Fifth Generation Cellular Networks for Underground Block Cave Mining: A Position Paper

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***Abstract*—In this position paper we put forward the case for the fifth generation of cellular networks (5G) to be the successor for WiFi in underground mining. 5G promises increases in bit rates, a redesign of the Radio Access Network, low energy consumption for sensor communications and very low latencies. These make it a potentially attractive technology for underground mining, particularly Block Cave mining. Block Cave mining is a large scale form of underground mining. The communications needs of Block Cave mining span a wide range of data rates, latency requirements and distances. Underground mining is becoming more automated requiring increasingly more sophisticated communications technologies able to transmit high volumes of data quickly. It is also becoming more reliant on sensor technologies which, although generating little traffic, must survive using battery power for very long periods of time. 5G is a suitable technology for this wide range of applications. In the past the very great expense associated with base station deployment and maintenance has limited cellular use underground. However, the 5G Radio Access Network has been completely redesigned making 5G cellular a potentially more economic proposition than previous cellular generations. 5G also makes available very large amounts of bandwidth which potentially makes possible increased use of video and highly accurate and quick localisation underground. This paper provides an overview of 5G and then summarises the processes involved in Block Cave mining and the challenges the environment presents for communications technologies. The paper then shows how 5G can meet the requirements of underground mining and how the redesign of the Radio Access Network make 5G cellular networking a much more economical proposition than previous generations.**

***Index Terms*—5G, underground communications, underground mining**

I. Introduction

In this position paper we put forward the case for 5G being the natural successor to WiFi for communications in underground mining. We identify existing and emerging data communications requirements of Block Cave mining, discuss the limitations of WiFi in meeting them, and discuss how the fifth generation of cellular networks (5G) can meet them.

5G has many attractive properties for underground mining. It promises very high bit rates which are becoming more important as mining becomes more reliant on video located on vehicles, crushers and other machinery. It promises very low delay (latency) which has a direct impact on how fast autonomous vehicles underground can travel. It provides very high bandwidth which promises very accurate determination of position underground where satellite based systems are not available. There are also advantages for an organisation in having to support only one kind of networking technology. 5G can support all mining operations from underground, to mill operations, to conventional business and office activities.

However, one of the most important developments of 5G has been to enable base station functionality to be geographically distributed. The penetration of cellular technologies in underground mining has increased over time but has been limited because of the great cost in base station infrastructure. In previous generations the base station has been a largely monolithic and expensive piece of infrastructure. Installing a base station to cover a single 300 metre tunnel has not been economically viable. However, developments starting in 4G cellular and completed in 5G make cellular underground an economic proposition.

In previous cellular network generations the transmit and receive antenna were separated by a short length of coaxial cable from the Baseband Unit (BBU) that converted the Radio Frequency signal to a baseband signal suitable for transmission over an optic fiber 'backhaul network'. In 4G this interface was standardised in the Common Public Radio Interface (CPRI). In 5G this was further developed to become the enhanced CPRI (eCPRI). This development makes it possible for low cost manufacturers to compete in equipment provision as well as greatly extending the possible distance between antennae and BBU and enabling multiple antennae to share a single BBU.

Based on eCPRI 5G introduces two new networks that allows the base station to essentially become a distributed entity. These are the 'fronthaul network' that separates the antenna, now referred to as the Remote Radio Head (RRH) from the BBU. The interface between the antennae and the BBU is now standardised and can be extended to a distance of up to about 20 kms. The functionality of the BBU itself is also distributed. It has been split into two components: The Distributed Unit (DU) and the Centralised Unit (CU). The DU deals with Medium Access Control, Radio Link Control issues such as power control, beam forming, channel selection and similar matters. The Centralised Unit deals with higher layer functions such as packetizing data and overall radio resource management. The network that connects the DU to the CU is referred to as the 'midhaul network'.

