On the Deployment of Private Broadband Networks in Surface Mines

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***Abstract*—Future mines are expected to be operated by increasingly autonomous construction equipment, requiring dependable intercommunication between control centers, human operators, and construction machines such as excavators, drill rigs, and scrapers. Achieving stable, reliable and timely communications in such harsh and ever-changing environments is quite challenging. However, the changes in the three-dimensional (3D) topography of the mine are mostly predictable and scheduled through mine planning methods, which consequently can be used for radio communications network planning, namely to dimension, orientate and locate Base Station (BS) antennas in the mine field. In this context, we consider BSs to exist in the form of *fixed* cells or *Cell on Wheel (CoW)*. The former is deployed in fixed locations throughout a long-term mine operation, while the latter is expected to be moved based on the changes in the topology of the terrain. We present an optimization framework that builds on an evolutionary algorithm to plan private 5G networks based on a given mine plan, featuring both fixed and movable base stations. We assess how the changing terrain affects the wireless coverage on the mine's surface and demonstrate that, in certain scenarios, CoWs improve the average *Signal-to-Interference & Noise Ratio* (SINR) by 1 to 10 dB.**

***Index Terms*—Radio Network Planning, Open Pit Mines, Mine Planning, Fixed and Movable Base Stations**

I. Introduction

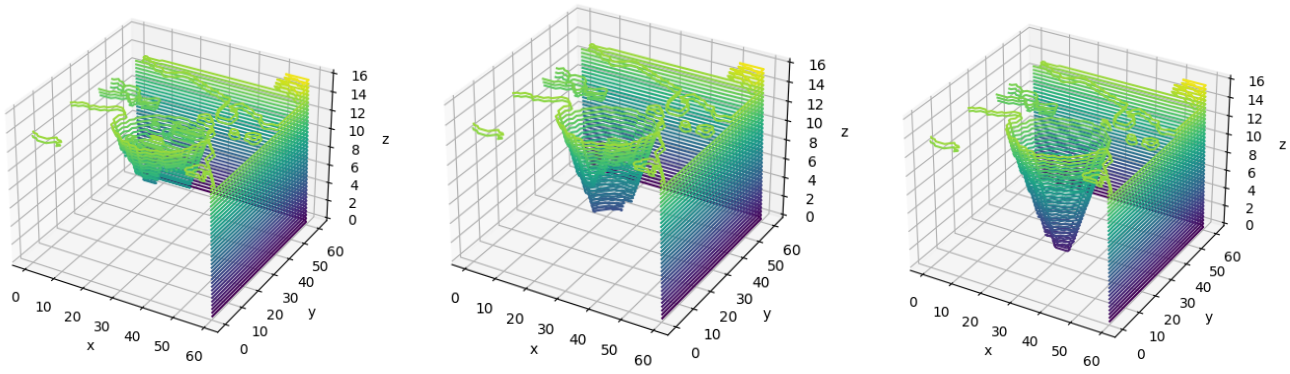
Connectivity is an integral part of automated mines, and private 5G networks are providing the foundation required to support safe, efficient, and sustainable mining operations. Different types of surface mines including quarries or open pit mines present a predominant method for mining rocks, sand, or minerals from the earth's surface. In open-pit mines, wireless networks are critical for managing haulage operations and monitoring safety parameters such as slopes and tailing ponds [1]. The mining industry is actively pursuing unmanned operations, including autonomous machines and remote operations of extraction and transportation equipment, to enhance safety and productivity. State-of-The-Art wireless infrastructures (in open pit mines) that have been conceived for non-critical monitoring tasks must now be redesigned to support reliable and timely broadband communications. Mine networks, akin to their other industrial counterparts, call for increasing performance, timeliness, and availability [2].

Surface mines are often located far from urban areas, turning it difficult to rely on public networks and thus requiring the operators to deploy private networks. However, these mines pose unique challenges to radio communications due to their ever-changing terrain profiles and radio shadowing effect caused by heavy machinery [3]. During the life cycle of the mine, a terrain initially covered by greenery changes to an area full of waste rock or ore. As tons of material are extracted on a daily basis, the pits become deeper and wider, significantly altering the radio propagation condition including Line-of-Sight (LoS). This may require repositioning the Base Stations (BSs) over time which reduces profit margins [4]. As a result, traditional network planning tools are inadequate to support constant planning and reconfiguration.

The temporal evolution of the terrain differs from mine to mine and so do the radio propagation and the fleet's communication requirement. For example, the SINR associated with a specific mine in Brazil was shown to be improving for 5 years and then declining for the next [5]. A mine plan can provide an estimate of how the terrain profile evolves over time. Uncertainty is an inevitable part of the industry, and deviations from the mine plan may occur, but such deviations are usually short-term and thus unlikely to affect the radio network.

