A New VLC Channel Model for Underground Mining Environments

(Invited Paper)

Jia Wang[1], Ahmed Al-Kinani[2], Wensheng Zhang[1], and Cheng-Xiang Wang[1,2]

[1]Shandong Provincial Key Lab of Wireless Communication Technologies, Shandong University, Jinan, Shandong, 250100, China.

[2]Institute of Sensors, Signals and Systems, School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK.

Email: wangjia082111@163.com, {aa1304, cheng-xiang.wang}@hw.ac.uk, zhangwsh@sdu.edu.cn

***Abstract*—Due to the frequent dramatic disasters of underground mining collapses, the establishment of a reliable communication system in the underground mining environment is of vital importance. Instead of using the conventional wired and radio communication systems, researchers have considered the use of visible light communication (VLC) for underground mining communications (UMCs). In this paper, we extend the recursive method to model VLC propagation channel and focus on two different parts of underground mining communication, namely the working face and mining roadway. Both the required illuminance and VLC channel characteristics are thoroughly investigated for miner-to-miner (M2M) and infrastructure-to-miner (I2M) communication scenarios. It is shown that the illumination standard requirements can be fulfilled in the two parts and the mining roadway is brighter than the working face environment. Furthermore, VLC channel characteristics, such as the channel gain, mean excess delay, root mean square (RMS) delay spread, are thoroughly investigated. It is found that the proposed channel model is sufficiently accurate when taking the line-of-sight (LoS) and the first order reflections into consideration.**

***Keywords* – Underground mining communications, visible light communications, channel modeling, channel gain, illuminance.**

I. Introduction

Underground mining industry is vital to today's global economy. However, it is considered as one of the most hazardous environments since it is composed of tunnels exhibiting risky properties due to presence of dangerous gases, substances, and corrosive water along with dust [1]. One of the key underground mining industry challenges is to keep information flow maintained during mining operations. Information such as measuring the atmosphere of the mine, detecting hazardous gases and/or smoke, monitoring mining machinery, and, most important of all is monitoring miners and locating them when an accident occurs. Nowadays, the most common communication systems of underground mine communication are either wired, or wireless radio communication systems. The information in the first systems, are fed into the existing wiring infrastructures. While, in the second systems, low-frequency waves are utilized to penetrate dirt and rock towards the mining cavity. The later system known as through-the-earth (TTE) communication system. As it is well known that the structure of underground mining is very complicated, radio signals can be extremely faded in underground mine galleries. Furthermore, wired communication is very susceptible to be damaged. These challenges inspired the researchers to think beyond the use of the classical aforementioned communication systems. Since underground mining experiences of poor lighting conditions, the idea of using VLC technology has been triggered, since it provides data transmission and lighting simultaneously. It is worth mentioning that some researchers have introduced infrared, Bluetooth, ultra-wideband (UWB), and ZigBee to UMCs [2]. However, VLC seems in some aspects superior to the later technologies for short range communications, i.e., 1–10 m [3]. VLC is a newly emerging technology, which integrates communication and lighting purposes, and has become a very promising research topic in the areas of optical wireless communications (OWCs). VLC technology has many unique features, such as unlicensed spectrum, low-cost, green, support of high data rate, and resistance to electromagnetic interferences. VLCs are expected to be an important part of the next generation wireless communications in the underground mines.

In terms of UMCs, VLC in underground mining can utilize the off-the-shelf light-emitting diodes (LEDs) that can be fixed on the ceiling of the underground mining or miner's helmet to establish a communication link between either the miners with infrastructures or with other miners, respectively. LEDs are environmental friendly (without Mercury or any other hazardous substances), of long lifetime, dimmable, and of low cost. In order to improve the existing underground mining wireless communication systems, especially for coal mine environment, VLC can be a new potential candidate in UMCs.