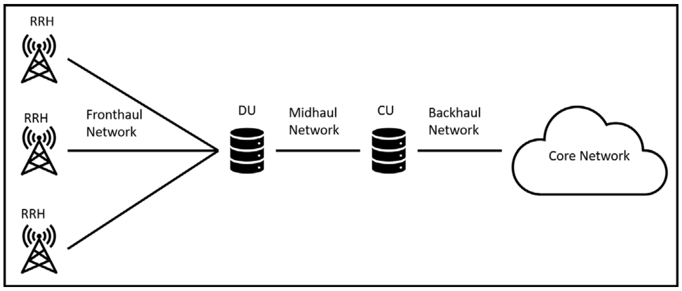

Fig. 1. 5G Radio Access Network

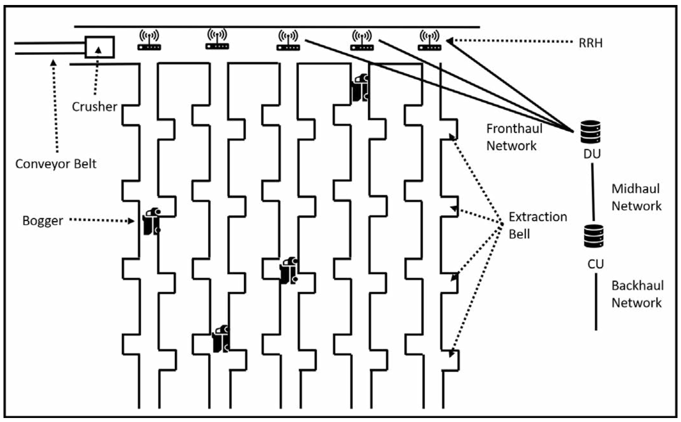

Fig. 2. Extraction Level (Vertical View)

In this model of the base station, shown in Fig. 1, the RRH is a simplified radio module which communicates with the DU, which is now a remote simplified hardware node that can be shared among multiple RRH. Most of the complexity of the base station is now implemented in the CU which can be located within a cloud based server.

This distributed base station architecture makes it potentially attractive to underground mining. Block Cave mining comprises a large number of tunnels situated directly beneath the ore body from which the ore is obtained and shipped to the surface. Typically there might be dozens of such tunnels of length of several hundred meters depending on the size of the ore body. A base station dedicated to each of these tunnels is economically unfeasible. However an RRH for each tunnel serviced by a single DU with CU functionality located within the cloud makes 5G much more economically viable for underground mining than previous cellular generations. Fig. 2 shows a topdown view of the extraction level with an individual RRH servicing each extraction tunnel connected via a fronthaul network to a DU.

There are other areas in which 5G could potentially benefit underground mining.

Processing of the ore on the surface makes use of a large number of PLCs usually connected by wired infrastructure. Using 5G wireless instead may provide some advantages. It has huge available bandwidth and promises very low latencies. The whole mining process is increasingly making use of video cameras coupled with machine learning to control processes. 5G provides the infrastructure to move the video quickly to where it can be processed and enable the very rapid activation of actuators in response.

5G supports RRH on Unmanned Aerial Vehicles (UAVs) as temporary communication infrastructure. This could be very useful during the construction of access tunnels and the extraction level.

Internet of Things (IoT) activities which occur in mining include activities such a water management, environmental monitoring, vehicle and personnel location. 5G supports IoT as one of its key use cases.

The rest of the paper develops these points and is structured as follows. Section II discusses work related to communications for underground mining and 5G. Section III presents an overview of Block Cave mining. Section V gives an overview of the current approach to mining communications. Section VI discusses how 5G could support the different activities involved in Block Cave mining. Section VII is our conclusion.

II. Related Work

Underground mines are usually serviced by a substantial wired and wireless network. Communications are often based on IEEE 802.11 Access Points connected by Ethernet [1]. Occasionally, LTE infrastructure is deployed in underground mines [2]. There has been some research into the use of LoRa for emergency services in underground networks [3]

There has also been some research on underground radio signal propagation. Zhou et al. took many measurements at frequencies ranging from 455 MHz to 5800 MHz [4]. They examined the effect on propagation of polarization and antennae position in mines and tunnels of different types, dimensions and shapes. They found path loss ranging from as high as 107.79 dB to as low as 1.49 dB per hundred meters. Hakem et al. measured the propagation of 2.4, 5.8 and 60 GHz signals and found that path loss increased as frequency increased [5]. In [6] there were some measurements of the propagation of LoRa in a Block Cave mine. A detailed exploration of LoRa in a Block Cave mine suggested that the steel lining the floor, walls and ceiling of extraction drives acted as a wave guide [7].

