Propagation Features in Underground Mining Visible Light Communication Link

Pablo Palacios Játiva, Cesar Azurdia-Meza, Fabian Seguel, Ismael Soto, and Carlos Gutiérrez

***Abstract*— Underground mining is an industry that supplies great income for several countries worldwide. Therefore, it is necessary to provide a proper communications infrastructure to this industry. Nevertheless, as is well known, underground mines are very hostile environments, making it difficult to implement current radio frequency (RF) communication technologies. Therefore, a practical and viable solution is given by systems based on visible light communication (VLC). This emerging technology can provide robust communication and continuous lighting in harsh environments. However, an exhaustive study of the use of VLC and its technical parameters in underground mines has not been carried out in detail. In this paper, we propose an introductory study of the main physical features present in an underground mining VLC environment. We also briefly discuss certain particular physical factors that affect underground mines, such as shadowing and scattering. This analysis generates a benchmark to develop a precise analytical VLC channel model of underground mining as future work.**

***Keywords*— Channel model, scattering, shadowing, underground communication, visible light communication.**

I. Introduction

For many years, underground mining has been an industry that produces large monetary income for many countries worldwide. Despite this advantage, the mining environment is one of the most dangerous to work in, due to the insecurity of the tunnels where the work is carried out, as well as the presence of many external agents that are generated in the excavations, such as dust, toxic components, among others [1]. Therefore, to solve emergencies such as landslides, fires or intoxication of workers, a stable communication system is required [2]. The system, in addition to being reliable and robust, must be designed to localize and monitor infrastructure and within the entire environment, as well as real-time information of the miners [3]. Such a communication system would guarantee the safety of workers, and maximize the productivity within the underground mines [4]. All these features make the design of communication environments for underground mining environments a difficult issue.

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On the other hand, the physical characteristics of underground mines is an influential factor in the design and implementation of proper communication systems for these environments. The geometric design of the environment, the heat, the shape of the walls and roof, as well as the interference and noise produced by the machinery used in mining, produce a difficult environment. Due to these factors, the current communication systems, wired or wireless, based on radio frequency, are not the best option to meet the necessary requirements in underground mines. The aforementioned problems are presented as opportunities for the research of complementary communications systems that adapt to these factors, both physical and technical. Therefore, one of the technologies that aims to solve the issues within these environments, and also provide continuous lighting, is visible light communication (VLC) [5].

Compared to traditional RF-based technologies, VLC systems have several benefits, among which the most important are: the use of spectrum without a license, reasonable prices of the elements of the VLC system, immunity to electromagnetic interference, among others [6]. These characteristics make VLC a strong technology and candidate to guarantee secure, robust, and reliable communication in underground mining environments.

A typical VLC link consists of two basic elements: the first component is a light source that is used on the transmitter side to send digital information to the receiver. These are usually light emitting diodes (LEDs), which are cold light sources that are used to form LED lamps [7]. These lamps could be installed on the walls or ceiling of underground mines. Then, on the receiver side, an electronic element transforms and demodulates the optical signal into an electrical signal to recover the transmitted data. These components are generally photo-diodes (PDs) [7], which could be installed on the helmet of the mining worker. Both LEDs and PDs create a VLC link through an optical channel between the miner and the mining infrastructure. There are several methods of transmitting information through the use of optical sources [8]. Among them, intensity modulation with direct detection (IM/DD) appears as the de facto method used in optical wireless communications due to its reduced cost and complexity.

In terms of system modeling or communication channel characterization, underground mining VLC scenarios are more challenging to characterize compared to a typical indoor VLC scenario [9]. Being an underground mine composed of small irregular tunnels, various factors that do not appear in indoor VLC environments must be considered, such as non-flat walls, angular position of the LEDs and PDs, dust particles [10] and shadowing. Since modeling the channel in all communication systems is an important stage for its correct design and operation, there is growing research associated with the characterization of the underground mining VLC channel [9], [10], [11]. However, and to the authors' best knowledge, none of these studies have presented a precise VLC mining channel model that characterizes all the details and factors that affect these scenarios.

In order to properly analyze all the factors and features that affect an underground mine VLC system, in this article, we present the theoretical bases of the physical and environmental conditions that must be considered in these scenarios and that affect the communication link. Therefore, and to the authors' best knowledge, this paper performs an initial analysis of the physical components that make part of the VLC underground mine channel model and its subsequent impact on the communication link.