There is a growing literature on VLC about advanced physical layer techniques and networking. The channel modeling is an important step for efficient, reliable, and robust VLC system design. Many studies have been done to characterize optical wireless channels. The recursive method was first proposed by Barry et al. [4], [5] in the infrared spectrum. Afterward, Barry's model was extended to visible light (VL) spectrum, e.g., [6], [7]. A deterministic ray tracing approach, based on Zemax®, was introduced in [8], [9] to investigate VLC indoor channels. The authors in [3], [10] proposed regular-shape geometry-based channel model for VLC.

However, an appropriate channel model for VLC systems for underground mining is currently missing in the literature.

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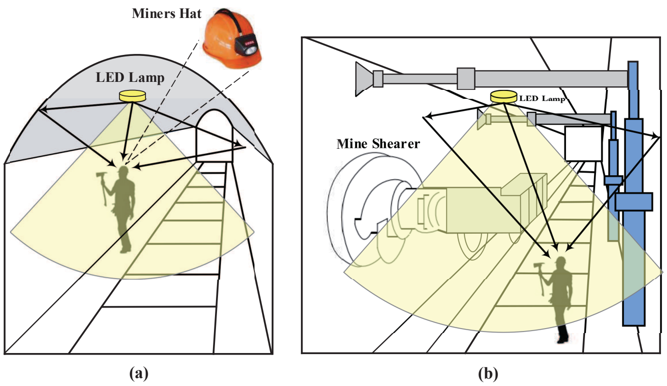

Fig. 1. System model, (a) Horseshoe mining roadway, (b) Mine working face.

This is due to that the employing VLC technology in underground mining is still in very early stage. Therefore, a massive research required before adoption in real-life application.

The rest of the paper is organized as follows. Section II introduces VLC in underground mining. Section III describes LED illuminance characteristics in underground mining. Results and discussions are presented in Section IV. Conclusions are finally drawn in Section V.

II. VLC In Underground Mining

In general, underground mines consist primarily of mining roadway and coal mine working face. In order to simplify the calculations, the horseshoe shape has been considered for mining roadway and a rectangle chamber for working face. The system model, which is describe there two parts, is presented Fig. 1.

1) Mining roadway: Mining roadway is a general term of shaft, tunnel, and chamber. The mining roadway is usually used to transport coal by miners. In addition, its shape can be divided into square, horseshoe-shaped, rectangular and trapezoid. In this paper, we use the horseshoe shaped as a reference model for mining roadway. The roadway is narrow (compared with cubic mining roadway) with short-distance visibility. Furthermore, this type is not identical, due to irregularities in the shapes of walls and ceiling.

2) Coal mine working face: Coal mine working face is the space where miners use large mechanized equipment to get coal from underground. In the procession of coal extraction, the electromagnetic radiation is generated and some radio waves are absorbed by water vapour and flammable gas in working face. Therefore, radio frequency (RF) wireless communication is seriously interfered be electromagnetic waves in underground mining. The shape of coal mine working face is generally rectangular.

A. Communication Scenarios

The current communication system in underground mines consists of wireless communication technology that utilizes ultra-low frequency band ($300 - 3000$ Hz) and the power line carrier (PLC) communication technology. Therefore, VLC can utilize the integrated PLC equipment to access industrial Ethernet for realizing communication between the ground and the underground mining. Hence, a VLC link can be built between a light base station and a miner. The LED lamp can be fixed on the top of the horseshoe mining roadway, mine working face and the helmets of miners which are considered as the base stations to transmit the information in the form of light. The optical receiver (Rx) can be fixed on the miners' helmets to receive the information.

In this study, two communication scenarios that are applicable for UMCs are proposed, namely, M2M and I2M communication scenarios in next subsection.

1) Miner-to-miner (M2M) communication: The miner can wear a LED lamp as a mobile end user in the mine. The human eye perceives only the average intensity when light changes fast enough. Therefore, LEDs can transmit data without a noticeable effect on the lighting output or the human eyes. Miners can communicate with each other by the LED lamp that is fixed on their mine helmets. The miners use the light to transmit information about the mine environment and their location to other miners. Therefore, VLC channel modeling for the M2M scenario can be characterized by considering only the line-of-sight (LoS) propagation within the underground mining environment.