The mine planning phase can generate elevation maps in different formats. One classic and common model of the topography of the mine is the *block model*, where the mine is modeled by a set of production blocks, each containing an estimated ratio of ore [6]. We plot the 3D terrain model (generated using the block model) used to demonstrate a hypothetical open-pit mine called Marvin as it changes over time in Fig. 1 (for details on the Marvin mine see table II in section IV).

To overcome the dynamism in the environment, vendors provide proprietary wireless solutions for the surface mines which take advantage of CoWs [7]. Our network planning takes a similar approach in deploying movable micro-cells, along with fixed macro-cells. Although connectivity of the mobile nodes has been studied as a challenge in the context of wireless networks [8], we argue that taking advantage of the mobility of the BSs can be beneficial to optimize the radio coverage of harsh terrains. We propose methods that engage in the planning of the radio network based on the evolving mine plan. Our proposed framework takes the block model of the mine as input and generates the *Digital Terrain Model* (DTM) in a raster format. This DTM is later used to calculate the wireless link quality, measured in terms of SINR, which is used by an evolutionary algorithm to optimize the number



(a) (b) (c)

Fig. 1: Marvin mine getting deeper and wider over time; (a) period 1, (b) period 5, and (c) period 8.

and location of the BSs.

In the work outlined in this paper, we identify the following contributions to the state-of-the-art:

- We formulate an optimization problem for long-term radio network planning based on evolving raster data from the mine planning tools and apply a well-known meta-heuristic.
- Our model accounts for the propagation of the wireless signal in surface mines and incorporates 5G-specific propagation models. We make the implementation of our model and results are publicly available[1].
- We analyze and demonstrate the effectiveness of deploying fixed and movable BSs for improving connectivity on the mine surface.

The remainder of the paper is structured as follows: Section II reviews the related works and the gaps that we want to address. Next, we formulate the problem of optimizing the radio deployment in Section III and evaluate the deployment strategies in Section IV. Finally, section V concludes the paper.

II. Related Works

In this section, we review the proposed models for radio propagation for surface mines and the literature on radio network planning in these environments.

A. Radio Propagation in open-pit mines

The quality of the network planning tools drastically depends on the accuracy of the channel modeling. However, unlike underground mines [9], radio propagation in open-pit mines is not a well-studied subject. Nilsson et. al. [10] performed channel sounding using *Universal Software Radio Peripheral* (USRP) devices in Aitik mine in North Sweden. The results suggest that a guard interval (GI) of at least 10ms is required to cover the channel impulse response. This is mainly due to the strong echoing and dispersion of the signal in the mines.

[1] https://github.com/iliar-rabet/5G_mine

Empirical models such as *Standard Propagation Model* (SPM) allow calibration based on drive test data to outperform the other models. However, due to the mutant nature of the mines, up-to-date drive tests can not be available all the time. This requires propagation models that are solely based on the terrain model to address the diffraction [11], [12].

Almeida et. al. [12] analyzed the propagation of the 2.6 GHz signal in open-pit mines in Brazil and compared the empirical data with some elaborate propagation models including ITU-526, Okumura-Hata, COST-Hata, and the SPM. Small cell results could be predicted much more accurately. However, for macrocells, the authors reported a Root Mean Squared Error (RMSE) of at least 10dB when comparing the signal strength to those predicted according to the Alpha-Beta propagation model [13].

B. Network planning in the dynamic environment of the mines

The mining industry presents a uniquely challenging environment for wireless networks due to factors such as Radio Frequency (RF) interference and unpredictable terrain. Consequently, there has been a surge of interest among researchers in exploring deployment strategies for private 5G infrastructures, as a potential solution to overcome these obstacles. Chang et. al. [14] formulate the problem of deploying 5G macro and micro base stations in an open-pit mine as an optimization algorithm and compare different optimization techniques including the *Sparrow Search* Algorithm and *Random Walk Sparrow Search* Algorithm to find the best placement of the base stations. However, their approach does not take into account the ever-changing environment in the mines and the impact of extreme blocking and shadowing effects.

The long-term planning of the mine can also be integrated with the deployment strategies of the wireless network [15]. For example, the pits and the hills can be extracted in a way that creates favorable conditions for the radio. The RF-favorable conditions range from blocking the interfering signals from the neighbors to creating elevated terrain for the BS with LoS over a larger area. Altering the mine plan is not

