Underground Mine Communications: A Survey

Serhan Yarkan, Sabih Güzelgöz, Hüseyin Arslan, and Robin R. Murphy

***Abstract*—After a recent series of unfortunate underground mining disasters, the vital importance of communications for underground mining is underlined one more time. Establishing reliable communication is a very difficult task for underground mining due to the extreme environmental conditions. Until now, no single communication system exists which can solve all of the problems and difficulties encountered in underground mine communications. However, combining research with previous experiences might help existing systems improve, if not completely solve all of the problems. In this survey, underground mine communication is investigated. Major issues which underground mine communication systems must take into account are discussed. Communication types, methods, and their significance are presented.**

***Index Terms*—disaster, extreme environment, mobile radio communications, seismic transmission, underground mine, wireless communications**

I. Introduction

ALONG with agriculture, mining is considered to be one of the oldest endeavors of mankind [1]. Despite its long history, mining still maintains its importance in modern life by supporting mankind with energy (*e.g.*, oil, uranium, and so on) and valuable resources (*e.g.*, water, iron, gold, and so on). In a broader sense, *mine* is defined as "an excavation made in earth to extract minerals," whereas *mining* is defined as "the activity, occupation, and industry concerned with the extraction of minerals" [1].

Mining can be divided coarsely into two groups according to the excavation type: 1) Strip (surface) mining and 2) Underground (sub–surface) mining. Two major distinctions between these groups are as follows: In 1), the mining machinery and people work on the ground together, whereas in 2), the work needs to be carried out under the ground. Underground mining can be divided further into sub–groups depending on access methods to the mineral to be mined. Major sub–groups based on accessing methods are shaft, slope, and drift mining [2], illustrated in Figure 1, Figure 2, and Figure 3, respectively.

Underground mining is one of the most extreme occupations from several perspectives. First of all, mining operations are carried out in very hazardous environments. Some major types of hazards are in–mine vehicle accidents, roof falls, fire, explosions, toxic gases, and floods. Any accident might end up with fatalities and/or disabilities within such environments

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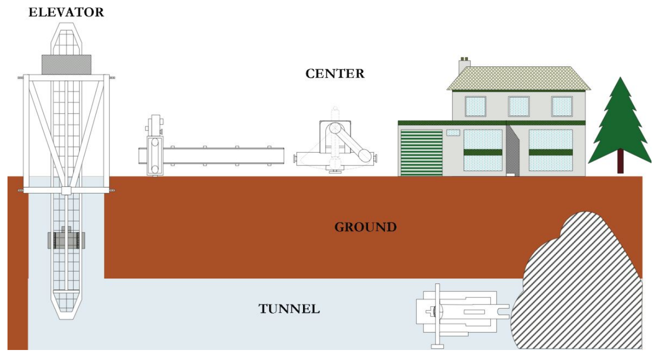

Fig. 1. An illustration of a typical shaft mine.

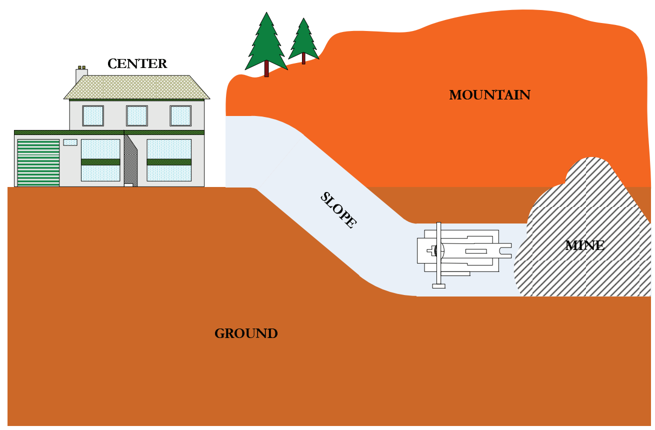

Fig. 2. An illustration of a typical slope mine.

under these conditions. Second of all, when a serious accident happens during mining operations, emergency response for underground mines is much more difficult than those for other types of working environments. This stems from the fact that the structure of underground mines does not allow immediate response to accidents. In spite of these extreme environmental conditions, efficiency and productivity are two essential concerns which must always be maintained during mining operations.

Communication is the intersection point for all of the aforementioned concerns and considerations, since it is used at every stage of mining operations. Day–to–day operations, extracting and moving the product are handled with the aid of communications, which increases the productivity. Remote monitoring and control operations depend completely on communications, too [3]. The vital importance of communication for underground mining appears when an accident occurs. Information flow, including coordination of the workers and locating them, is carried out by communications in emergency conditions. Depending on both the environmental character-

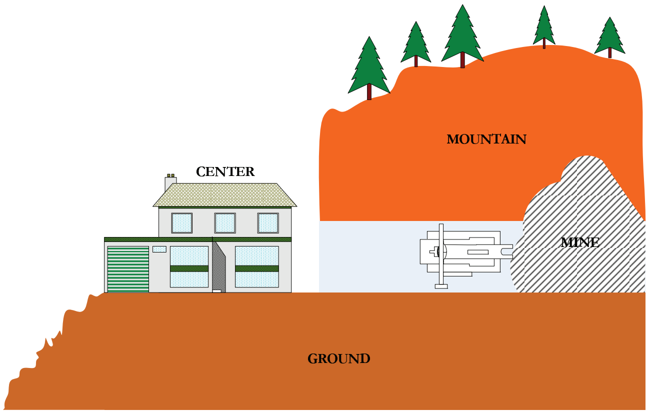

Fig. 3. An illustration of a typical drift mine.

istics and behavior of the transmission method (*e.g.*, radio or seismic transmission), several communication categories can be formed. One of the plausible categorizations of underground mine communication, which is also depicted in Figure 4, can be as follows:

- Wired communication systems,
- Radio communication systems,
- Carrier current communication systems,
- Hybrid systems,
- Other systems.

In this study, underground mine communication is surveyed. Main communication types for underground mining are investigated along with relevant communication considerations and concerns. Examples of communication systems are presented and discussed. The rest of the paper is organized as follows: Section II gives a general perspective on the underground mines and discusses why communication is essential for such environments. Section III outlines main underground mine communication systems, emphasizing communication, devices and mining equipment. Section IV provides some insight into the current status of underground mine communications along with possible future research directions.

II. Underground Mines and the Importance of Communications in These Environments

Generally, underground mines are very humid environments where relative humidity can go up to 90% or above. Corrosive water and dust are two other substances that are present in most of the mines. Moreover, many of the underground mines contain very toxic and explosive gases, such as carbon dioxide and methane [4–6].

Another interesting characteristic of underground mines is that the environment is dynamic. As long as the products are taken out, mines expand. From a general perspective of communications, expansion of a mine means that the coverage area of communications will expand. Thus, the expansion of the operating environment necessitates having a bigger communication infrastructure. Specifically, when radio communication is considered, the dynamic operating environment creates extra challenges to communication. Dynamic operating environment introduces not only coverage problem, but also change in radio propagation behavior since radio signals are prone to changes in the physical environment.

