Brasília, Brazil, in 2004. From 2003 to 2006 he worked at Brazilian telecom operators. Since 2006 he has been a researcher at the Institute of Technology Development (INdT), Brazil. From 2006 to 2015 he worked on GERAN, UMTS/HSPA+, LTE/LTE-A system performance evaluation. His research interests include IoT, LTE, critical communications, and 5G.

Ignacio Rodriguez received his M.Sc. in mobile communications from Aalborg University, Denmark in 2011. He is currently working toward the Ph.D. degree in wireless communications. also at Aalborg University, Denmark. His research interests are mainly related to radio propagation, measurements and field trials, channel modeling, and radio network planning and optimization of heterogeneous networks.

Hernani Mota de Lima graduated in mining engineering from the Federal University of Ouro Preto (UFOP). He received an M.Sc. in metallurgical and mining from the Federal University of Minas Gerais (UFMG), and Ph.D. in environment management from the University of Wales, Aberstwyth. He is an associated professor in the Mining Engineering Department of the School of Mines at UFOP. He conducts studies in mining engineering, with an emphasis on mine development, mine closure, and environment management in mining.

Troels B. Sørensen received his Ph.D. degree in wireless communications from Aalborg University in 2002. Upon completing his M.Sc. E.E. degree in 1990, he worked with a Danish telecom operator developing type approval test methods. Since 1997 he has been at Aalborg University, where he is now an associate professor in the Wireless Communication Networks Section. His current research and teaching activities include cellular network performance and evolution, radio resource management, and related experimental activities.

Preben Elgaard Mogensen received his M.Sc. E.E. and Ph.D. degrees in 1988 and 1996, respectively, from Aalborg University, Denmark. He is currently a professor at Aalborg University, leading the Wireless Communication Networks (WCN) Section. He is also associated on a part-time basis with Nokia Networks as principal engineer. His current research interests include 5G and MTC/IoT.