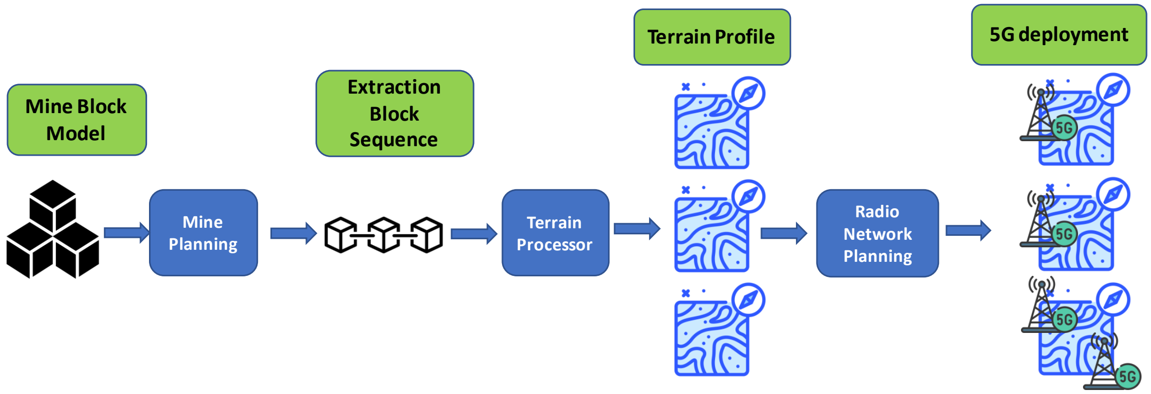


Fig. 2: The flow of information in different modules of the optimization framework. The CPIT module takes the initial block model of the mine and generates a sequence of blocks that need to be extracted. This extraction sequence is then used to calculate the terrain profile based on which the radio planning is performed.

always viable since creating the RF-favorable condition may reduce the amount of processed ore.

SkyHelp adopted Unmanned Aerial Vehicles (UAV) [16] to improve communication during emergencies such as a bench collapse. Such accidents not only render the equipment non-functional but also result in severe injuries to the mining staff requiring rescue operations for the miners. Their simulations results show improvement in the connectivity of the temporary and emergency networks that are based on UAV systems in terms of packet error rate, end-to-end delay, and per packet retransmission.

As an extension to the facility location problem [17], radio network deployment has been proven to be NP-hard. Researchers have incorporated plenty of different methods to solve variations of this problem including force-based methods, Geometric methods such as Voronoi-based algorithms, and meta-heuristic methods such as particle swarm and genetic algorithm [18]. To the best of our knowledge, no previous work has studied the implications of extensive terrain profile changes in the 5G deployment strategies. We aim at filling this gap by proposing a model that improves the radio network planning based on the information available after the mine planning phase.

III. Method

This section formulates the problem of locating the BSs in evolving open-pit mines and proposes a solution for determining the requirement resources (dimensioning) and planning a 5G heterogeneous network in such an environment. By network planning, we refer to selecting the optimal position for the fixed BSs and CoWs in the mine, given the constraints such as not interrupting the mining operation. First, we introduce the mine planning module which generates a list of blocks for extraction. Then the terrain processor module creates a series of terrain profiles that serve as input to the network planner module. This process is illustrated in Fig. 2 and we further study these modules in the next subsections.

A. Mine Planning

Mine planning module takes as input a set of blocks (β), dependencies (β_b), required resources (q_{br}), and a time horizon in which it is supposed to maximize the obtained profit. The *Constrained Pit Limit Problem* (CPIT) is a well-known formulation for mine planning that introduces a dimension of time to the optimization problem. CPIT entails determining a sequence of blocks to be extracted that maximizes the total profit as defined in (1). x_{bt} is the decision variable and equals 1 if block b is scheduled to be extracted at time t. The problem is subject to the constraints as follows (The notation is summarized in Table I.):

- precedence between the blocks (Eq. 2)
- minimum and maximum operational resource requirements per period (Eq. 3),
- integrality of the blocks (Eq. 5)
- each block being extractable only once (Eq. 4)

This Mixed-integer Linear Programming problem is proved to be strongly NP-hard. While plenty of solutions have been proposed for CPIT, our framework is not limited to adopt any specific CPIT solution as long as we can feed the solutions to the next module which uses the block extraction sequence to develop the terrain profiles. We use the MineLib library [19] and its solution, which is based on linear programming relaxation.

$$\max \sum_{b\in\beta}\sum_{t\in T} p_{bt}x_{bt} \tag{1}$$

$$\text{s.t.} \sum_{\tau\le t} x_{b\tau} \le \sum_{\tau\le t} x_{b'\tau} \quad \forall\ b\in\beta \text{ and } b'\in\beta_b \text{ and } t\in T \tag{2}$$

$$\underline{R} \le \sum_{b\in\beta} q_{br}x_{bt} \le \overline{R} \tag{3}$$

$$\sum_{t\in T} x_{bt} \le 1 \quad \forall\ b\in\beta \tag{4}$$

$$x_{bt}\in\{0,1\} \quad \forall\ b\in\beta \text{ and } t\in T \tag{5}$$

Parameter	Explanation
$t \in T$	set of time periods
$b \in \beta$	set of blocks
$b' \in \beta_b$	set of blocks that precede b
$r \in R$	set of operational resources
p_{bt}	profit for block b and time t
q_{br}	the amount of resource r required to extract block b
$\underline{R_r t}, \overline{R_r t}$	minimum and maximum of resource r in time period t.