Apart from general characteristics of underground mines, there are some other characteristics peculiar to each mine. First and foremost, mines differ from each other in minerals (*e.g.*, coal, rock, or iron) excavated. This is very important from the perspective of radio communications, since electromagnetic characteristics of each mineral, such as dielectricity and conductivity, are different. In addition to mineral type excavated, the style of excavation might differ from one mine to another. For instance, some of the mines are excavated by leaving pillars to support the roof of the mine, whereas some of them are excavated in a special way called longwall mining, which does not contain any pillars. The difference between excavation styles is an important factor in both installation of the communication infrastructure and behavior of radio propagation inside mine galleries. Structures of the upper layers of underground mines are not the same either. Differences between ground structures become important especially when through–the–Earth (TTE) communication is considered because penetration capabilities of the signals transmitted differ from one ground structure to another.

As outlined above, the physical characteristics of underground mines have a great impact on which communication systems will be used for underground mining. However, the following question has not been answered: Why is communication so important for underground mining?

Without loss of generality, almost in every industry, communications will improve information flow, reduce confusion, increase confidence in decisions, and improve the likelihood of success of the goal [7]. Although these are very basic factors, they become vital when underground mining is considered.

Underground mining is a very big industry which is composed of numerous units such as mine workers, managers, mining machinery and so on. As in other industries, underground mining tries to achieve the following goals simultaneously: working safety, maximum productivity, and well–planned post–disaster relief. Communication is key to success in each of these goals.

It is obvious that working safety is the most important goal, since underground mines are very hazardous environments as discussed earlier. When day–to–day operations are considered, it is extremely important for underground mine environments to be checked whether they are safe. For instance, monitoring the atmosphere of a mine for detecting hazardous gases and/or smoke must be one of the most crucial tasks. Continuous monitoring of workers and equipment can be considered as another crucial safety item [8]. All of these operations and monitoring processes can only be handled and coordinated appropriately by communications.

Maximum productivity depends on how well the units of underground mine system can be managed. Management is carried out based on three operations: commanding, controlling, and monitoring the vital functions of mining process [9, 10]. Communication is an interface that binds all of these operations and maximizes the productivity.

In underground mines, the possibility of having a disaster is very high due to the environmental characteristics and conditions. When a disaster occurs, miners should be evac-

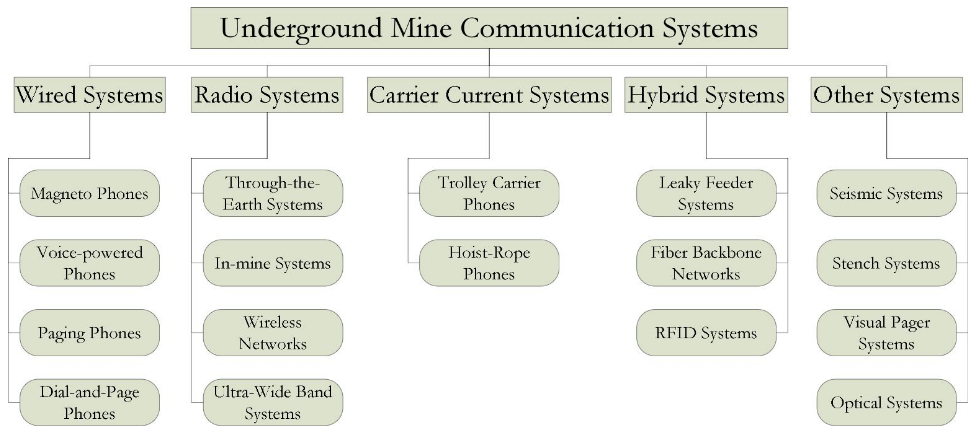

Fig. 4. A classification of underground mine communication technologies.

uated as soon as possible. Evacuation process is very critical during the crisis and this can only be handled successfully by communication. Miners need to communicate with each other in order to make decisions as well as to provide emotional support to one another [11]. Unfortunately, sometimes disasters do not allow miners to escape. Under these circumstances, communication is used for locating the trapped miners. It is clear that communication in these sorts of situations is the most difficult and, at the same time, most crucial item that leads to success in rescuing operations.

III. Communications in Underground Mines

Communication systems for underground mines are classified in Section I and illustrated in Figure 4. Before getting into details, it is appropriate to discuss some issues such as device, equipment, and communication considerations, since environmental conditions of underground mines impose additional operational restrictions on these systems.

Because underground mines are very hazardous environments, first and foremost, one should make sure that the equipment or system must operate in "permissible" levels for safety reasons [6]. Moreover, it is known that devices that are designed to operate in regular environments might break down faster in underground mines due to extremely harsh conditions. Devices that will operate in underground mine environments must be immune to high–moisture (over 90% relative humidity level), wide temperature ranges, and dust. Immunity to harsh conditions is not solely enough to meet the device requirements. It is reported that especially electronic devices may cause very serious problems such as heat and short circuits by reacting with the substances (*e.g.*, dust and corrosive particles) present in underground mines. Therefore, insulating devices from hazardous substances is a must for underground mine communications [3].

Other considerations about communication equipment in underground mines are related to the design of the equipment and surrounding physical conditions. Small and light–weight devices are essential due to the space considerations and mobility limitations in underground mines. Especially for mobile devices, having a long–lasting battery is very important. Shock proof and rugged designs are two prominent criteria in designing the communication devices regarding the physical environments in which the devices will operate. In conjunction with all of the items mentioned above, reliability and maintenance of the devices must be considered as well [3]. Although the requirements may seem similar in both regular and underground mine environments, it is important to bear in mind that the regulations for underground mine environments (*e.g.*, permissible power levels and heat dissipation) are quite different than those for regular ones.

TABLE I
Major Considerations for Underground Mine Communication Devices and Equipments

Consideration	**Requirements**
Safety	Short circuit, voltage and operational heat levels
Immunity and protection	Moisture immune, having wide temperature ranges, dust–proof, corrosion–proof
Size	Small and light in weight
Design	Rugged and shock–proof
Reliability	Always maintained

Apart from device and equipment considerations, as in many fields, there are some specific requirements for communication systems which will be used in underground mining. Here, "requirements for communication systems" are emphasized, because there is no single communication system that can meet all of the requirements simultaneously for underground mine communications. This stems mainly from the fact that underground mining consists not only of in–mine communications, but also of mine–to–ground communications. Therefore, it is reasonable to investigate communication considerations from the perspective of in–mine and mine–to–ground communications separately.

In–mine communication requires complete coverage inside the mine galleries. It is extremely important for information to be conveyed to and gathered from every point of mine due to both safety and productivity reasons. However, it is known that sometimes radio communication is either not possible or of very low quality because of the propagation characteristics of radio signals in underground mine galleries. This mandates the use of wired systems for in–mine communications. Nonetheless, wired communication is very susceptible to damages to wires. Therefore, installation of wired communication infrastructure must be handled in such a way that possible damages to wires are minimized.

Even though there are some other high priority considerations for underground mine communications such as safety and coverage, cost must also be taken into account along with other aspects. Underground mines are very dynamic environments. As mines expand, the area to be covered expands automatically. In case of the use of a wired communication infrastructure, expansion of a mine comes at the expense of installation of new wires. For radio communication infrastructures, expansion corresponds to an increase in the number of relay stations. Therefore, when cost is of interest, communication systems must be designed in an optimum way such that the cost is minimized while the high priority issues are not abandoned.

Mobile communication is the most desired type of communication among all underground mine communication types. It is generally established by using radio waves. From the radio communications perspective, mobility introduces a more complicated propagation channel compared to those of wired and fixed wireless communication systems. This implies more complex transceiver designs. The designs must take into account not only the propagation characteristics, but also the practical use of the devices. Recalling that underground miners must carry several items along with life support systems such as self–contained self–rescuers (SCSRs), communication devices must not prevent miners using SCSRs when they want to communicate with each other.