2) Infrastructure-to-miner (I2M) communication: In this communication scenario, the LED lamp that is fixed on the mine wall is regarded as the light source and information source to provide both illumination and communication. It acts as an optical wireless base station. LEDs can transmit data by changing switches fast enough. So, human eyes cannot notice it. The miners can receive the information by the mine helmets.

Unlike M2M, the channel model of I2M can be characterized by considering both LoS and non-line-of-sight (NLoS) propagation within the mine environment.

B. VLC System Model

1) Optical Transmitter: VLCs use the intensity modulation (IM) scheme. This is because of the phase or frequency modulation of the incoherent waves is difficult. On the other hand, the direct detection (DD) is considered as the most practical down-conversion technique [3]. The LED is used as an optical source (Tx). The generalized Lambertian intensity model is usually regarded as the distribution of the LEDs and m is the Lambertian mode number which is interrelated with the semi-angle $\phi_{\frac{1}{2}}$ at half power. The Lambertian mode number is written as [11]

$$m = \frac{-\ln 2}{\ln\left(\cos \phi_{\frac{1}{2}}\right)}. \tag{1}$$

The radiation intensity is the maximum value when semi-angle equals zero. The angular distribution is given as [11]

$$S(\phi) = \begin{cases} \frac{(m+1)}{2\pi} \cos^{m}(\phi) & \text{if } \phi \,\epsilon \left[\frac{-\pi}{2}, \frac{\pi}{2}\right] \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

Here, ϕ is the incident angle. As the value of m increases, the beams of LEDs will be more directional .

2) Optical Receiver: At the receiving side, VLCs utilize a photodetector (PD) Rx of area A_r collecting the radiation incident power. The PDs are normally attached with a non-imaging concentrator (lens) which is an effective solution to improve the collection area and an optical band-pass filter to decrease ambient noise. The optical gain $g(\theta)$ of non-imaging concentrator is expressed as [11]

$$g(\theta) = \begin{cases} \frac{n^2}{\sin^2(\theta)} & \text{if } 0 \leqslant \theta \leqslant FoV \\ 0 & \text{if } \theta > FoV. \end{cases} \quad (3)$$

Here, n denotes refractive index of the concentrator and θ is the received angle. In addition to the above lens, an optical band-pass filter of $T_s(\theta)$ transmission gain, is commonly attached to the PD. The equivalent baseband model of an IM/DD VLC link can be written as

$$y(t) = R \cdot x(t) \otimes h(t) + n(t) \quad (4)$$

where the optical transmitted signal is $x(t)$, the received signal is $y(t)$, $n(t)$ is assumed to be real-valued additive white Gaussian noise which is signal-independent shot noise and thermal noise, and R denotes the photodetector responsivity.

3) Optical Channel: In the case of M2M scenario, the Tx and Rx are located on the helmets of the miners. In this case, only LoS will be considered. Because the received energy is mainly obtained from the direct radiation. We assume that $\theta_0 < 90°$, $\theta_0 < FoV$, and $d_0 >> \sqrt{A_r}$. Therefore, the impulse response of the LoS component can be expressed as [11]

$$\begin{aligned} h_{\text{LoS}}(t) = & \frac{A_r(m+1)}{2\pi {d_0}^2} \cos^m(\phi_0) T_s(\theta_0) g(\theta_0) \\ & \cos(\theta_0) \delta\left(t - \frac{d_0}{c}\right). \end{aligned} \quad (5)$$

Here, the LoS transmit angle and the receive angle are ϕ_0 and θ_0, respectively, d_0 is the distance between the LED and the Rx, c is the speed of the light in free space, $\delta\left(t - \frac{d_0}{c}\right)$ is the Dirac function that represents the signal propagation delay. The channel DC gain $H(0)$ for M2M communication is given by [12]

$$H(0) = \int h_{\text{LoS}}(t)\, dt. \quad (6)$$

Let us assume that the receiving plane is an extension of the location of mine Rx and the transmitted optical power is P_t. The received optical power P_r for M2M communication can be written as [11]

$$P_r = P_t \cdot H(0). \quad (7)$$

In the case of I2M scenario, the Tx is located on the top of horseshoe roadway and the Rx is installed at the helmet of miner which can move anywhere in the roadway. Not only the LoS component but also the diffuse part will contribute to the received energy for the I2M communication scenario. In other words, the reflected waves are composed of single reflection and multipath components with many reflections.