The organization of this paper is presented as follows: the VLC system configuration in underground mines is explained in Section II. Then, in Section III, we briefly introduce the features of the light propagation model of a typical VLC underground mine communication link. Finally, conclusions are given in Section IV.

II. Visible Light Communication System Configuration

Generally, underground mines are made up of narrow tunnels [9], [11]. Each tunnel can represent a different section with different physical conditions. Compared to indoor VLC environments, mining VLC scenarios have different characteristics, among which are mentioned: The LED luminaries installed inside the tunnel can be placed both on the ceiling and on the walls. When luminaries are placed on the tunnel walls, the LEDs may be left with a random inclination that affects the VLC link. The same effect occurs with the PDs in the receivers, since these will be installed in the helmets of the mining workers. Another important factor is the effect of shadowing that can be caused by the working machinery inside the mines. Finally, the effect of the work environment, presented as dust particles suspended in the environment, can cause scattering of the light signal before reaching the optical receiver [9].

In order to model a generic VLC system inside an underground mine tunnel, the three main components that must be analysed are the following: light sources (transmitters), light propagation model, and the properties of the detector (receivers). These elements are described in the following subsections.

A. Light Sources

The most commonly used lighting devices in indoor optical wireless communications are LEDs. To keep the communication in underground mines as optimal as possible, the light intensity in the mining scenarios should be uniformly distributed. Therefore, multiple optical transmitters T_xs (LED lamps) must be installed throughout the entire tunnel structure within the mine.

Generally, the LED angular distribution of the radiation intensity pattern is modelled using a generalized Lambertian radiant intensity. Assuming that each T_x has the same generalized Lambertian radiation pattern [6], [7], the angular distribution $S(\phi)$ of the radiation intensity of a LED light emitter is given by [6], [7]

$$S(\phi) = \begin{cases} P_t \frac{m+1}{2\pi} \cos^m(\phi) & \text{if } \phi \in [-\frac{\pi}{2}, \frac{\pi}{2}] \\ 0 & \text{otherwise} \end{cases}, \quad (1)$$

where ϕ is the radiation angle, P_t is the LED power, and m is the Lambertian mode number that is defined as follows [6], [7]

$$m = \frac{-ln(2)}{ln[cos(\Phi_{1/2})]}. \quad (2)$$

Where $\Phi_{1/2}$ is the LED semi-angle at half power and normally the maximum intensity will be given when $\Phi_{1/2}$=0.

B. Light Detectors

At the receiver side of the VLC link, an element capable to transform the modulated light intensity into an electrical signal is used, i.e., a PD. The PD, which is normally composed of a non-imaging concentrator (lens), collects the incident power produced by the light intensity of the T_x. The PD optical gain, $g(\theta_0)$, whis is based on a non-imaging concentrator is given as follows [6], [7]

$$g(\theta_0) = \begin{cases} \frac{\eta^2}{sin^2(\theta)}, & \text{if } 0 \leq \theta \leq \Theta \\ 0 & \text{if } \theta \geq \Theta \end{cases}, \quad (3)$$

where η is the refractive index of the concentrator, θ is the incidence angle, and Θ is the FOV of the light detector. Along with the PD lens, an optical transmission gain band-pass filter $T_s(\theta)$ is added. Typically, this parameter is taken as $T_s(\theta)$=1. The geometric features of the light sources and light detectors are shown in Fig. 1 .

In this section, light sources and light detectors for the VLC link have been presented along with their respective mathematical models. As the most important point of our research, in the following section, we will analyze the main physical phenomena that affect the light propagation model, which in the future will allow to design an analytical model for the underground mining VLC channel.

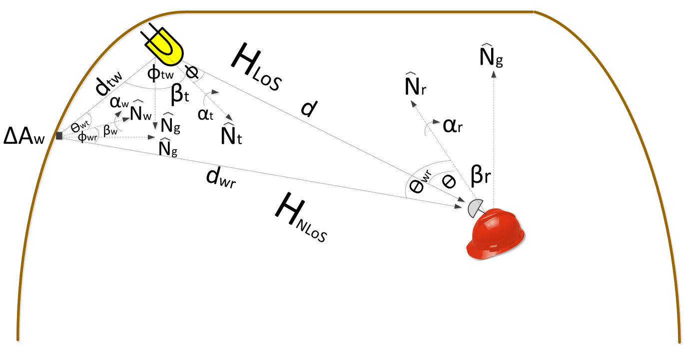

Fig. 1. Geometric features of the VLC underground mine link: light source and light detector.