When mine–to–ground communication is considered, the most important issue is to be able to detect the signals coming from the mine. Therefore, in order to detect or hear the signals coming out of the mine, the relevant (*i.e.*, electromagnetic or seismic) noise level must be exceeded [6]. However, other sort of requirements as outlined earlier should not be violated while trying to satisfy the requirements of mine–to–ground communications.

A summary of the aforementioned considerations is given in Table I. In light of these issues, considerations, and requirements, the communication systems for underground mines can be investigated in detail.

A. Wired Communication Systems

Wired communication systems depend on a wire connection that conveys the information between two communication nodes.[1] Public switched telephone network (PSTN) can be considered as an example of wired communication systems.

In underground mine communications, some of wired communication systems depend on a common communication wire to which each individual phone (or terminal, or node) is attached. This sort of wired communication system is called 'party line' system. Main characteristic of this system is that the transmission of any node can be received by all other individual nodes because of the common line. A more complicated version of party line system is known as 'private line,' which includes a central switch to handle the private transmissions connecting only desired nodes to each other. Switching mechanisms of early private line systems were governed by an operator, whereas those of current systems are controlled and processed by computers. Based on the line systems explained above, the following wired communication systems are employed in underground mines:

1) Magneto (Crank Ringer) Phones: One of the earliest sorts of underground mine communications through wires is known as magneto (or crank ringer) phones. A magneto phone is composed of a transmitter, receiver, hook switch ringer, battery, and magneto (hand generator) [12]. The basic principle of this type of system is to generate a current that is strong enough to make bells of other phones ring in a private line manner. The station that is being called is identified by coding in which short and long rings are used [13]. Once the desired station picks the phone, the conversation is supported by the battery power. It is obvious that supporting a large number of nodes with enough signal strength is difficult for magneto phone systems. Therefore, as mine grows, magneto phone system setup must be divided into smaller areas to operate on a reasonable signal level [13].

2) Sound–powered (Voice–Powered) Phones: Sound–powered phone systems take the voice of the speakers and convert them into electrical signals by electro–mechanical transducers. Transducers are sensitive to air pressure which is provided by the voice of the speakers. In contrast to magneto phones, sound–powered phones do not require an external power source. The only power source for this type of system is the air pressure input to the transducer; therefore, any party can begin to transmit any time [14]. The wire that connects two transducers constitutes the transmission line for communications.

Ability to transmit without requiring any external power source renders sound–powered systems essential in emergency communications. This type of system is still widely used especially in rescue operations [6]. The main shortcoming of sound–powered phone systems is its limited and short distance usage.

3) Paging Phones: One of the most widely used wired systems in underground mines is paging phones. Paging phones are based on party line principle. Each individual device has its own internal battery to feed audio amplifiers which strength the audio signal on loudspeaker. Paging phones are widely used in underground mines; because, in contrast to magneto phones, they do not require a particular coding to page a user.[2] Paging is established by announcing the name of the desired person, which benefits from the party line architecture. In addition, loudspeakers fed by internal batteries provide a very high sound level, which is a very important property in very noisy environments such as underground mines.

Paging phones have some other advantages such as being reliable, easy to install and maintain systems [12]. However,

[1] Although some contemporary wireless communications systems such as Global System for Mobile (GSM) have a wire connection at some points of the system, the main intention is here that the system of interest allows radio transmission at particular level.

[2] Paging a person by calling his/her name is always easier compared to paging him/her by using a specific code. Therefore, in underground mines, the use of code information for a specific person or terminal is avoided, since it might not be very convenient in emergency cases.

they have some disadvantages as well. For instance, party line architecture prevents simultaneous transmission. Besides, as stated in Section III-A1, expansion of the mine causes power sufficiency problems for the system, since new page phones will be installed into the areas recently excavated. In order to overcome this problem, additional devices (page relays) must be deployed [3].

4) Dial-&-Page Phones: By looking at the previous communication systems, one might ask: Why cannot the surface–type telephones be simply deployed in underground mines? This is a valid question, since surface–type telephones have the selective call ability and multiple private lines. However, there are two main reasons preventing surface–type telephones from being used in underground mines. First, there is a very serious potential hazard of using this sort of phone system in a methane atmosphere, since it employs 120V voltage. Second, paging cannot be carried out to locate a person who is not working in the vicinity of the telephone [3, 12].

These concerns lead to the idea of combining the dial function with paging. This unified system employs a multiple–pair cable as infrastructure. The hazardous aspect is eliminated by isolating high voltage levels from underground line and converting the ring voltage inside the underground mine terminal into a lower voltage level. An additional interface modifies the signal depending on which terminal (in–mine or any other ground terminal) is being dialed. There is an extra "common–page" button for the device to function as a pager. With this functionality, this system allows announcements as well.

Dial-&-Page phones require complex infrastructures and installation. Despite their superiority, it must be stated that they are very prone to line breaks which are highly probable in underground mine environments due to collapses and/or roof falls.

A brief description of the above mentioned systems along with their advantages and disadvantages is summarized in Table II.

B. Radio Communication Systems

It is obvious that one of the biggest challenges for wired systems is the existence of wire connection between communicating terminals. For any type of environment it is desired that communication can be carried out on the move while maintaining two–way communication. However, underground mines are very challenging environments for radio communications. It is observed that the behavior of radio signals is very different in underground mines compared to that in other regular environments. Therefore, there is a need to investigate how radio signals behave in underground mine environments.

Underground mines possess special environmental characteristics which are totally different from the other environments in which wireless communication technologies are popularly used. Generally, underground mines are composed of tunnels exhibiting hazardous properties due to presence of dangerous gases, substances, and corrosive water along with dust [4, 5]. The tunnels are not straight leading to different form of turns *e.g.*, U–turn, angle turn, and so on) most of the times. The ceiling of tunnels may be fortified with pillars as well. Besides, the walls of tunnels generally consist of rough surfaces and materials depending on the mine. An illustration of a typical underground mine environment is shown in Figure 5. All these extraordinary properties have different effects on radio signals. Furthermore, it is desired for radio communication not only to cope with these challenges related to propagation, but also to satisfy the following three goals: I) to operate seamlessly while protecting and rescuing the workers under emergency conditions; II) to cover the entire working area in order to keep in touch with workers and to track them during the work; and III) to help monitoring/warning inside mines [15–17].

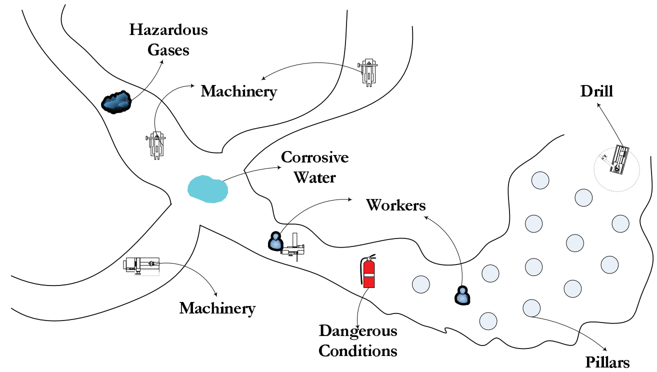

Fig. 5. A typical underground mine environment.

Radio communications in underground mining can be divided into the following main parts:

1) TTE communications,
2) In–mine radio communications,
3) Wireless networks,
4) Ultra–wide band (UWB) systems.