In order to model the reflection from the underground mining environment, each differential reflecting element with area A_{ref} and reflectivity ρ acts the following rules. First, it considered as a receiver with area A_{ref}. Second, as an optical source with total power $P = \rho\, dP$.

Correspondingly, the impulse response of the Rx with the k-th order reflections can be expressed as

$$\begin{aligned} h^k_{\text{NLoS}}(t) = \int & \frac{cos^m(\phi_1) \prod_2^{k+1} \cos(\phi_i) \prod_1^{k+1} \cos(\theta_j)}{2\pi^{k+1} \prod_1^{k+1} {d_\varepsilon}^2} \\ & \times {A_{ref}}^k A_r (m+1) \rho^k T_s(\theta_{k+1}) g(\theta_{k+1}) \\ & \times \text{rect}\left(\frac{\theta_{k+1}}{FOV}\right) \delta\left(t - \frac{d_1 + d_2}{c}\right) dA_{ref}. \end{aligned} \quad (8)$$

Here, $\text{rect}\left(\frac{\theta_{k+1}}{FoV}\right)$ is the rectangular function that represents whether the signal can be accepted. The angles of incidence and received can be written as ϕ_1, ϕ_i and θ_1, θ_j, respectively. The received power is inversely proportional to the square of the distance d_ε, which is the distance between source element and destination. To simplify the calculation, we only consider LoS and first reflection in the I2M communication scenario. The impulse response of single reflection of I2M communication can be expressed as

$$\begin{aligned} h^1_{\text{NLoS}}(t) = \int & \frac{\cos^m \phi_1 \cos\phi_2 \cos\theta_1 \cos\theta_2}{2\pi {d_1}^2 {d_2}^2} \\ & \times\ A_{ref} A_r (m+1) \rho\, T_s(\theta_2) g(\theta_2) \\ & \times\ \text{rect}\left(\frac{\theta_2}{FoV}\right) \delta\left(t - \frac{d_1 + d_2}{c}\right) dA_{ref}. \end{aligned} \quad (9)$$

III. Underground Mine Illuminance

The idea of illuminance in coal mine is meaningful for communication and security. LEDs cannot only provide illuminance in mine without the natural light, but also be convenient for communication between miners. According to [13], the light source can be recognized as a point source when the distance between the light source and the Rx is greater than 5 times the size of the light source. Therefore, the LED arrays will be regarded as a LED light source. The mathematical illumination model of the Tx will be given in the next subsection. It is worth to mention that the illumination has been calculated for only direct light.

A. LED Illuminance

The LED lamp is fixed on the top of the mining roadway and working face. The distance between LED lamp and Rx is d, and the centre luminous intensity of the LED is I_0. The radiation spectrum distribution is $S(\lambda)$ and the number of LED is N. We assume the Lambertion modes of all LED lamps are the same. The luminous flux Q is the optical power which human eyes obtain and is defined as [14]

$$Q = N \int_{380\text{nm}}^{720\text{nm}} 683 \frac{\text{lumen}}{Watt} S(\lambda) v(\lambda)\, d\lambda. \quad (10)$$

Here, $v(\lambda)$ is the human eye sensitivity function. The illuminance $I(\phi)$ on receiving surface is given as [11]

TABLE I
Model Parameters Used in Simulations.