5G research has been a very topical area for some years, particularly innovations in the RAN [8], [9]. UAV in the RAN is discussed in [10]. An excellent overall reference on 5G standards, architecture and implementation is [11].

III. Block Cave Mining

Block Cave mining is a large scale, underground mining technique used for extracting large, low grade ore bodies particularly for valuable metals such as gold and copper. In terms of ore body size, scale of activity, life time of the mine which may be fifty or more years, and very large initial capital expenditure Block Cave mining it is often likened to open cut mining for ore bodies deeper underground.

Block Cave mining begins with the construction of an access tunnel (the 'main decline') to underneath the ore body

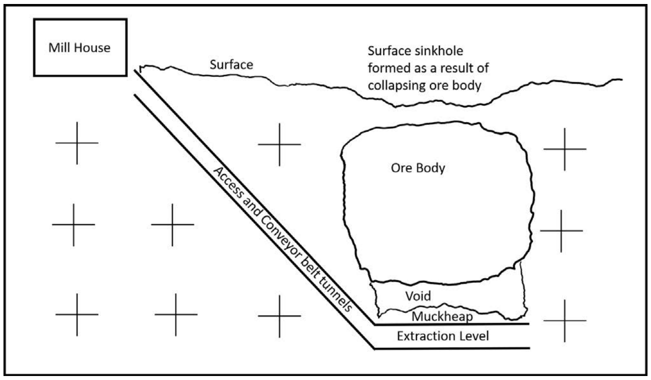

Fig. 3. Block Cave Mining

where the extraction level is constructed. The extraction level is made up of a regular set of reinforced tunnels ('extraction drives') with alcoves used to extract the ore ('extraction bells'). Above the extraction level another level is constructed to form the undercut level. After completion of this level, over the life of the mine, the ore body fractures and falls into extraction bells at the extraction level. From there it is transported via loaders ('boggers') to an underground crusher and then via conveyor belt to the surface. The components of a Block Cave mine are illustrated in Fig. 3.

Block Cave mining is so called because a cave is formed between the fallen fractured material and the ore body (the 'Block'). The fallen fractured material is referred to as the 'muck heap'. The airgap between the muck heap and the fracturing ore body is the 'void'. This approach to mining requires large capital costs but for large ore bodies is very cost effective over the life of the mine. It is energy efficient since the extraction zone is long lived and because the process makes use of gravity to fracture the ore body and deliver it to the extraction zone. It also means there is limited need of explosives. However, if gravity does not break the ore body sufficiently quickly high pressure water ('hydrofracturing') or blasting may be used.

Once extracted and delivered to the surface the ore is milled to extract the minerals. This involves additional crushing and flotation and purification. The process also produces tailings that are transported to a tailings dam.

This form of mining consumes large quantities of water mainly in the mill, but also for keeping dust levels under control on the surface and underground and for hydrofracturing the ore block. Water will usually be recycled. Water resources must be managed through pumping and storage, typically in a dam.

One danger of this type of mining is that of an air blast should the gap between the ore body and the muck heap become too great and it collapse with a catastrophic compression of air. To mitigate this risk, regular inspection of the void is carried out. This can be done directly through an open hole camera or indirectly through techniques such as time domain reflectometry [12].

A key goal of this kind of mining is automation. Having processes controlled as much as possible from the surface is both safer and potentially more economical than having personnel underground operating loaders and crushers. Given the long lived nature of these mines; typically decades, any efficiency in the extraction process, no matter how small, can give very big returns over the mine's life.

A consequence of the move to automation and the reliance on many sensors is that communications infrastructure is an essential requirement of this approach to mining. However, communications underground presents many challenges which are discussed in the next section.