In the subsequent sections, each type of radio communication will be investigated.

1) TTE Communications: When an underground mine disaster occurs, generally, miners are trapped inside the mine waiting to be rescued. The rescue team is located on the ground. In order to employ an effective and timely rescue operation, accurate locations of the survivors must be known. This mandates to have a sort of communication between victims and the rescue team. However, the regular communication options are not available under such circumstances due to the impact of the same disaster. This leaves only the option of TTE communications.

The idea of using the Earth as a common medium for communication goes back to Nicola Tesla, as early as 1899, through the use of extremely low frequency (ELF) waves [18]. Theoretical works were pioneered by [19, 20], which set the mathematical basis for propagation through the ground along with some simplifying assumptions.

Following the theoretical works, practical efforts took place at the beginning of the previous century. One of the earliest attempts at using radio communications in underground mines was established by the United States, Bureau of Mines in 1922 [21]. The trials went on even though [21] was reported as an unsuccessful effort in terms of establishing a radio connection between underground and ground stations. Upon these efforts,

TABLE II
HIGHLIGHTS FOR WIRED COMMUNICATION SYSTEMS

Communication System	Highlights	(+)Advantages/(−)Disadvantages
Magneto (Crank Ringer) Phones	Generating a current that is strong enough to make bells of other phones ring in a private line manner.	(+)Simplicity (−)Battery power requirement (−)Modification requirement with mine expansion (−)Specific coding requirement to page a person (−)Weak and noisy received signal due to absence of amplifier
Sound-powered (Voice-Powered) Phones	Taking the voice of the speakers and converting them into electrical signals by electro-mechanical transducers.	(+)No external power source requirement (+)Suitability for rescue missions (−)Limited and short distance use due to its inherent structure
Paging Phones	Based on party line principle. Each individual device has its own internal battery to feed audio amplifiers which strengthen the audio signal on loudspeaker.	(+)Reliable, easy to install and maintain (+)No specific coding to page a person (−)No simultaneous communication (−)Internal battery requirement for each phone
Dial-and-Page Phones	Combination of dialing and paging functions.	(+)Multiple functionality (dial and page) in a single system (−)Complex installation and infrastructure

the basics of TTE communications were established. For instance, the frequency dependency of waves penetrating the Earth became clear. It has been understood that the higher the frequency, the shorter the distance the radio could penetrate the Earth.[3] In addition to the studies regarding penetration capabilities of the signals, effects of the structure of the Earth were studied as well. The impact of metallic conductors on penetration was explored and found to be crucial to successful transmission and detection. Similarly, effects of different rock, soil types, and the presence of water were also explored. In parallel to both frequency dependency and structural characteristics of the Earth, power requirements were studied and the directional characteristics of antenna configurations were investigated [22–24]. Despite these efforts, the question regarding whether or not radio waves could penetrate the Earth in the absence of metallic conductors was still open. Therefore, this question needed to be answered. J. Wallace Joyce performed several experiments to answer this question and he concluded that although the low frequency signals could be detected, the attenuation was so high that the use of radio waves in TTE communications would be impractical [25]. These results disappointed many researchers and TTE communication efforts almost stopped until World War II [26].[4]

The first successful TTE system was developed in South Africa [30, 31]. In [30], TTE was achieved at 100 and 350kHz by using a horizontal wire antenna to transmit the signal to a distance of 6000ft down to miners wearing helmets with built–in loop antennas. It is worth mentioning that the conductivity of Earth and the sedimentary formations of the ground where the experiments were carried out could be the major reasons behind the success or failure. In the following years after World War II, TTE communication studies were performed in the United States as well [32, 33]. However, none of the efforts provided a satisfactory result [34]. After some unfortunate mine disasters, many studies have been carried out with the support of U. S. Department of the Interior, Bureau of Mines [35, 36]. One of the earliest attempts was established by Westinghouse Georesearch Laboratory [36]. In [36], a prototype electromagnetic location system was developed including six miniature transmitters, six miniature receivers, and one multichannel receiver. The system was designed in such a way that it operates in a deep coal mine of relatively high overburden conductivity. The electromagnetic spectrum interval used in that study was $900-2900$Hz. In [36], two different types of receivers were investigated: (i) a portable single channel receiver utilizing an air core loop antenna tuned to one particular frequency and (ii) a multichannel receiver utilizing a broadband loop antenna and preamp combination to receive up to six frequencies simultaneously, which was installed on a helicopter hanging over the area of the experiment. This setup exploits the fact that miners equipped with a radio transmitter and a loop antenna which generates a vertical magnetic dipole moment can be located by measuring the electromagnetic fields on the surface. Generally, in TTE experiments, a single null is formed in the total horizontal magnetic field right above a transmitter which is placed under the ground. This null is used for localization purposes. Accuracy of the location is based on the depth of null which depends on signal level and electromagnetic interference (EMI). Accuracy depends also on the axis orientation of the source under the ground and the slope of the terrain on the surface and some other environmental conditions. Operating frequencies and transmitter power, and detection schemes can be adjusted in order to optimize

[3]Of course, one should keep in mind that having a better penetration capability by using lower frequencies comes at the expense of conveying less information, since the frequencies of interest are considered almost in the range of "baseband transmission."

[4]Yet, it must be stated that there were some efforts at using radio waves penetrating the Earth for other purposes such as underground exploration of minerals and ores [27–29].

the signal–to–noise ratio (SNR) at the receiver and thereby increase detection range and location accuracy. Some further modifications such as terrain slope correction factors can be developed to reduce the localization errors.

In the following years, the studies mostly focused on understanding the characteristics of TTE communications including EMI behaviors [37, 38]. These results combined with previous experiences led to even some practical implementations [39–41]. Later on, the research focus slightly shifted to improving practical implementations under operational conditions of underground mining [42, 43]. In parallel to these efforts, new methods and equipments were also developed to improve the success rate of locating trapped miners even employing helicopters during the rescue operation at the detection stage [44]. Considering the fact that penetration depends on the underground mine structure, mines were classified according to their ground structures, then, the penetration characteristics were investigated accordingly. As mentioned previously, the signal penetrates better in the presence of metallic substances; therefore, some efforts were put on investigating the penetration behaviors in metal/non–metal mine structures [45–47]. With the increase in the number of unfortunate disasters, some studies focused on finding the optimum frequency interval with the highest rate of success in rescue operations and relevant monitoring applications for safety [26, 48–52]. In connection with these advances, the accuracy limitations were improved for locating trapped miners. Instead of using conventional ways, such as simple direction finders or time difference pulse systems, the use of full–vector field measurements[5] were also studied [53]. It has been reported that even though these methods had the drawback of the necessity of accurate measurements, employing continuous wave radio signals with phase differences that can be measured accurately would greatly improve the location accuracy [53, 54]. Although it has been understood that the penetration characteristics are of different type for each mine, studies still go on in order to describe and unify the relationships between penetration capability, depth, transmission frequency, and conductivity [55–57].