System Model Parameters	
Mining Roadway	
Dimensions	$2 \text{ m} \times 5 \text{ m} \times 3.7 \text{ m}$
Radius	1 m
Coordinates of the Rx	(0,0,-1)
Working Face	
Dimensions	$2 \text{ m} \times 5 \text{ m} \times 4.7 \text{ m}$
Coordinates of the Rx	(0,0,-2)
Other Parameters	
The height of miner's helmet	1.7 m
Number of LEDs (N)	400
Semi-angle at half power	70°
Concentrator refractive index (n)	1.5
Coordinates of the Tx	(0,0,1)
Center luminous intensity (cd)	10
Reflection coefficient (ρ)	0.8
Photodiode Area (A_r)	1 cm^2
Field of view (FoV)	60°
Band-pass filter of transmission (T_s)	1

$$I(\phi) = \frac{\partial Q}{\partial A_r} = \frac{I(\phi)}{d^2}. \tag{11}$$

LED obeys the Lambert radiation distribution and the luminous intensity in angle ϕ is given as [15]

$$I(\phi) = \sum_{j=1}^{N} j I_o \cos^m(\phi). \tag{12}$$

Here, I_0 is centre luminous intensity of LEDs.

B. Mine Lighting Standard Requirements

The lighting requirements are associated with the illumination of LED lamp and the numbers of the LED lamps. In consideration of lighting requirements in a VLC system, the distribution of illuminance in underground mining is meaningful. The number of the LEDs must be taken into account in underground mining because the illumination of LEDs largely determines the distribution of light. According to the requirements of underground mining lighting standards in [16], the minimum lighting power density of 0.158 W/m^2 and the minimum illuminance of 107.65 lux need to be maintained. These criteria considered the minimum requirements to deliver lighting and communications. To avoid blind spots and make the light distribution of the receiving plane as uniform as possible, it is important to design the number of LED lamps reasonably in underground mining environment.

IV. Results and Discussions

In performing simulations using the software Matlab, the system model parameters are summarized in Table I.

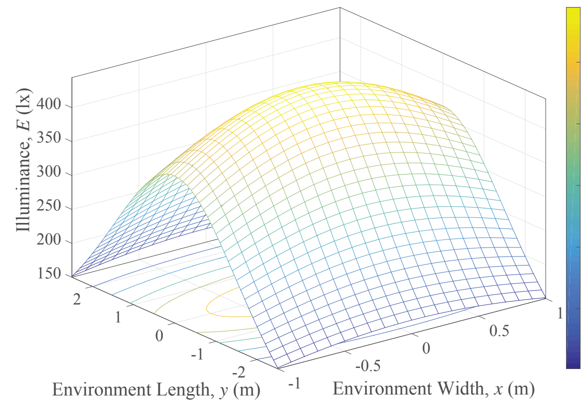

Fig. 2. Illuminance of the mining roadway.

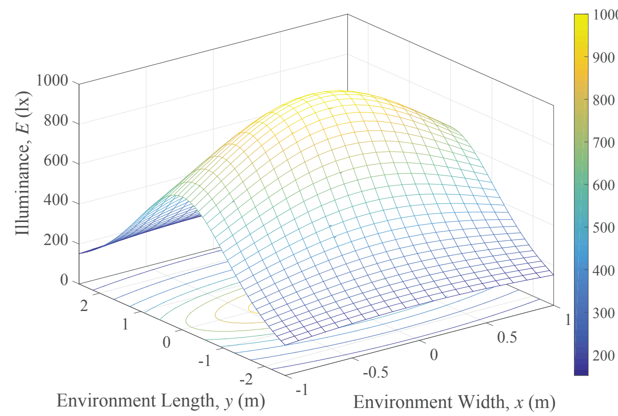

Fig. 3. Illuminance of the working face.

A. Environment Illuminance

Since VLC technology delivers illumination and communication simultaneously, lighting function must be guaranteed as well. Firstly, we considered the illumination requirements of mining roadway. According to the lighting standard in [16], a 107.65 lux span is suitable to illuminate such environment. The illumination is assessed at 1.7 m (men's average height) above the floor. Simulation results illustrated that the assumed number of LEDs are able to illuminate mining roadway with brightness of (151-1000) lux as shown in Fig. 2.