IV. Communications Challenges for Block Cave Mining

Communications for underground mining is challenging. The physical environment is often hot, humid and dusty, signal propagation is complex, and the applications using communications infrastructure have a wide variety of requirements in terms of bit rate, delay and loss. Underground mines are dynamic environments with regular movement of people and machinery. The need to keep track of where equipment is, where people are, and keeping both safe, is paramount. Communications infrastructure needs to be robust, reliable, economic and flexible.

The physical environment is often hot and dusty. To counter this, water is usually sprayed on the floor of the mine which reduces dust but make the environment humid. Dust and humidity can affect transmission of radio frequency signals. Dust scatters radio waves with frequency around 1 GHz while humidity absorbs radio waves at some frequencies greater than 10 GHz [13], [14].

The propagation environment is complex. There is some evidence that steel lined extraction shafts act as a waveguide meaning that at some frequencies, signal propagation is actually less severe than on the surface [7]. Extraction tunnels are usually several hundred meters in length. Signals will propagate without line of sight but only a limited distance [6].

The way communications is used underground has become increasingly sophisticated over the past few decades. In particular, largely autonomous boggers are being increasingly used. These scoop up the fallen ore body from the extraction bells, transport and tip it into the crusher. Some remote control is necessary in selecting ore to be scooped up by the bogger since large boulders may require explosives to make them an acceptable size for the crusher, but apart from that boggers are able to travel to the crusher, empty their load and return to the extraction bell without human intervention.

The use of sophisticated machine learning based algorithms to control processes such as crushing and ore extraction is also being explored. There are many sensors and actuators underground used for environmental monitoring and vehicle location monitoring. These require a variety of different Qualities of Service (QoS). Video for remote control of vehicles requires high bit rates and low latencies. By contrast sensors require only low bit rates but in order to avoid frequent replacement of batteries, or mains power supplied to every sensor, need to be very energy efficient. Voice can tolerate some loss but requires very low delay.

Communications infrastructure needs to be such that it does not obstruct equipment nor is stopped from operating by the presence of equipment between transmitters and receivers. The location of equipment and workers needs to be known to ensure the efficient operation and safety of the mine and miners. This is particularly difficult in the absense of access to a Global Navigation Satellite System (GNSS) such as GPS. Location monitoring underground is a difficult problem that, if it can be solved at economical cost, would greatly improve the potential of automation. In particular the accuracy of the location of a Bogger carrying ore directly affects the speed at which boggers can travel between the extraction bells and the crusher. If accuracy is only poorly known the bogger must travel at a slower speed or slow down sooner as it approaches the crusher than if accuracy is better known. Bogger speed directly affects the rate at which ore can be extracted and hence the output of the mine.

Communications solutions for underground operations need to be robust to deal with the challenging physical and dynamic propagation environment. At the same time, they need to be sufficiently flexible to deal with the different bit rates, latency and loss requirements of the applications that use them. Finally, communications needs to be economical.

Block Cave mining includes significant above ground activities. Although there are more communications options above ground than underground, such as access to existing cellular networks and satellite, mining typically takes place in remote or rural areas which often have little installed communications infrastructure.

Processing of ore is usually done on site in a mill house. Milling is a complex process with many systems controlling the extraction of the mineral from the ore. Typically the ore will be crushed further in a large tumbler powered by electric motors before being processed further in a flotation system. These processes rely strongly on sensors and actuators for control.

Water management is a key issue in this type of mining. Water quality and quantity needs to be regularly monitored. Collection of water from local sources and storage in dams all need to be monitored and may be subject to strict environmental controls.

Environmental monitoring above and below ground is another communications based activity. Water quality, air quality, tailings volume and make up need to be monitored. Dust from tailings and from crushed ore needs to be monitored and controlled.

Mining also includes conventional office activities such as voice and data communications, warehouse stock control and similar. When conducted in remote areas with limited pre-existing infrastructure this can be far more challenging than in areas with well developed infrastructure. Surface operations of an underground mine may span an area of several kilometres with warehouse, operations control, and administration potentially spread right across this area.

V. Current Approaches to Underground Mining Communications

Not surprisingly, given the diversity and complexity of underground mining operations, communications used for Block Cave mining often uses a mix of communications technologies. On the surface cellular or fixed wireless might be used to provide office communications and environmental monitoring while underground WiFi with optic fiber backhaul and leaky feeder antennae are commonly used. Additionally, some Internet of Things technologies such as LoRa and Bluetooth Low Energy (BLE) are finding a role in mining with sensor networking for environmental, water, and location management both underground and on the surface [3], [15].