2) In–mine Communications: Although TTE constitutes the most vital part of the underground mine communications, a complete underground mine communication system consists not only of sending the radio signals to the ground, but also of communicating inside galleries. Therefore, the propagation behavior of radio signals in mine tunnels has been studied as well. Some earlier theoretical works considered the propagation characteristics of ultra high frequency (UHF) waves in tunnels [58, 59]. Extension of these works took the attenuation losses, which are caused by different dielectricity characteristics and shapes, into account for underground mine environments [60]. In order to simplify the problem, some researchers assumed that the tunnels consist of perfectly reflecting walls so that this simplification can be extended to more realistic cases in which the tunnels consist of imperfectly conducting walls [61]. However, in order for these simplifications to be reasonable, a very distinct characteristic of underground mines, namely curved tunnels, must be accounted for [58, 62]. This forces the researchers to think how radio waves propagate inside mines.

a) Natural wave propagation in mines: It is known that when the wavelength of the electromagnetic wave to be used is decreased so that it becomes smaller than the dimensions of tunnel, the transmission of the signal can be considered as though there is a waveguide [60, 63–66]. The shape, the structure of the walls, and the dimensions of the waveguide along with the objects inside (such as pillars, machinery, and so on) are of vital importance for modeling the radio propagation. Modeling the natural wave propagation in mines is very important, because all of these factors cause some parameters of the radio propagation channel to vary drastically [67].

There are two approaches in modeling the radio propagation: (1) Theoretical Modeling and (2) Empirical Modeling. Theoretical modeling is established by using either (a) Modal approach or (b) Ray tracing methods. Modal approach has some challenges in terms of its mathematical tractability (such as the conditions of the separability of Helmholtz equation [66, 68, 69]). Moreover, since the shapes of galleries are not uniform and regular, establishment of a general framework in theoretical modeling becomes even more complicated. In these cases, ray–tracing methods can be adopted [67, 70]. However, the required numerical calculations can be overwhelming in (b) [66].

Empirical modeling is based on extensive field measurements performed in the environment of interest. Collected data are evaluated in such a way that the statistical characterization of the radio propagation is obtained for that specific environment. Since empirical modeling characterizes the propagation statistically, the model obtained can be employed in similar environments. In contrast to the theoretical approaches, due to the level of effort, hard to obtain permissions, and safety issues, empirical approaches are not vast in the literature. However, empirical approaches in underground mines have been drawing a significant attention. This attention has provided the researchers with some opportunities to better characterize the underground mine radio propagation channel.

b) Measurements of wave propagation in mines: One of the earliest efforts that combines theoretical works with experiments in radio propagation channel modeling was established in 1963 [71]. Low frequency waves were employed and the relationships between frequencies, propagation distances, and noise levels were studied based on the considerations about the propagation and penetration capabilities of radio signals. Following studies showed that there were some efforts to combine in–mine results with TTE in order to have a comprehensive communication system for underground mining including emergency, day–to–day operations, and mine environment monitoring [72, 73]. In parallel to these studies, several improvements were employed for already existing communication systems and methods too. As in evolution of many radio communication systems, increased range, efficient use of the transmission bandwidth, and reduced power consumption were the main criteria in underground mine communications [74]. As mentioned previously, the coverage of radio signals increases significantly in the presence of

[5]Generally, full–vector field measurements refer to the measurement of channel transfer function (CTF) usually with a network analyzer or, of the channel impulse response (CIR) with a channel sounder.

conductors such as metals. Keeping this fact in mind, some specific studies took place in investigating the improvement options of coverage by making use of metallic substances in mines. It was seen that the coverage might be enhanced at medium frequency (MF) bands in the presence of conductors whereby radio signals are coupled into and are carried by these conductors [10, 46, 75–93]. However, it must also be noted that the attenuation along the conductors strongly depends on their position referred to the tunnel walls, the number of conductors, the cabling/pipes architecture, and so on. In connection with these results, studies regarding the employment of advanced techniques into existing systems, such as the employment of different coding formats and modulation types, were also in progress [94, 95]. In addition to these efforts, as in TTE communications, researchers investigated the impact of the type of the mines on in–mine communications as well. For this purposes, several types of mines such as coal, iron, and silver mines were examined in terms of their radio propagation characteristics [96–98].

Although there are many studies on low and medium frequency for in–mine communications, very high frequency (VHF)/UHF communications were also investigated in detail beginning from 1973. One of the earliest mine measurements accomplished for several transmission frequencies including 200, 415, and 1000MHz bands in the presence of obstructions such as pillar and for relatively small mine rooms [99]. However, the number of studies and measurements for VHF/UHF was not as many as those for low and medium frequencies between years 1973 and 1985. VHF/UHF related studies afterward took place again in the literature [3, 100]. This period also coincides with the era of communication devices and techniques employed in underground mines with micro–processors [101, 102].

Due to ever increasing need for high data rate applications, the studies related to UHF communications increased significantly over the last two decades. Within this period, propagation characteristics of UHF signals are investigated from many aspects and some key findings are revealed. For instance, it is reported that radio signals at 900MHz can propagate in a potash mine with low loss and low multipath distortion [103]. These and similar other results show that UHF communications can be used in underground mines for providing multiple channels of two-way voice communications, monitoring and controlling applications, and eventually streaming compressed digital video [104, 105]. In order to increase the data rate further, the use of antenna arrays was also considered for UHF band communications in underground mines [106]. Achieving high data rate communications depends on the bandwidth of the transmission as well. It is known that when the transmission bandwidth increases, assumptions made for narrower band transmissions are not valid anymore [107]. Therefore, small–scale propagation characterization[6] of VHF/UHF bands required to be investigated from the perspective of both narrow– and wide–band transmission [108].

The systems that operate on these frequency ranges with high transmission bandwidth were tested in underground mine galleries in order to see how off–the–shelf systems perform under such harsh conditions [109]. In parallel to VHF/UHF studies, there were also some efforts to use low frequency and ultra low frequency (ULF) signaling schemes for in–mine communications [8, 110]. It is worth mentioning that, recently, the use of super–conducting devices in underground mines in the range of low frequency band has attracted some attention. For instance, in [111], a high–temperature super–conducting receiver is used for communicating in underground areas with voice. The system takes advantage of low frequency band (*i.e.,* 4000Hz) to carry the voice, since these frequencies can penetrate typical rocks over distances of several hundred meters with moderate power levels.

Although high bandwidth off–the–shelf UHF systems are tested in underground mine environments, as discussed previously, propagation characteristics peculiar to underground mines must be taken into account in order to have a better performing system. For this purpose, some measurements were performed considering the radio propagation in different tunnel shapes and rooms in the presence of pillars. More specifically, radio propagation measurements need to consider straight, curved, and parallel tunnels and junctions with LOS and obstructed line–of–sight (OLOS) [112]. The results must be evaluated in detail in terms of the statistics defined earlier in this section [112–114]. Based on these results and findings, some wideband radio communication systems were tested for several purposes including emergency and day–to–day operation communications [66, 115–117]. Similar to low frequency (LF) and MF communication efforts, the propagation measurements were performed and time–varying radio propagation channel parameters were identified at UHF bands as well [118, 119]. Some recent efforts on characterization of radio propagation and relevant applications (*e.g.*, geolocationing and positioning) operating in wide band and UWB including super high frequency (SHF) bands can be found in [120–142].[7]

3) Wireless Networks: Wireless networks can be divided into two sub–classes based on whether they require an infrastructure or not. One of the most popularly deployed network types which requires an infrastructure is wireless local area network (WLAN). However, ad hoc networks can be deployed without the requirement of any infrastructure. Both types of networks are implemented for underground mine communication purposes.

