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

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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

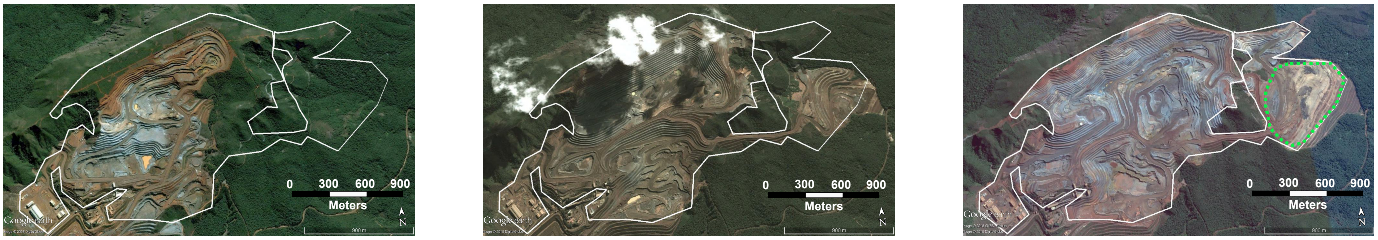
Being essentially an outdoor factory, surface mines are part of the Industrial Internet of Things (IoT) landscape. Wireless networking in surface mines has not been as intensively explored as in underground mines. This gap might be explained by two reasons. The first one is that a surface mine, or an 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.

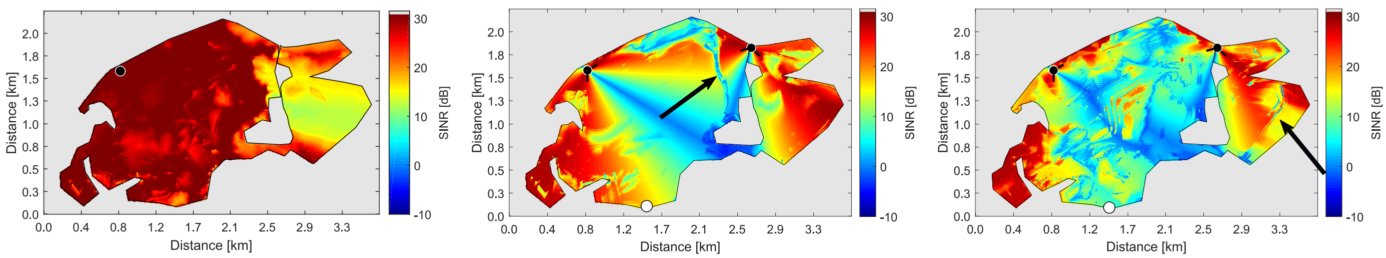
In 2013, the authors of [2] presented a survey of the distribution of wireless technologies in 20 open-pit mines, and discussed the challenges in planning a network for this environment. The identified challenges were: (i) topology, (ii) scalability and re-deployment, (iii) simultaneous coverage of active 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



(a) Aerial Image, year 1. December 12, 2007.
(b) Aerial Image, year 5. February 8, 2012.
(c) Aerial Image, year 10. July 16, 2017.

Fig. 1: Aerial images of the mine area over the course of 10 years. Source: Google Earth. August 16, 2018.



(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.

Fig. 2: Downlink (DL) Best Server SINR, LTE TDD, 10 MHz.

of LTE and 5G NR. The work is concluded in Section VI.

II. Scenario and Topographic Variation

An example of the topographic variation in an open-pit mine is given in Fig. 1, which shows aerial images of an operational iron-ore mine – located in Minas Gerais, Brazil – over the course of 10 years. Fig 1(a) 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. 1(b). 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. 1(b) and 1(c). Besides the deepening and widening of the pit, the waste pile, highlighted in green in Fig. 1(c), 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. 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. 2(a), 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. 2(b)), the interference from one transmitter to the other is contained by the hill highlighted by the black arrow. Finally, in year 10, Fig. 2(c), 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.

The cumulative distribution function, CDF, of the SINR values for each year is depicted in Fig. 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

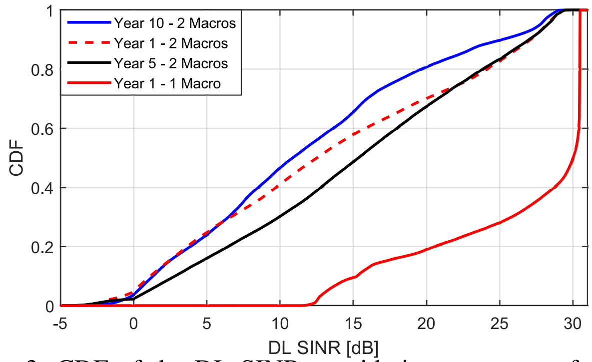


Fig. 3: CDF of the DL SINR considering ten years of mine development.

sides of the hill highlighted in Fig. 2(b) 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

The 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 I. 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 II. 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.

TABLE I: 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 II
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

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 II, 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 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 II: 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

The 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:

$$SINR_{DL_n} = \frac{P_{RX_{l,n}}}{\sum_{c \neq l} I_{c,n} + N} \quad (1)$$

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

$$P_{RX_{l,n}} = \frac{P_{TX_l} G_{TX_{l,n}} G_{RX}}{PL_{l,n}} \quad (2)$$

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:

$$I_{c,n} = \frac{P_{TX_c} G_{TX_{c,n}} G_{RX}}{PL_{c,n}} \quad (3)$$

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:

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

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 II.