TABLE I: The notation used in the CPIT problem.

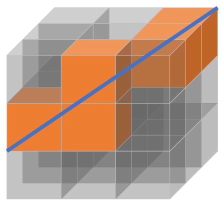


Fig. 3: 3D Bresenham algorithm projects the line between the BS and the target on a 3D mesh.

B. Radio model

For optimizing the radio coverage, our solution incorporates a radio model that is tailored for surface mines. Given that the primary cause of signal coverage loss in mines is diffraction, it is essential to assess the Line of Sight (LoS) conditions based on the terrain map. 3D Bresenham's Algorithm [20] determines the blocks in a 3D mesh on the line between BS and the target point, as illustrated in Fig. 3. The algorithm efficiently processes the block model given the two end points of a straight line in a three-dimensional grid. First, it calculates the slope in all dimensions and next it selects the driving axis (the one with the maximum slope). Then the algorithm loops over the driving axis until it reaches the other end-point. By projecting the line on the neighbor planes, the algorithm chooses the blocks. The LoS condition will be achieved if the terrain elevation is lower than the elevation of the blocks selected by the 3D Bresenham, as formally defined in (6).

$$LoS(BS_i, P_j) = \begin{cases} 1 & \forall (p_x, p_y, p_z) \in Bres(BS_i, P_j) \\ & Terrain[p_x][p_y] < p_z \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

When deploying the cells, we aim at maximizing the SINR since it considers not only the main received signal but also noise and inter-cell interference. Here, we assume vehicles connect to the BS with the highest signal strength. Let $SINR(j, A)$ denote the SINR at point j when it associates with BS_A (a certain BS).

$$SINR(j, A) = \frac{P_{j,A}}{\sigma^2 + \Sigma_{i=1, i \neq A}^{N} P_{j,i}} \quad (7)$$

where $P_{j,A}$ denotes received power from BS_A and σ^2 represents the noise in the environment. $P_{j,A}$ depends on the transmission power of the BS (TXP_A), the transmitter and receiver's antenna gain (G_{TX} and G_{RX}), and the *Path Loss* ($PL_{j,A}$).

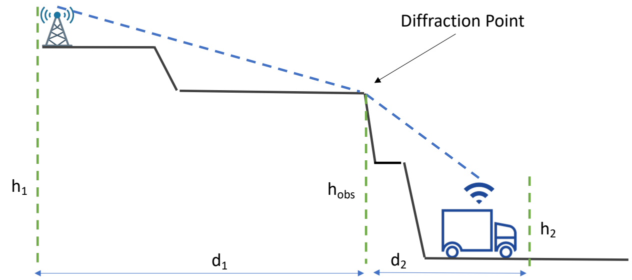


Fig. 4: Diffraction point and the relative height of the transmitter and receiver.

$$P_{j,A} = \frac{TXP_A G_{TX} G_{RX}}{PL_{j,A}} \quad (8)$$

For estimating the *Path Loss*, an extension of the ITU-526 [21] called the vale model was proved to be the most accurate model for 700 MHz and 2.6 GHz band [12]. The *Path Loss* is considered to be the sum of *Free Space Path Loss* (FSPL), *Diffraction Loss* (L_D), and a k multiple of the logarithm of of *Efficient Antenna Height* (H_{eff}) (k being a constant).

$$PL = FSPL(f) + L_D + k \times \log_{10}(H_{eff}) \quad (9)$$

For calculating the diffraction loss, a knife-edge model is used, which depends on the distance and the height of the obstacle (h_{obs}) and the position of transmitter and receiver sites. The Fresnel parameter (v) is calculated as in (11):

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

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \quad (11)$$

with λ being the wavelength in meters.

The diffraction loss $L_D = 20\log_{10}(F(v))$ where the

$$|F(v)| = \begin{cases} 1 & v \leq -1 \\ 0.5 - 0.62v & -1 < v \leq 0 \\ 0.5\exp(-0.95v) & 0 < v \leq 1 \\ 0.4 - \sqrt{0.1184 - (0.38 - 0.1v)^2} & 1 < v \leq 2.4 \\ \frac{0.255}{v} & v > 2.4 \end{cases} \quad (12)$$

We are interested in an algorithm that optimizes the time-average coverage for the whole mine surface. The radio planning tool is designed to maximize an *Objective Function* (OF) that represents the time-average SINR of all the points in the terrain as defined below. Our proposed OF does not classify the surface based on how it is used and tries to guarantee connectivity for the whole grid.