WLAN is a well–established technology for regular environments; hence, it is considered as a solution for underground mine communications as well. Some field tests for IEEE 802.11b based systems were conducted in a real mine environment and it was observed that the coverage range can be up to 1500ft for straight tunnels [143]. There are some other field tests in the literature which consider issues other than the propagation range such as the impact of Fresnel zone

[6]These characterizations include power delay profile (PDP), distribution of path amplitudes and arrivals and so on for both line–of–sight (LOS) and non–line–of–sight (NLOS) cases.

[7]Interestingly, in the original paper [122], the results are reported to be based on an article with another title "Narrowband and wideband radio channel measurements in an underground mine with narrow veins at 2.4GHz." But the absolute reference, which is "*IEEE Transactions on Wireless Communications*, Volume 4, Number 5, pages 2441–2453 on September 2005 points out the paper cited as [129]. To the best knowledge of the authors, a paper entitled as "Narrowband and wideband radio channel measurements in an underground mine with narrow veins at 2.4GHz" does not exist in the literature.

obstructions, multipath effects on propagation, and optimal antenna configuration [141]. In addition to these efforts, IEEE 802.11b is deployed for wireless localization in underground mine environments as well [133].

Similar to WLAN, ad hoc networks are also deployed in underground mines. It is reported in [143] that the coverage range can extend up to 1800ft for straight tunnels with IEEE 802.15.4 operating at 900MHz. The trial tests also showed the necessity of placing repeaters in almost all of tunnel branches since it did not perform well around the corners when there exists an NLOS condition between the repeater and the user. In addition, [137] and [140] consider the deployment of sensor networks for localization purposes.

Power of each node is one of the major issues in both network types which should be addressed before employing such systems in a real mine environment. Especially, it becomes even more important in case of an emergency or a rescue operation. The limited hours of operation of the nodes is one of the disadvantages of such systems. Congestion at the leaving node where the entire traffic is collected is another shortcoming of all wireless networks, which in turn, limits the aggregate data rate.

4) UWB Systems: UWB communication is becoming very popular especially for consumer electronics applications. It is based upon using very narrow pulses with low power. It is believed that this technology will fundamentally change the short range wireless communication by providing very high data rate with low power consumption.

A trial test was conducted in a real mine environment to understand the feasibility of employing this technology in such harsh environments. The test was performed in the track entry of McElroy Coal Mine, which is operated by McElroy Coal Company, in Marshall County, West Virginia, U. S. A. At the track entry, the test area was measured to be 18ft wide and 6ft high on average. The side walls are rough, uneven, and covered with lime powder. It is also reported that there are pumps, metal jack posts, and some other mining equipment in the test area. Optical LOS could not be maintained in the track entry test area due to elevation changes and slight turns. The system tested used the full frequency range from 3.1GHz to 7.3GHz along with a power level 10dB above the Federal Communications Commission (FCC) requirement for UWB transmission.[8] The test revealed that a coverage area of 2000ft was achievable within straight tunnels with some dead spots. It was also observed that the system was able to penetrate two stoppings over the distance of 100ft, though its performance around the corners was very poor [143].

UWB technology is very promising as far as the location and tracking applications are concerned. Due to very high time resolution of this technology, high accuracy can be achieved in these types of applications [144].

A brief description of the above mentioned systems along with their advantages and disadvantages is summarized in Table III.

In this sequel, one should bear in mind that when the use of radio signals is considered for underground mine communications EMI must be taken into account. EMI is mainly caused by the machinery used during the normal mining operations. However, when the power is cut off, which is the general case when an accident occurs, the residual EMI does not create a serious problem unlike the noise in the regular environments [145]. In case of a disaster, the presence of EMI becomes even more important since the lives of trapped miners depend on the accuracy obtained from received signals propagating through the ground which generally requires the use of frequencies ranging from ELF to very low frequency (VLF). In rescue operations, it is reported that lightning and atmospheric noise can contribute to EMI significantly [39, 40, 49, 145–148]. Susceptibility of EMI to the environmental conditions along with further studies suggests that it can be described by a non–stationary random process [3, 12]. This forces one to evaluate the time and amplitude statistics of the observations in order to describe EMI in mines adequately. These statistics include inter–pulse spacing distributions, pulse duration distributions, average crossing rates, and amplitude probability distribution [146, 149]. All of these parameters and statistics are of vital importance to adjust the appropriate sensitivity level of the receivers as well as the appropriate frequency selection especially for the rescue operations [37, 51, 145, 146]. Studies point out that when the transmission frequency decreases, the penetration capability of the signal TTE enhances leading to a stronger signal reception on the ground. Therefore, for the same ambient EMI level, the lower frequency signal leads to a higher SNR value. In–mine noise levels at higher frequencies are typically the same as in other industrial operations under normal mining operation conditions [3, 12]. Although a reliable radio communication for underground mining highly depends on the propagation characteristics of the radio signal and EMI, there are some other factors that need to be taken into account. For instance, considering the variety of applications such as video transmission, voice, or simple paging, the transmission bandwidth must also be contemplated. Furthermore, depending on the type of the communication style, such as in TTE, penetration capability of the portion of the electromagnetic spectrum to be used becomes extremely important. Hence, in order to employ a radio communication system for an underground mine, all of the aforementioned concerns must be investigated in detail.

C. Carrier Current Systems

When radio waves are fed into any underground wire or cable, they are distributed throughout its length. Carrier current systems make use of this fact, since there are already existing wiring infrastructures, such as alternating current (AC) and/or direct current (DC) power lines, hoist ropes, phone lines, rails, trolley lines, water pipes, ventilation lines, or some other wiring in underground mines. Studies show that the best propagation is obtained when medium frequency bands are used throughout these media [3]. These sorts of communication systems are considered as the most dependable communication systems in many cases. Compared with the telephone circuits, carrier current systems have higher mechanical strength and a better insulation. Besides, damage caused by roof falls is very seldom, and even if damage occurs, they can quickly be repaired [12].

[8] According to Federal Communications Commission (FCC) Part 15 rules, UWB devices cannot exceed a power level of -41dBM/MHz in this spectrum band.

TABLE III
HIGHLIGHTS FOR RADIO COMMUNICATION SYSTEMS

Communication System	**Highlights**	(+)**Advantages/**(−)**Disadvantages**
TTE Communications	Establishing communication between surface and the underground generally through the use of very low radio frequency signals.	(+)Very useful in rescue operations (−)Huge transmitter power and antenna sizes (−)Highly dependent on the depth, frequency and the characteristics of the ground
In–mine communications	Based on the fact that underground mine communication system consists not only of sending the radio signals to the ground, but also of communicating inside galleries.	(+)Mobility within the mine environment (−)Galleries, w/o pillars and generally uneven and rough walls considering the propagation characteristic (−)Significant path loss (−)LOS requirement
Wireless Networks	Consists of several repeater nodes which are able to store and forward information to other nodes.	(+)Very limited human intervention for system configuration (+)Robustness (−)Power requirement for the repeater nodes (−)Limit on the data rate due to congestion at the leaving node (−)Poor performance around the corners
Ultra–Wide Band Systems	Based on using very narrow pulses with low power.	(+)High data rate with low power (+)Very high accuracy in location tracking applications (−)Poor performance around the corners (−)Short range due to low power

There are two prominent carrier current systems used in underground mine communications:

1) Trolley Carrier Phone: In a trolley carrier current phone system, the receiver and transmitter are connected to the trolley wire through a coupler capacitor. The coupler capacitor acts as a short circuit at the frequency of the modulated voice signals, but as an open circuit to the trolley wire DC power voltage. The high voltage levels on the trolley wire are thus blocked from entering the receiver and transmitter sections of the carrier phone, while the modulated voice signals pass freely through the coupler capacitor [3, 12].