Secondly, in term of working face environment, the illuminance distribution at the receiving plane (1.7 m above the floor) is illustrated in Fig. 3. By using the same LED lamp which is used in mining roadway, the obtained illumination is (151-444) lux. It can be noticed that the mining roadway is brighter than working face environment. Because the ceiling height of the working face is higher. Here, only direct illumination is considered in I2M communication scenario.

B. VLC Channel Characteristics

1) Channel Impulse Response (CIR): In this subsection, the CIR of VLC channel is computed in both mining roadway and

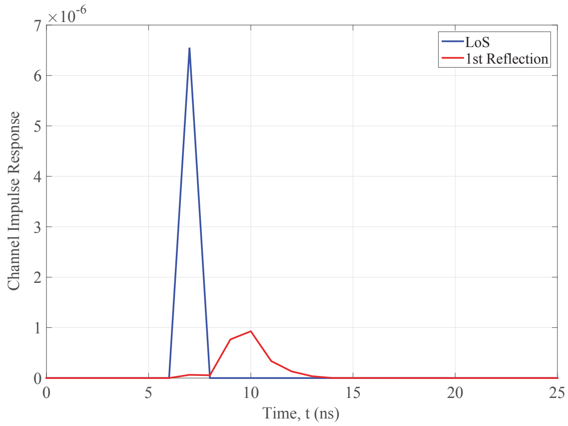

Fig. 4. Channel impulse response in mining roadway.

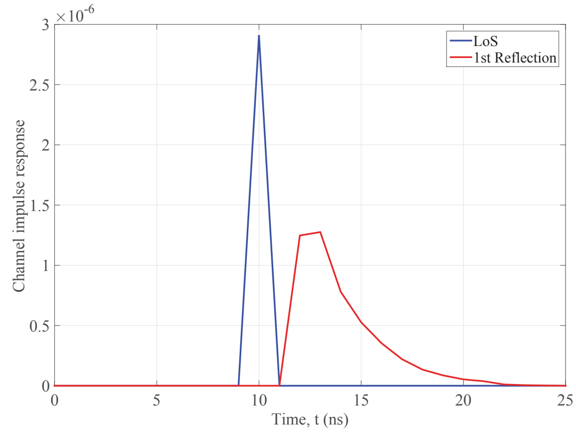

Fig. 5. Channel impulse response in working face.

working face environments. In order to model the horseshoe roadway, we have divided it into two parts. The first part is a semi-cylindrical, which represents the ceiling of the horseshoe roadway. The second part has represented by only two walls. The ends of both parts have been considered as open ends since we have considered a specific segment along the roadway. On the other hand, in terms of the working face case, we model this part as a rectangular with open ends, similar to the horseshoe roadway. CIR of mining roadway is presented in Fig. 4, and we can easily recognize two overlapped peaks. The earlier one is obtained by (5). It can be seen that the CIR of the LoS signal is a delta function, scaled by 0.6549×10^{-5}. While, the first-order response is seen to have the second peak that corresponding to the ceiling and two walls of the mining roadway. The first-order CIR is 2.1244×10^{-6}. In the context of talking about the first-order in Fig. 4, a small early peak (close to the arrival time of LoS) can be seen in Fig. 4. This peak represents the power which arrives from the semi-cylindrical part. In terms of working face environment, the CIR is shown in Fig. 5. Here, the CIR of the LoS and first-order components are 0.2911×10^{-5} and 4.731×10^{-6}, respectively. This is because of the width of the underground mining is only 2 m, no long optical path that will be taken.

The above simulation results are related to I2M communication scenario. Channel characteristics of M2M communication scenario are detailed in Table II. Fig. 6 presents the received power distribution at miner plane from the proposed recursive method. The minimum received power in miner plane is -55.5 dBm. The maximum received power is -51.5 dBm, which is larger 4dBm than the minimum one. One can observe from the figure that the received power drops as either the T-R distance or the angle increases.