$$OF(BS) = \frac{\sum_{t \in T} \sum_{j \in map} SINR(j)}{|map| \times T} \quad (13)$$

C. Radio Network planning

For mines with multiple pits or those with extended lifetimes, determining the optimal number and placement of BSs can be a significantly complex task. The first phase in our framework is *dimensioning*, which refers to determining the number of Base Stations to guarantee a certain radio coverage, materialized by the SINR. Algorithm 1 presents a mechanism that guarantees that the OF as in (13) exceeds two thresholds: (i) θ_{fixed} using only fixed BSs and (ii) θ_{CoW} when using both fixed BSs and CoWs. The placement of fixed BSs is restricted to blocks that will *remain intact until the final mine layout is established*. In contrast, CoWs can be relocated and *can be positioned in blocks that will be extracted later*. We assume the range of macro and micro-cells, DTM is given as input.

Algorithm 1 Terrain-aware 5G deployment

Require: Z[periods][X][Y], ▷ The terrain profile in time
1: $Candidates_{fixed}$ = GenerateRandomPoints()
2: Filter($Candidates_{fixed}$)
3: **for** $p \in periods$ **do** ▷ Dimension the fixed BSs
4: **while** $OF \leq \Theta_{fixed}$ **do**
5: $N_{fixed} = N_{fixed} + 1$
6: $OF = SA(p, N_{fixed}, Candidates_{fixed})$
7: **end while**
8: **end for**
9: **for** $p \in periods$ **do** ▷ Dimension the CoWs
10: **while** $OF \leq \Theta_{CoW}$ **do**
11: $N_{CoW} = N_{CoW} + 1$
12: $Candidates_{CoW}$ = GenerateRandomPoints()
13: TMPFilter($Candidates_{CoW}$)
14: ▷ Only if the block will not be extracted in this period
15: $OF = SA(p, N_{CoW}, Candidates_{CoW})$
16: **end while**
17: **end for**

The algorithm (Alg. 1) generates a random set of candidate positions for BSs and filters them based on the operational constraints (in lines 2 and 3). Then (in lines 3-8) increases the number of fixed BSs in a loop to realize the θ_{fixed}-requirement. Once the fixed BSs are selected, the next loop (lines 9-16) focuses on deploying CoWs. To reduce the size of the search space to a reasonable level, we generate a certain number of candidates for the BSs. These candidates have to be filtered based on the related constraints. For fixed BSs, the constraints are harsher since they can only be deployed in a location that will not be extracted later. As for the CoW candidates, constraints change after each period and the CoWs will be forced to move out from the locations that are currently being extracted. That is the reason why filtering the candidates is repeated in every iteration in the second loop (line 13) but for the fixed BSs, filtering is only executed once (in line 2).

Each iteration of the loop consists in selecting the optimal candidate locations and calculating the associated OF. This is performed by running our evolutionary optimizer which plans the network through running the Simulated Annealing algorithm (explained in Alg. 2). SA is a meta-heuristic known for its capability of finding a global optimal even after finding a local minimum. We choose SA due to its convenience for optimizing this computation-intensive OF. SA runs a preconfigured number of iterations, and in each iteration, a neighboring state of the solution will be compared with the currently accepted solution. A new solution will replace the accepted solution with a probability that is guided by the difference in the solutions' OF as well as a tunable variable called *temperature*. With a certain probability that is determined based on the temperature, SA accepts solutions with a worse OF to escape local minimums (lines 9-14). The *temperature* tends to zero as the algorithm iterates decreasing the probability of accepting worse solutions.