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

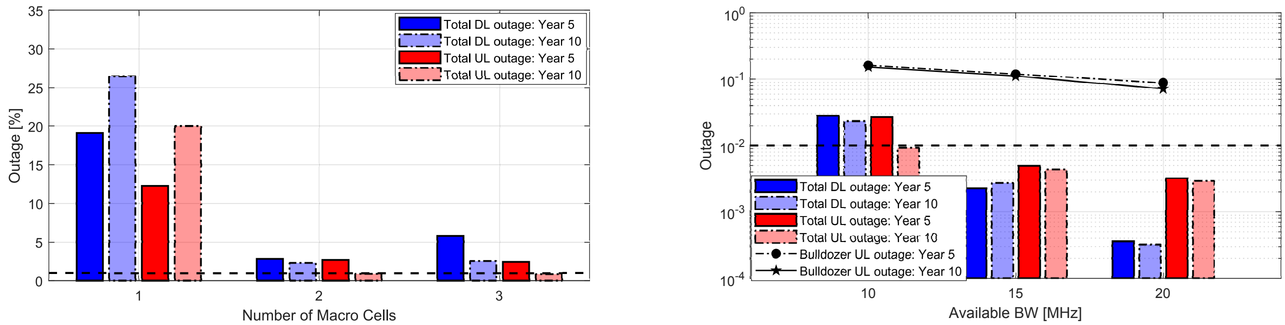
The simulations consider different deployment strategies, such as small-cells only, macro cells as well as heterogeneous networks (HetNets). The placement strategy of macro and small cells takes into account some specifics of this environment, for example: macro cells are deployed on locations along the optimum ultimate pit, i.e. the contour of the mine at the end of its life, to preclude frequent and costly relocations of cell towers. On mine sites, small cells tend to be nomadic in nature. They can and may need to be frequently repositioned 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. 2. The third macro cell was placed in the white dot in Figs. 2(b) and 2(c). 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. 4(a) 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. 4(a), 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



(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. 4: Outage in a macro cell deployment.

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. 4(a), 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. 4(b). 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 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

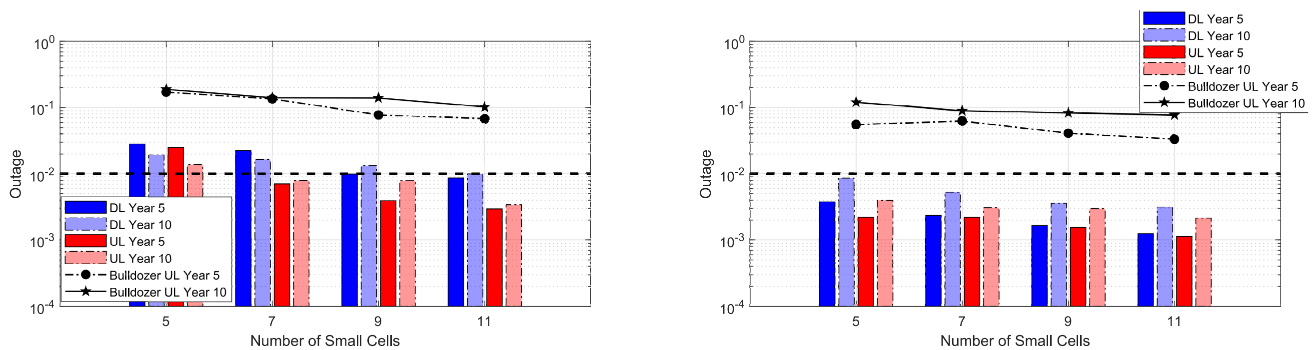
In this subsection, we investigate the results in a heterogeneous deployment.The macro cell layer is used to provide coverage, while the small cell layer provides capacity in high traffic areas. We assume a microwave backhaul connection between the small cells layer, and the macro cell layer. Although 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.

1) In-band deployment: The in-band deployment results are shown in Fig. 5(a), 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 4(b)), 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. 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.

2) Out-of-band deployment: Following what was done for the macro cell, in Section IV-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



(a) 10 MHz (2.6 GHz)

(b) 10 MHz (700 MHz) + 10 MHz (2.6 GHz)

Fig. 5: Outage in a heterogeneous deployment, with two macro cells, as a function of the number of small cells.

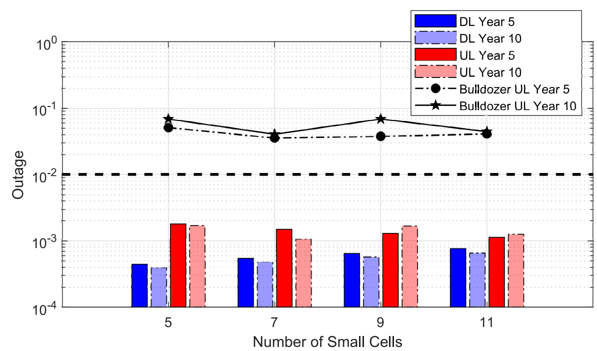


Fig. 6: Outage in HetNet deployments combined with eICIC and beamforming, as a function of the number of small cells.

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. 5(b).

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. 5(a), 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.

3) 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. 5(a).

Taking this into consideration, we investigated the performance when combining the two techniques, and the results are in Fig 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.

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