WiFi underground has been very successfully used underground for many years but as mining processes above and below ground become more automated some limitations are becoming apparent as applications that need increased bandwidth and reduced latency are used more.

Firstly, WiFi has a limited distance. The standards for WiFi 5 (IEEE 802.11ac) and 6 (IEEE 802.11ax) specify 50 metres as the maximum distance beyond which performance can be expected to deteriorate [16], [17]. These versions of WiFi have an absolute distance of 1.6 km beyond which timeouts and very poor performance can be expected. WiFi distance limitations underground are usually dealt with in access and conveyor belt tunnels (which may be several kilometres long) by using a leaky feeder antenna or multiple access points and in extraction drives by using directional antennae. However, leaky feeder antennae have some limitations. In particular they require powered amplifiers installed at regular intervals and have limitations on bandwidth and consequent bit rates [1].

Secondly, WiFi does not have deterministic delay. WiFi is a shared medium technology where multiple users share a channel through the use of a Medium Access Control protocol. While effective when the number of users is small or the demand on the network is light, delays can become great when load increases. For time sensitive applications WiFi can become unusable under loads of around 10% of capacity [18]) where there are multiple devices contending for the shared medium.

Finally, although WiFi is an excellent technology for data transmission it is a comparatively energy hungry technology that is not the best choice for low bit rate, long lived sensors powered by batteries [19].

On the surface and to some extent underground, cellular technology is becoming increasingly popular for mining. The fourth generation cellular technology LTE has been deployed for communications in access tunnels. However, for extraction drives they have some limitations. LTE base stations are very expensive. A base station at every extraction drive (of which there may be 20 or more) is unlikely to be economically feasible. One proposal to mitigate this is to use a single base station served by multiple leaky feeder antennae in each extraction drive. However, this too has its challenges. Leaky feeders have limitations on their bit rate and also need to be mounted some distance from the steel mesh roof of the tunnel which may not be feasible with large equipment such as boggers regularly traversing the drive. However, LTE as a fixed wireless technology on the surface, either run privately or contracted to a carrier is an excellent solution for surface communications.

Supporting multiple communications technologies across the whole mining operation has consequences for cost and reliability. There needs to be sufficient expertise to manage all the network technologies being used, as well as their interactions, adding to the operational cost. Also, interworking between technologies may increase delay and affect reliability.

Consequently, there is interest in a single network technologies that can span all the scenarios of Block Cave mining, including underground and above ground communications at a reasonable cost while supporting the emerging Quality of Service (QoS) requirements of increased automation, and the deployment of long-lived battery powered sensors. The remainder of the paper explores the potential of 5G to be such a suitable technology.

VI. 5G for Block Cave Mining

In this section we consider how 5G might support underground activities of Block Cave mining.

A. Mine Development

During mine development, access and conveyor belt tunnels are constructed, excavation of extraction and undercut levels carried out, infrastructure such as conveyor belts, crushers and the like are installed. Infrastructure such as lighting, power, ventilation and communications are installed. On the surface the mill house, roads and other buildings are constructed, water resource management plans implemented and administrative activies established.

During this phase 5G could potentially be useful during the development of tunnels and the extraction and undercut levels. One of the innovations of 5G is use of spectrum of shorter wavelength than in previous generations, notably in the millimetre wavelength range. The size of antennae is directly related to the wavelength leading to 5G devices needing much smaller antennae than previously. 5G's high bit rate, small antennae size, and ability to be deployed on UAVs may be of potential use for remote video inspection of the development of the underground levels.

B. Extraction Levels

Once established, efficiency of the extraction process is crucial to the profitability of the mine. Small gains in efficiency can, over the life of the mine, mean substantial increases in the value extracted. Consequently, it is here that great effort is being made in automation.