Algorithm 2 Simulated Annealing

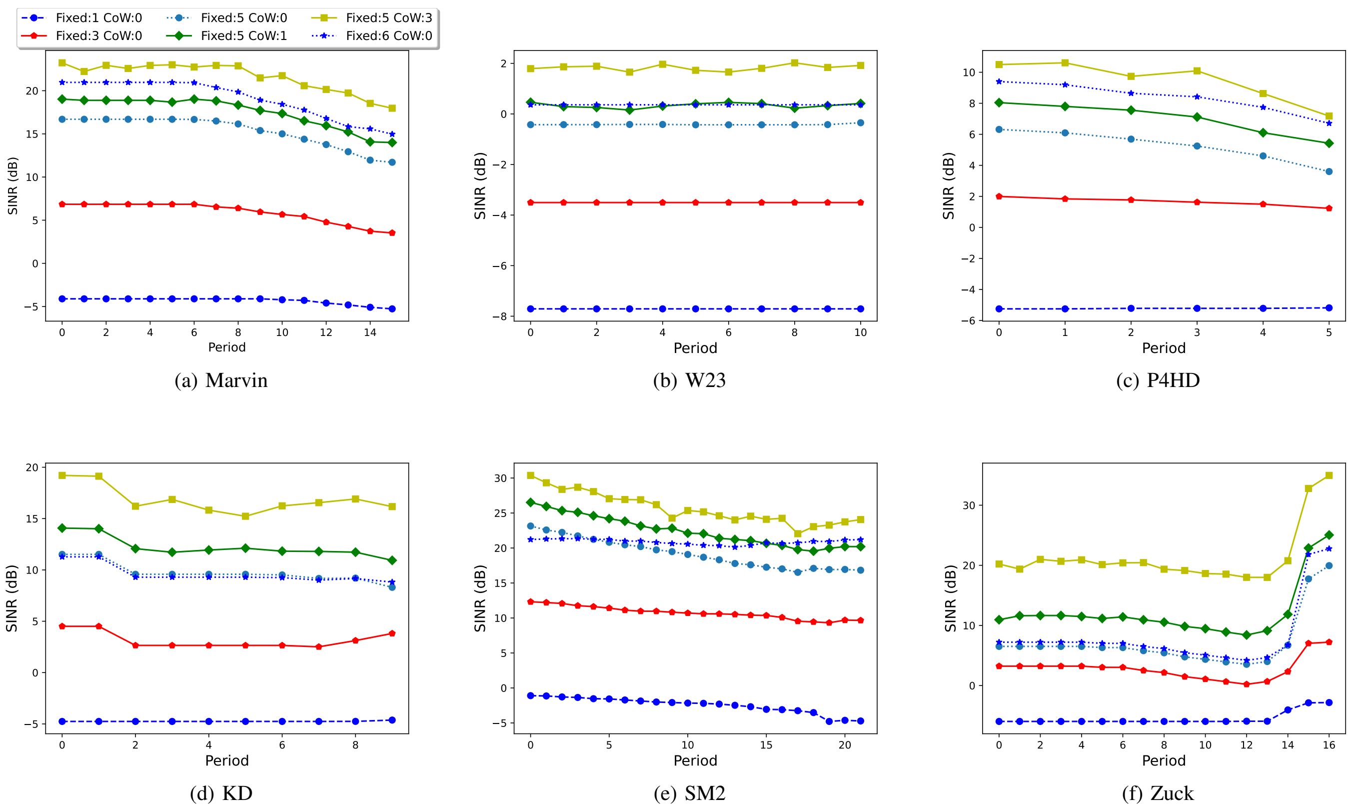
Require: Z[periods][X][Y], ▷ The terrain profile in time
1: initialize InitTemp, State, $OF_{selected}$
2: **for** $iter \in Iterations$ **do**
3: Create a random Neighbor State ▷ Change one BS
4: $OF_{curr} = OF(NeighborState)$
5: $\Delta_{OF} = OF_{curr} - OF_{selected}$
6: $Temp = InitTemp/iter$
7: $Metropolis = \exp(\Delta_{OF}/Temp)$
8: $r = random(0, 1)$
9: **if** $\Delta_{OF} > 0$ **or** $r > Metropolis$ **then**
10: Accept the Neighbor State
11: $OF_{selected} = OF_{curr}$
12: **else**
13: Reject the Neighbor State
14: **end if**
15: **end for**

IV. Evaluation

In this section, we evaluate our Base Station deployment framework in six mining sites by analyzing the variation of radio links quality over time. Table II summarizes the size, operation period, and type of the mines under evaluation. The Marvin mine is a hypothetical yet realistic mine, featuring a single deep pit. The W23 is the deepest and widest mine presented here, modeling phases 2 and 3 of a gold mine in the US. The P4HD and KD are pit mines with hills on the side. In the Zuck mine, an entire pit with the surrounding hills is scheduled to be excavated, which presents a significant challenge for deploying fixed base stations. SM2 has the longest operation plan but all parts of the mine are being extracted evenly.

Our deployment method assumes that fixed BSs act as macro-cells and CoWs create micro-cells. CoWs are assumed to be less costly to install than fixed ones and thus are used for future network expansion. Also, the macro and micro cells are configured to have ranges of 50 and 30 blocks, respectively.

Here we analyze SINR which is the most decisive factor for the performance of the wireless network. Analyzing metrics such as throughput, packet delivery ratio, and delay



(a) Marvin (b) W23 (c) P4HD

(d) KD (e) SM2 (f) Zuck

Fig. 5: Average SINR in time for the mines in time.

Name	Type	Blocks (#)	Size (Blocks)	Periods
Zuck	Hypothetical	1060	22×22	4
KD	Real/Copper	9400	78×42	10
P4HD	Real/Gold+Copper	40947	62×69	6
Marvin	Hypothetical	53271	61×60	17
W23	Real/Gold	74260	106×91	11
SM2	Hypothetical/Nickel	99014	55×35	30

TABLE II: Characteristics of the block models and the corresponding mines are sorted based on the number of blocks. Each period can be associated with *one year*, and one block corresponds to a volume of $30 \times 30 \times 30m^3$ but the model can capture finer granularity.