III. Light Propagation Model

In this section, we will analyze the principal physical phenomena that affect underground mining VLC links. In general, the received power of the line-of-sight (LOS) signal component from each LED light is expressed as [7]

$$P_r = P_t R_{PD}(H_{LoS} + H_{NLoS}) + N, \tag{4}$$

where P_r is the power received by the PD, R_{PD} is the PD responsivity, $HLoS$ is the channel gain component of LoS link, and H_{NLoS} is the non-line of sight (non-LoS) component. The additive noise component N is modeled as the sum of thermal noise and shot noise.

It is possible to observe the H_{LoS} component of the VLC link in Fig. 1. As noted, the LoS link depends on the light source and the light detector, as previously discussed in section II. Therefore, the H_{LoS} component can be represented as follows [6], [7]

$$H_{LoS} = \frac{A_{eff}(m+1)}{2\pi d^2}\cos^m(\phi)T_s(\theta)g(\theta)\cos(\theta)\delta(t-\frac{d}{c}), \tag{5}$$

where A_{eff} is referred to the effective area of the PD, which is the active physical area of the PD that effectively collects the incident radiation and its value is less than the value of the FOV. Furthermore, d is the distance between T_x and R_x, $T_s(\theta)$ is the optical filter gain, $g(\theta)$ is the optical concentrator gain, c is the speed of the light in free space, and $\delta(\cdot)$ is the Dirac's function, which represents the signal propagation delay.

The H_{NLoS} component is caused by the reflection of the light, as can seen in Fig. 1. This reflection generally occurs when light hits the surface of the mine walls. Usually, reflection of light in a surface can be one of two types, i.e., specular or diffuse. In a mine, the walls have many irregularities, so the predominant type of reflection is diffuse reflection. This phenomenon occurs because the light that is reflected from the wall surface, it scatters at many angles instead of just one angle. A common model for diffuse reflection is Lambertian reflectance, in which the light is reflected with equal radiance in all directions.

The following recursive method is used to evaluate diffuse reflections within an indoor environment, which can be extrapolated to the underground mining environment. First, the wall surfaces are divided into Q small reflector elements with an area A_w. Then the H_{NLoS} component is calculated using a two-step method as follows: i) each element on the surface with the area of A_w is considered a receiver, and ii) each element is then considered as a point lambertian source that re-emits scaled light by reflectivity ρ_w. Therefore, given a T_x and a R_x in a mine environment, the H_{NLoS} component can be written as an infinite sum of reflections as follows [6], [7]

$$H_{NLoS} = \frac{A_{eff}(m+1)}{2\pi}\sum_{q=1}^{Q}\frac{\Delta A_w \rho_m}{2\pi d_{tw}^2 d_{wr}^2} cos^m(\phi_{tw}) cos(\theta_{tw}) \times cos(\phi_{wr}) cos(\theta_{wr}) T_s(\theta_{wr}) g(\theta_{wr}) \delta\left(t - \frac{d_{tw}+d_{wr}}{c}\right), \tag{6}$$

where ΔA_w represents the area of the considered reflecting element, Q is the total number of reflective elements considered in the method, ρ_m is the reflecting coefficient of the surface area ΔA_w, d_{tw} is the distance between T_x and the reflective element, and d_{wr} is the distance between the reflective element and R_x. All of these characteristics are shown in Fig. 1. Given the special conditions of underground mines, we must consider several factors that do not appear in the typical indoor VLC scenarios, which we will describe below.

A. Tilted and Rotated LEDs and PDs

As mentioned in section II, LED luminaries can be installed on the ceiling or on the walls of mine tunnels. To facilitate maintenance and replacement work, the placement of LEDs on the walls is preferred. When placing the luminaries on the tunnel walls, the normal vector of the T_x, $\hat{N}_t$ will be affected since it will not point vertically downwards. Thus, the T_x will have random angles of rotation and tilt.

The tilt and rotation angles on the transmitter side will affect the radiation angle ϕ. The new radiation angle now depends on the azimuth rotation of the LED, α_t, and the horizontal tilt of the LED, β_t. The position of the LED directly affects the H_{LoS}, specifically in its factor $\cos^m(\phi)$. On the other hand, when placing the R_x in the mining helmets, the normal vector of the PDs, $\hat{N}_r$, is not oriented vertically upwards. Hence, T_x and R_x will have a random azimuth rotation and horizontal tilt, represented by angles α_r and β_r, respectively. When the tilting and rotation angles are considered, incidence angle θ is affected. This PD positioning directly affects the H_{LoS}, specifically in its factor $\cos(\theta)$. The graphical representation of the inclined transmitters and receivers, with their respective azimuth and inclination angles, can be seen in Fig. 1.