2) Hoist Rope Phone: Another one–way, carrier current communication system employed in underground mines is known as “hoist bell signaling.” This sort of communication is used for communicating between different levels of underground mines. This system is based on a switch to be pulled and a special sort of coding for command. When the switch is pulled, the circuit is closed and signaling is carried out through the coding which is established by the number of the pulls of the switch. The system consists of two signal couplers and two transceivers. Each unit is of the push–to–talk, release–to–listen design. During transmission, the sending unit feeds its coupler with a frequency modulated carrier. The coupler induces a signal in the hoist rope, which is then picked up by the coupler of the second unit. Both couplers are electrically identical, and each operates both as a transmitting and a receiving element. Operation of the hoist radio is the same as that of a trolley carrier phone, except that the hoist radio signal is inductively coupled to the propagation medium (*i.e.,* hoist rope) [3, 12]. There are two distinct advantages of hoist bell signaling: it is easy to implement and removes the language barrier. However, with the recent advances, this system is replaced with automatic elevators with telephone–based systems [3, 12, 34].

A brief description of the above mentioned systems along with their advantages and disadvantages is summarized in Table IV.

D. Hybrid Systems

Wireless and wired communication systems are discussed in the previous sections. Each of those systems has some advantages besides their disadvantages. The existence of a wire connection is the biggest challenge of wired communication systems in very harsh environments because wires are susceptible to physical damages. Wires limit the mobility of the users as well. However, wired systems are preferable to wireless systems since they offer relatively better coverage and higher data rates. These reasons lead us to employ *hybrid systems* which benefit from both features of the wired and wireless systems in underground mines.

1) Leaky Feeder System: Leaky feeder cable is designed to “leak” signal, which allows radio transmissions to both leak from the cable and also to enter the cable [150]. Leaky feeder cable can be either a twin-core, coaxial cable in which the sheath (outer conductor) is pierced by a series of apertures: loose–weave cables, cables with holes or continuous lengthwise slots in the sheath. The cables radiate over their entire length. Leaky feeder system increases the propagation range, because the degree of attenuation throughout the cable is lower than that of free–space propagation in the mine [6, 65, 151–158]. In spite of this better range characteristic, leaky feeder cables still require specially placed line amplifiers and repeaters to compensate for signal loss. Each of these devices requires power and battery backups for operation when power fails. In leaky feeder systems, distance between mobile radio unit and the cable can exceed 100ft for typical environmental conditions. Some experimental studies also show that this distance can go up to 300ft in LOS conditions [12, 65, 158].

TABLE IV
HIGHLIGHTS FOR CARRIER CURRENT COMMUNICATION SYSTEMS

Communication System	**Highlights**	(+)**Advantages/**(−)**Disadvantages**
Trolley Carrier Phone	Based on the connection between the receiver and transmitter through the trolley wire and a coupler capacitor.	(+)High mechanical strength (+)A better insulation compared to the telephone systems (+)Easy to maintain (−)Highly dependent on the carrier frequency
Hoist Rope Phone	Based on a switch to be pulled and a special sort of coding for command.	(+)Easy to implement (+)Removes language barrier (+)High mechanical strength (−)Highly dependent on the carrier frequency

Although leaky feeder system has some advantages, it actually suffers from the same problems from which wired systems suffer. Collapses constitute a very big danger for cabling infrastructure. Besides, expanding mines require new installations to expand the coverage as well.

Single cable cut results in a failure in regular wired systems. "Self–healing" architecture is one of the architectures to make leaky feeder systems more robust against a single cut. The architecture is based on the idea of reversing the signal flow at the far end of the damaged cable and using it as two separate systems provided that both ends of the cable are accessible.

2) Fiber Backbone Networks: A fiber backbone network is very similar to a leaky feeder system, but has much greater transmission capability. The network can be realized in a way that it provides wireless communication to the final users [159]. Considering its relatively high transmission capabilities, it may help overcome the congestion problem discussed in Section III-B3.

"Self–healing" architecture described in Section III-D1 was originally used in fiber networks and can easily be adapted to the fiber backbone networks. This feature makes the network more robust against undesired damage to the cable.

Duration of operation is one of the most important disadvantages of such systems. Power consumption of a possible interface between fiber backbone network and the wireless units is one of the restrictions on the realization of such systems in underground environments.

3) Radio Frequency Identification (RFID) Systems: RFID systems are widely used in many commercial applications. Location–based applications are one of the most popular among others [160]. Since location information is very valuable in case of an emergency situation in underground mines, it is very convenient to use RFID systems in such circumstances. Each miner carries low–power personalized radio devices (tags) which are able to communicate with the fixed transceivers. The location information of the miner is extracted by tracking the last instance of communication between fixed transceiver and the tag carried by the miner. RFID system capabilities are only limited to revealing the last location of the user without offering any other communication services. It must be noted that the use of RFID systems is not limited to location–based applications. There are some other applications in which RFID systems are employed such as mine monitoring.

Power requirement of the tags is one of the limitations on the system. In some of the RFID systems, tags are powered by the radio frequency (RF) energy emitted by the fixed transceivers. However, this necessitates the use of high power transceiver and limits the range of communication between a tag and a transceiver.

A brief description of the above mentioned systems along with their advantages and disadvantages is summarized in Table V.

E. Other Systems

Apart from electromagnetic radiation based systems, some other forms of communications are also possible in underground mining. The main difference between these systems and those mentioned in Section III-A and Section III-B is that "other systems" are generally employed when a disaster occurs. As will be discussed subsequently, the information flow in these systems is very limited.

1) Seismic Systems: Seismic systems are based on the fact that the shock vibrations which occur when a stiff material is hit with a heavy object can travel through the Earth. If a trapped miner strikes a roof bolt or rib of the mine with a heavy object, shock vibrations spreading can be utilized to locate the trapped miner. The vibrations can be converted into electrical signals by different seismic transducers, which are called "geophones," and processed (*e.g.*, amplified, filtered, and recorded) in order to determine the location of the miners [161]. However, it must be stated that analysis of the seismic signals requires different expertise [3].

2) Stench Systems: One of the one–way communication systems for underground mines is stench systems, since they can only be used for warning the miners inside underground mine galleries. Stench is introduced into the mine with the intake air and compressed air. Because stench is based on the stimulation of olfactory sense, it requires the use of a clearly distinguishable odor. When an emergency occurs, the stench gas is released and the miners are warned [162].