2) *Delay Spread:* The RMS delay spread σ_τ is an important characteristic of the VLC channel in underground mining. This is because of that the maximum bit rate is given as $R_b \leq 1/10\sigma_\tau$ [15]. The received signals, which are copies of the transmitted signal, arrive at different times. This is due to different path lengths of reflections between the Tx and Rx. Multipath dispersion and it affects the channel bandwidth and causes intersymbol interference (ISI). The channel RMS delay spread is given by σ_τ [11]

TABLE II
Channel Characteristics.

M2M in underground mining			
Distance (m)	CIR	$\mu_\tau(ns)$	
3	2.9109×10^{-6}	10	
6	7.2772×10^{-7}	20	
9	3.2343×10^{-7}	30	
12	1.8193×10^{-7}	40	
I2M in working face (LoS)			
Distance (m)	CIR	$\mu_\tau(ns)$	
3	2.9109×10^{-6}	10	
I2M in working face (first reflection)			
Distance (m)	CIR	$\delta_\tau(ns)$	$\mu_\tau(ns)$
3	4.731×10^{-6}	12.6551	9.7685
I2M in mining roadway (LoS)			
Distance (m)	CIR	$\mu_\tau(ns)$	
2	6.549×10^{-6}	6.667	
I2M in mining roadway (first reflection)			
Distance (m)	CIR	$\delta_\tau(ns)$	$\mu_\tau(ns)$
2	2.1244×10^{-6}	14.1412	9.3998

$$\sigma_\tau = \sqrt{\frac{\sum_i (\tau_i - \mu_\tau)^2 h_i^2(t)}{\sum_i h_i^2(t)}} \tag{13}$$

where, the mean excess delay μ_τ is given as [11]

$$\mu_\tau = \frac{\sum_i \tau_i \; h_i^2(t)}{\sum_i h_i^2(t)}. \tag{14}$$

The RMS delay spread will be decreased when the reflections are mitigated. The CIR, the RMS delay spread σ_τ, and μ_τ in underground mining are listed in Table II. The delay spread decreases from mining roadway to working face considering the single reflection. It can be noticed that μ_τ of I2M and M2M, is related to the distance between the LED and the Rx in underground mining. Furthermore, the RMS delay spread of I2M for the diffuse components is 14.1412 ns in mining roadway.

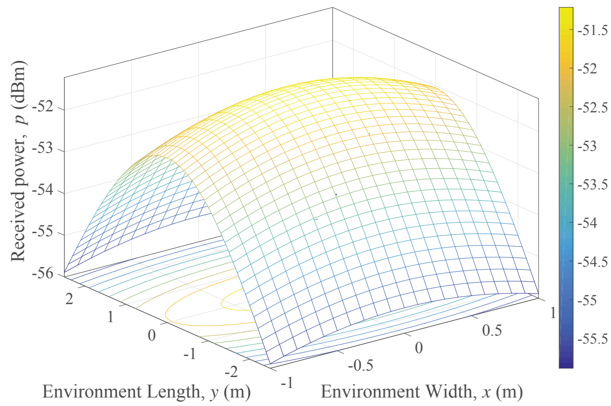

Fig. 6. Power distribution at the miner plane.

V. Conclusions

In this paper, the recursive method has been extended to investigate the channel characteristics of VLC for UMCs. VLC has been introduced in two different parts of coal underground mining, i.e., mining roadway and working face. The simulation results have shown that in terms of illumination, both scenarios can fulfill the illumination standard requirements and the mining roadway is brighter than working face environment. Meanwhile, the results have shown that although CIR cannot consider all reflections, the LoS and first reflections are able to provide most of the signal strength in the mining environment. In I2M communication scenario, because the width of the underground mining is only 2 m, the power brought by the first-order response components is comparable to the LoS power in the case of working face environment. While in the case of M2M, the received power at the miners plane is -51 dBm. The mean excess delay for the first reflection for I2M in mining roadway and working face are 9.3998 ns and 9.7685 ns, respectively. The RMS delay spread in the working face is smaller than that in the mining roadway, which indicates that the working face has a larger optical transmission bandwidth than the mining roadway.

Acknowledgments

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