B. Non-regular Tunnel Walls

Usually, in traditional indoor environments, i.e., offices, hospitals, etc., walls are consider perpendicular to the ceiling. Nevertheless, this assumptions is not valid for underground mines since most of then are U-shaped. Moreover, in these traditional environments, plane walls are depicted. However, walls in underground mines are not plane. Due to this, each surface area of reflection A_w has a different normal vector, $\hat{N}_w$. As previously indicated, reflections are considered as Lambertian sources. The radiation intensity of these "sources" depends on the $\hat{N}_w$. Due to this, reflections inside underground mines are different from reflections studied in traditional environments and, as a consequence, the channel capacity will differ.

The mathematical analysis for reflections in non-plane surfaces is similar to the one done for tilted/rotated transmitters and receivers. The rotated and tilted $\hat{N}_w$ will affect the incidence angle from LED to surface, θ_{tw}, and the irradiance angle from the surface to the PD, ϕ_{wr}. Hence, $\hat{N}_w$ will depend directly on α_w and β_w, which are the rotation and tilted angles of the non-plane and non-parallel mining wall, respectively. Non-regular tunnel walls in underground mining environments directly affects the H_{NLoS}, specifically in its factors $\cos(\theta_{tw})$ and $\cos(\phi_{wr})$.

C. Shadowing

Another particular physical phenomenon that affects the underground mining VLC communication link that needs to be modeled is shadowing. Due to the mining infrastructure, in which there are miners walking along the tunnels, as well as large machinery and vehicles moving along the tunnels, the shadowing effect must be considered. However, for our study we are only considering the helmet-mounted PD of the miners walking along the tunnels. Because of this, the effect of shadowing produced by miners walking along the tunnels is neglected. In general, by using the underground mining VLC configuration previously described, we should only take into account the blockage caused by vehicles moving along the tunnels and machinery deployed within the infrastructure.

The optical diffraction phenomenon is used in this type of systems to overcome the shadowing effect on the VLC link. According to the literature, shadowing for VLC has been modeled by some authors as a Binomial Gaussian Distribution [9], [12] and a Poisson process [13]. However, an in-depth analysis must be carried out to decide which statistical model describes and emulates properly the phenomenon.

D. Signal Scattering

Generally, scattering produced by the suspended dust is not considered in traditional indoor environments since it is not applicable for traditional indoor VLC systems; such as in offices, hospitals or non-hazardous industries. As for underground mines, the dust is produced by crushing, grinding, blasting and drilling the rock within the mine and should be considered. The effects of dust particles on the VLC link have been analyzed primarily on free-space optical (FSO) links [7], [14]. Therefore, the scattering produced by suspension of the molecules and particles (also known as aerosols), is often considered the most important parameter to model.

Aerosols can have a wide range of shapes, sizes, and nature. In addition, they can vary in distribution, concentration, and constituents. Due to this, its interaction with the light beam can have great dynamics. In general, the size of an aerosol particle is comparable to the wavelength of interest in optical communications. Thus, Mie scattering theory is used to describe the effect of aerosol particles with radius between 0.01-1 μm [7], [14].

Hence, and according to these criteria, it is necessary to introduce the scattering factor to the VLC channel model in underground mines. However, a more detailed analysis is necessary in order to find the appropriate mathematical model for the particular physical phenomenon.

IV. Conclusion

In this paper, a theoretical analysis of the principal physical factors and features that affect VLC systems in underground mines was provided. The mine channel model for light propagation is not similar to the traditional indoor model environment, due to the special characteristics found in this scenario. In particular, five factors/features make this channel model unique. These features are: randomly oriented light sources (LEDs), randomly oriented light detectors (PDs), non-flat and non-regular walls, the presence of vehicles and machinery that can produce shadowing, and the presence of dust particles that can produce scattering. The effect of the mentioned phenomena must be evaluated in a mathematical channel model, which will be presented as future work.

Acknowledgment

This work was partially funded by Project STIC-AMSUD 19-STIC-08, Project Ayuda de Viaje VID Universidad de Chile AYV 014/01/19, ANID PFCHA/Beca de Doctorado Nacional/2019 21190489, and SENESCYT "Convocatoria abierta 2014-primera fase, Acta CIBAE-023-2014", and Grupo de Investigación en Inteligencia Artificial y Tecnologías de la Información (IA&TI).

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