Although stench gas is used extensively in many mines, it has some drawbacks. First, the diffusion of the stench takes a very long time to reach miners, which can go up to 15 minutes or more. Second, after the stench is released, it still lingers in the mine galleries, which causes the miners to get confused whether the emergency situation is still intact or it is just an after–effect of the previous warning. Third, maybe the most

TABLE V
HIGHLIGHTS FOR HYBRID COMMUNICATION SYSTEMS

Communication System	**Highlights**	(+)**Advantages/**(−)**Disadvantages**
Leaky Feeder System	Designed to "leak" signal, which allows radio transmissions to both leak from the cable and also to enter the cable.	(+)Good coverage when properly installed (+)Self-healing architecture under certain conditions (−)LOS requirement for reliable communication (−)Power requirement for the components (−)Susceptibility to single cable cuts
Fiber Backbone Network	Similar to leaky feeder systems, it is based on the idea of utilizing fiber backbone networks to provide wireless communication to the miners.	(+)Very high transmission capability (+)Self-healing architecture under certain conditions (−)Power requirement for a possible interface between network and the wireless units (−)Susceptibility to single cable cuts
RFID System	Based on the communication between RFID tags and fixed transceivers.	(+)Easy to implement (−)Very limited information (−)Power requirement of the radio devices

dangerous one, is that stench cannot provide miners with any information such as what has happened and what to do. This sort of lack of information sometimes can be more dangerous than no information at all [3].[9]

3) Visual Pager Systems: Stench systems are for olfactory sense, whereas visual pager systems are for the visual sense of the miners. Due to high level environmental noise, many calls are lost inside underground mine galleries. In order to alleviate this problem, visual pager systems are also employed in mines. In this system, strobe lights are located at some strategic locations inside the mine. The lights are controlled by a dispatcher. The dispatcher can set or reset the light when it is necessary. Generally, this system is used along with pager phones [3].

4) Optical Communication Systems: Bright flashing light is widely used in the parts of the mines where acoustic noise level makes other types of communication impossible. Using high-intensity light in rescue operations are thought as a way of penetrating smoke, determining the possible pathways through the blockades and communicate with those trapped under the debris [163].

A brief description of the above mentioned systems along with their advantages and disadvantages is summarized in Table VI.

IV. CONCLUDING REMARKS AND FUTURE RESEARCH DIRECTIONS

Despite the fact that underground mine communication has a rich history, when a disaster occurs, it is seen that some of the fundamental problems have not been resolved yet. This stems from the fact that underground mines have many different types of communications such as ground, in–mine, TTE, and disaster communications. Since each communication type comes with its own problems, it is extremely difficult to come up with a single system that can provide solutions to all of them simultaneously.

Although many different communication systems for underground mines exist, wireless communication draws considerable attention compared to other communication systems. Wireless communication offers solutions to some of the fundamental challenges of all tethered communication systems such as easy maintenance, higher robustness against failures stemming from physical damages, and mobility. Recently, many wireless technologies and standards have been developed and employed in underground mines. This rapid development of technologies and standards leads researchers to face some challenges such as interoperability and seamless connectivity. Software–defined radio (SDR), a type of radio communication system which can operate at any frequency band and handle several types of communication signals, is initially proposed as a solution to the problem mentioned above. SDR introduced limited flexibility to the application specific radios; however, it is clear that SDR does not address all of the concerns in wireless systems as the functionality of mobile units is enhanced. Those concerns added some intelligence to SDR and introduced the term "cognitive radio" (CR). CRs are radio devices which observe their environment and react upon the changes in it to achieve a designated goal in an intelligent way. The most striking feature of CRs is their ability to adapt to the changing environmental conditions. Mine communications require radio devices to work in different scenarios such as in–mine operations, ground and disaster communications. Since each of these scenarios takes place in different environments, CR can provide a good solution to all of them.

Requirement of most radio applications is the maximum user satisfaction. Power levels of both transmitters and receivers are one of the limitations of mine communication systems. For instance, CRs may help reduce the power consumption of the transmitter and receiver by intelligently adjusting their transmission parameters leading to a longer battery life for both sides without causing any user dissatisfaction. In short, CR technology seems to be very promising for mine communication systems since it offers solutions to the adaptation and interoperability issues which are the fundamental limiting factors.

[9]Another highly interesting underground mine warning technique that is based on detection of odor employs canaries, which can be found in [17] along with the historical evolution of underground mining warning systems.

TABLE VI
HIGHLIGHTS FOR OTHER COMMUNICATION SYSTEMS

Communication System	**Highlights**	(+)**Advantages/**(−)**Disadvantages**
Seismic Systems	Based on the fact that the shock vibrations which occur when a stiff material is hit with a heavy object can travel through the Earth.	(+)No requirement for a special communication device, (+)No power requirement, (−)Very difficult to detect the signal, (−)Additional requirement of seismic signal processing expertise.
Stench Systems	Based on the use of a clearly distinguishable odor requiring very good in-mine ventilation system.	(+)Simplicity, (−)Very limited information, (−)Long diffusion times.
Visual Pager Systems	Generally used along with pager phones. Preferable in noisy in-mine environments & used visually warn miners.	(+)Multiple functionality in a single system, (−)Very limited information.
Optical Communication Systems	Based on the use of bright or high-density light for the purpose of communication.	(+)Various benefits in a possible mine accident (penetration through smoke, pathway determination through debris), (−)LOS requirement.

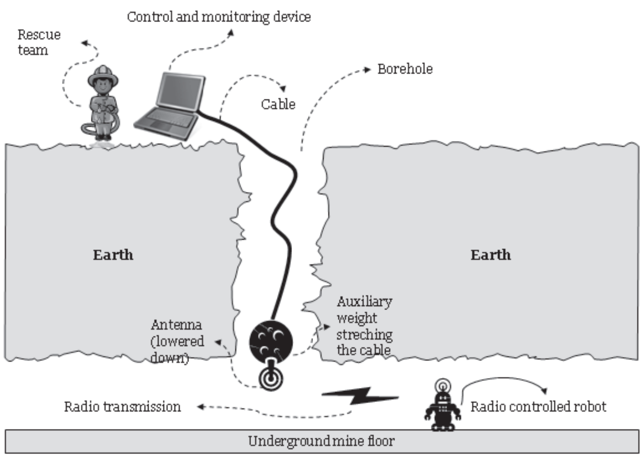

Fig. 6. The borehole experiment performed in [166, 167].

Underground mine communication problems might not be resolved by solely looking from communications point of view. One should consider this problem from the perspective of other disciplines as well. Recently, the use of robots, especially in rescue missions, have gained significant attention. They are able to perform many tasks such as victim locating, confined space searching, environment monitoring, biomedical monitoring delivery, and communication in various scenarios [164, 165]. It is important to note that an experiment incorporating robots into a rescue scenario in underground mines has already been performed [166, 167]. This scenario can be useful in case TTE communication cannot be established due to underground mine accidents. In [166, 167], one of the prominent aspects of the experiment is the use of a borehole to establish communication between surface station and a radio–controlled robot crawling in the underground mine as illustrated in Figure 6. The robot used IEEE 802.11b standard operating on 2.4GHz frequency band; specially designed laptop and control units have been used for controlling the robot. The robot was capable of sending video through wireless connection. The ground team controlled the robot over the surface while mine team was escorting it. The team observed that the robot can move up to 1000ft distance away from the antenna lowered down through the borehole and still be controlled and send video over the air.

As a final remark, it is worth mentioning that some of the communications applications for underground mines are implemented for other scenarios such as disasters, since there are some similarities between them. For instance, seismic methods, which are discussed in Section III-E1, are frequently used in search and rescue operations to detect those entrapped under a debris after earthquakes. Wireless networks, which are outlined in Section III-B3, are also used in continuous reporting of the structural changes of an environment. For instance, there are commercial applications in which a digital wireless camera is deployed to take images of the structure (*e.g.*, shape of the room, ceiling or roof) of an environment. These images are sent to a sink via IEEE 802.11b technology for processing and recording purposes in order to trigger an emergency plan. It is believed that these similarities between underground mines and disaster scenarios will lead to more interesting communication applications in future.

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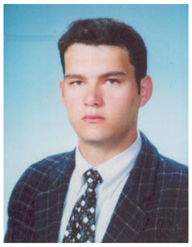

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