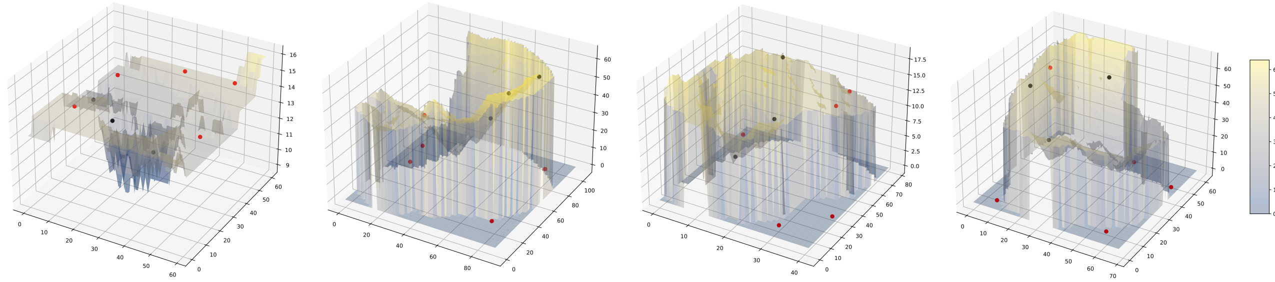
would require extra information such as fleet's location and traffic pattern which are out of the scope of our work. As we mentioned in the previous section, CoWs provide the possibility to serve the inner parts of the mines since there are fewer constraints limiting deployment of CoWs. The loose constraints explain a major trend in the simulation results. **For almost all of the tested mines, adding 1 CoWs contributes more efficiently to a mine with 5 fixed BS than adding another fixed BS**. This accounts for almost *a 1 dB increase for W23 and 10 dB for the Zuck mine*.

Fig. 6 demonstrates a snapshot for 4 of the tested mines and the optimized position for fixed BSs and CoWs (red and blue respectively). For these mines, the timeline is nearly identical to Fig. 1 and the pits get deeper with time. The evolution of radio coverage drastically depends on how the topography of the mine changes. Fig. 5 presents the average SINR of the benchmark mines with different number of BSs.

For Marvin, P4HD, and KD, the pit is in the middle and there are hills surrounding it which are not in the extraction plan (see Figures 6(a), (c), and (d)). So, our solution deploys the fixed BSs on those hills and the CoWs in the inner parts of the mine. As the mine gets deeper we see a decreasing trend in the SINR as illustrated in Fig. 5(a), (c), and (d). For KD, the coverage is considerably better than P4HD which is explained by the possibility of installing more fixed BSs on the hills and the size of the mine.

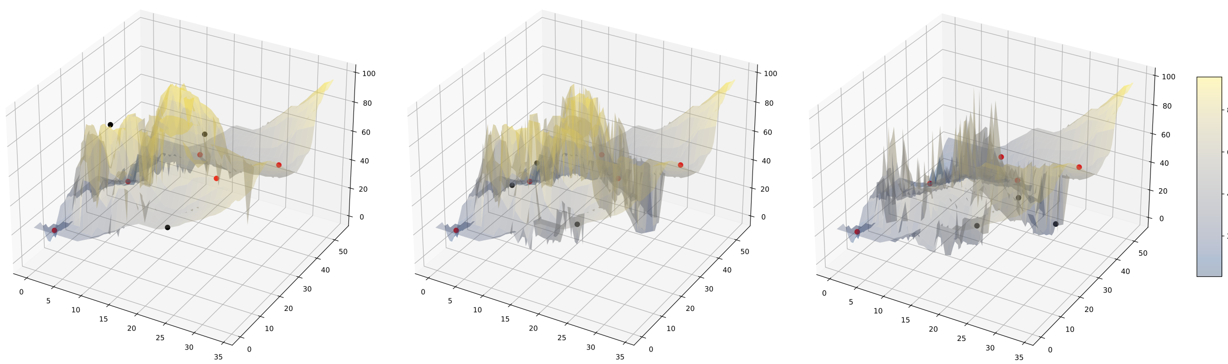
In W23, the connectivity of the surface of the mine remains stable in Fig. 5(b). W23 is the largest test mine and the SINR does not exceed 3 dB indicating a dire need for more BSs to cover the area. On the other hand, SM2 does not include a large pit like the other mines since most of the ore is extracted is from the body of the mountain in the middle as can be seen in Fig. 7. The initial hills had the advantage of being closer to a wider area in the beginning which diminishes in time resulting in the decreasing trend in SINR in Fig. 5(e). In the later stages of the SM2, the algorithm is forced to relocate CoWs to the lower parts of the mine.