The distributed nature and movement to the cloud of costly base station functionality make 5G a much more economic proposition for use in extraction drives than previous cellular generations. At the moment WiFi is commonly used to provide connectivity to devices in the drive. However, as mentioned earlier WiFi has limitations in terms of distance and variable delay. Cellular networks suffer from these limitations to a much lesser extent but the cost of placing a base station in each extraction drive is prohibitive. However with the separation of base station functionality into the RRH and DU/CU this new model reduces that difficulty. We now look at specific underground activities and how 5G might assist with them

Nearly fully autonomous vehicles (boggers) are commonly deployed in the extraction level with responsibility for taking ore from the extraction bells to the crusher. Video of the fractured ore in the extraction bell could be processed using machine learning algorithms to determine where ore should be scooped from and if explosives will be needed. This may well require processing of multiple video sources with the video shipped to cloud based servers able to carry out the computations needed to make decisions as to whether the ore is suitable for the crusher. 5G lends itself well to the rapid movement of high quality video.

Autonomous vehicles need to be able to recognize obstructions and stop when confronted with them. Again, video from cameras mounted on the bogger could be used as input to cloud based machine learning algorithms that could recognize obstructions and make decisions for the bogger as to whether or not it needs to slow down or stop.

Optimization of ore crushing is another area that could be enhanced by 5G. Ore is crushed in a number of locations underground and on the surface. Optimizing crushing so as to minimize crusher wear and energy consumption can have very long term effects on mine profitability. Such optimization will require the fusion of data from many sources. 5G supports both data transmission of video as well as data from low power sensors.

Similar communication of underground low powered, long lived sensors for monitoring temperature, humidity and roof deformation can also be catered for by 5G.

C. Location Monitoring of People and Equipment

One of the key issues for underground mining is location of equipment and personel underground.

Techniques based on 5G can be used to obtain very accurate measurements of distance from a fixed transmitter based on Time Difference of Flight (TDoF). In this approach to localization a node broadcasts a message that is received by a beacon which then responds to it. The node determines its distance from the beacon by recording the time when it transmits a location request message, when the responding beacon says it received and transmitted the reply and when it is received by the requesting node. By processing the messages received from multiple beacons at known locations a node can determine its location within a tunnel.

The accuracy of this method is limited by the basic time unit of the technology, denoted T_s. In LTE T_s is dependent on the bandwidth of the carrier which is 10 MHz. 5G allows carrier aggregation of up to 100 MHz and so consequently allows more accurate location determination. Some early experiments suggest distance accuracy of better than 10 cm can be readily obtained with low cost handheld devices [20]. Using multiple sources can also improve location accuracy.

D. Environmental Monitoring

Environmental monitoring such as dust, heat, humidity and the like are additional sources of data that can be readily monitored using energy efficient communications available in 5G [21].

E. Voice Communications, Office and Data Services

Because of its excellent propagation characteristics analog VHF is entrenched in mine communications. Nevertheless 5G may well complement VHF radio in personal communications with its ability to transmit video and data.

F. Conventional Office Communications Requirements

Finally, 5G is a suitable technology for supporting conventional office and warehouse requirements requiring voice and data.

VII. Conclusion

In this position paper we have presented an overview of what Block Cave mining is, what 5G is, and presented a case for the use of 5G in Block Cave mining.

Perhaps the key difference between 5G and past generations of cellular networking are the developments in the RAN where much of its functionality has been moved to cloud based software with consequent much lower cost (compared to previous generations) hardware deployed in place of the traditional basestation. These developments make base station functionality a more economic proposition for underground mining particularly in extraction drives.

5G provides very high bit rates as well as very low latency which for applications involving the movement and processing of video such as autonomous vehicles, crushing and milling may also be of significance. The great increase in available bandwidth has consequences for localisation underground. Large bandwidths correspond directly to high peak bit rates which in turn correspond to very low data transmission times. Low transmission times help improve the accuracy of localisation based on time difference of flight schemes. 5G includes low power wide area networking technologies suitable for sensor and actuator networks. Finally, there are advantages in terms of maintenance in having a uniform communications environment.

There is considerable research to be done. Design of fronthaul and midhaul networks specifically for underground mining is perhaps the key area for future research. Regardless, 5G clearly has potential as a wireless communications technology for Block Cave mining.

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