The Zuck mine (Fig. 5 (f)) represents an exception since the SINR increases with time. The timeline associated with the terrain (Fig. 8) shows that it is impossible to deploy fixed



(a) Marvin (b) W23 (c) KD (d) P4HD

Fig. 6: Snapshots of the initial states of the mines and the deployment of fixed BSs in (a) Marvin (b) W23 (c) KD and (d) P4HD mines. The red and blue dots represent the fixed BSs and CoWs, respectively. For Zuck and SM2 timelines of the topography are provided in Fig. 7 and 8. The measurement unit for all 3 axes is the number of blocks. The colors also represent the height of the terrains.



(a) Period 0 (b) Period 10 (c) Period 20

Fig. 7: In SM2, like most of the other mines, the SINR gets worse with the age of the mine.

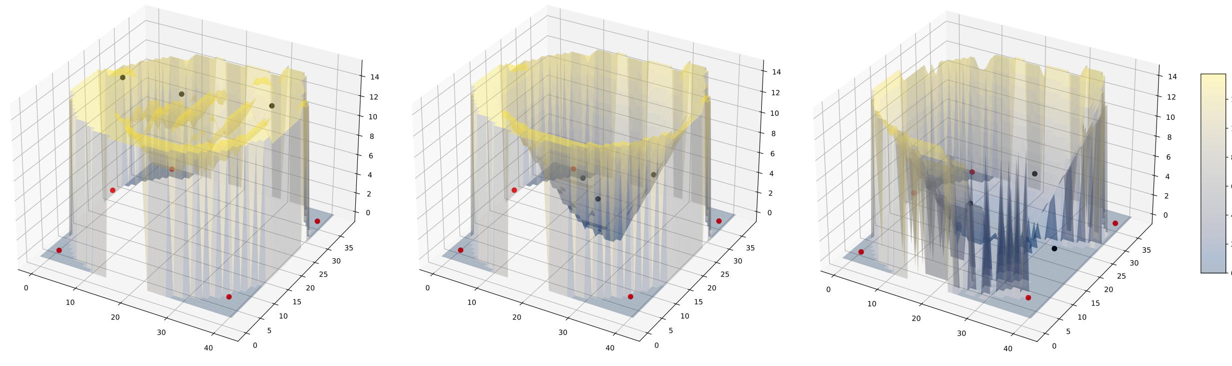
BSs on the heights as they are to be extracted. This renders the fixed BSs inefficient until the later stages of the mine's lifetime. Extraction of the obstacles leads to the increasing trend in SINR after period 13. For Zuck, Fig. 5(f)) indicates that the CoWs are way more effective than fixed BSs to maintain wireless coverage.

The stochastic nature of the evolutionary optimization including simulated annealing makes it necessary to analyze the ergodicity of the algorithm. In other words, it is necessary to analyze if the algorithm eventually evaluates the search space thoroughly and efficiently. This characteristic leads to convergence accuracy. The number of iterations in the SA algorithm and the number of candidates are essential parameters. Regarding the number of iterations, dimensioning can be performed with a medium level of iterations, and once we guarantee the thresholds $(\theta_{fixed}, \theta_{CoW})$ we can run SA with a larger iteration to optimize the final deployment. Let $Cand$ denote the number of candidate BS locations and $|BS|$ actual number of BSs, the total search space size would be the combination of $Cand$ items taken BS at a time $(\binom{Cand}{|BS|} = \frac{Cand!}{(Cand-|BS|)!|BS|!})$ leading to exponential growth in the size of search space. Furthermore, the time complexity of Algorithm 1 is: $O((X+Y) \times iterations \times X \times Y \times periods \times |BS|)$.

V. Conclusion

We studied the coverage of private broadband deployments in mining sites. These are environments that introduce varying, yet predictable terrain. Open-pit mines can benefit from the advantages of cellular networks, but in order to do so, we need to fill the gap between the radio network planning tools and mine models as they lack the support for an evolving terrain and the possibility of utilizing CoWs. We proposed a method that leverages the mine plan to enhance radio network planning and thus achieves better coverage and network reliability. The results show the efficiency of the network deployment drastically depends on the evolution of the mine terrain. CoWs improved the average SINR by up to 10dB due to their flexible deployment .

One possible direction for future work is improving the deployment model to encompass other aspects of mine operation such as fleet dispatch. Fleet dispatch is usually formulated as



(a) Period 0 (b) Period 10 (c) Period 14

Fig. 8: Evolution of the Zuck mine and deployment of 5 fixed BSs (red dots) and 3 CoWs (black dots). Zuck presents special constraints for the radio network deployment since the highest parts of the terrain act as obstacles and only get extracted in the final phases.

an optimization problem where it is possible to alter the fleet schedule in favor of the communication system. In that case, the CoWs can be scheduled in fine-grained periods to provide support for the fleet rather than covering the mine surface.

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