A Path Loss Channel Model for Visible Light Communications in Underground Mines

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***Abstract*—Due to the ability to support communication and illumination simultaneously, visible light communication (VLC) system is considered as a potential access to realize effective communication in underground mines. In order to achieve this goal, it is necessary to understand the underlying physical propagation phenomenon in underground mines. Accurate and efficient channel models including large-scale fading characteristics are crucial for the design and performance evaluation of VLC systems. However, the characteristics of the underlying VLC channels have not been sufficiently investigated yet. In this paper, based on the recursive channel model, a path loss channel model is proposed precisely with the path loss exponent determined by three different trajectories in the mining roadway and working face environments. Taking different numbers of transmitters into account , both line-of-sight (LoS) and non-line-of-sight (NLoS) scenarios are considered. Our results demonstrate that the path loss exhibits a linear behavior in log-domain when curve fitting technique is applied. An expression for path loss as a function of distance is derived. Finally, root mean square (RMS) delay spread has been investigated and analyzed.**

***Keywords* – Underground mining communications, visible light communications, channel modeling, path loss, delay spread.**

I. INTRODUCTION

The underground mining industry is a very special industry, which provides a significant boost to the global economy. More hazards are encountered due to the presence of toxic gases and substances resulting from mining and production, associated with the presence of dust [1]. So, it requires reliable communications, monitoring and tracking systems that guarantee safety and maximize productivity in underground mining. Therefore, maintaining information flow is considered as one of the key challenges during mining operations. The information includes detecting hazardous gases and/or smoke, monitoring mining machinery, and, most important is monitoring miners and locating them when disasters occur. The most common communication systems in underground mines are node mesh, leaky feeder, and through-the-earth (TTE). Moreover, information can be exchanged through hard-wires, wireless, or a combination of both. Common wire types for data transmission include twisted pair, coaxial, and fibre-optic. Considering the complex structure of underground mines, wired communication systems are very susceptible to be damaged. Furthermore, the wireless communication systems used on the surface cannot be directly applied in underground mines because of the high attenuation of radio waves in underground mine galleries [2]. In addition, poor lighting condition in underground mines treats miner's safety because miners depend on visual cues to see potential surrounding hazards. Hence, the idea of using VLC technology has been triggered. It is worth mentioning that some researchers have introduced infrared, bluetooth, ultra-wideband (UWB), and ZigBee to underground mining communications (UMCs) [3]. However, in some aspects VLC seems superior to the later technologies for short range communications, i.e., 1–10 m [4].

VLC technology has many advantages, such as unlicensed spectrum, low-cost, supporting high data rate, and resistance to electromagnetic interferences. VLC is expected to be an important part of the next generation wireless communications in the underground mines. VLC in underground mines can utilize the off-the-shelf light-emitting diodes (LEDs), which can be equipped on the ceiling of the underground mining or mounted on miner's helmet, to establish a VLC link between either the miners and infrastructures or with other miners, respectively. There is a growing literature related to indoor VLC channels characterization including path loss and shadowing. But, only a few authors have focused on VLC channels characterization for UMCs such as [5], [6]. However, VLC channel path loss has not been considered in previous studies. In this paper, the first study of VLC channel path loss is presented for UMCs. In this work we extended the work in [7] by developing optical channel path loss model for the working face and mining roadway environments.

The rest of the paper is organized as follows. Section II introduces VLC system model and path loss in underground mines. Results and discussions are presented in Section III. Conclusions are finally drawn in Section IV.

II. A VLC PATH LOSS MODEL IN UNDERGROUND MINES

Underground mines consist of tunnels in which the coal is cut and removed by special machineries. Usually, the underground mines can be divided into mining roadway and working face. In order to represent these environments easily, horseshoe shape and rectangle chamber with 2 m width are considered to model mining roadway and working face, respectively. In the proposed system model, the underground mines are equipped with LED lamps for the purpose of illumination and communication simultaneously, as presented in Fig. 1. The key

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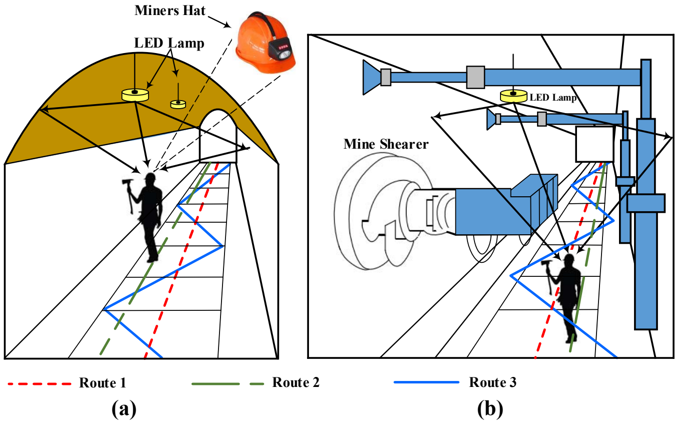

Fig. 1. System model: (a) horseshoe mining roadway and (b) mine working face.

parameters of the proposed underground mines VLC system are detailed in Table I.

A. VLC System Model

Assuming that each LED lamp has the same Lambertian radiation pattern, the angular distribution $S(\phi)$ of the radiation intensity pattern is given as [8]

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

Here, ϕ is the incident angle and m is the Lambertian mode number which is related to the LED semi-angle $\phi_{\frac{1}{2}}$, m is given as

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

The channel impulse response of the LoS component in the underground mines can be given as [8]

$$h_{\text{LoS}}(t) = \frac{A_r(m+1)}{2\pi {d_0}^2}\cos^m(\phi_0)\, T_s(\theta_0)\, g(\theta_0) \\ \cos(\theta_0)\,\delta\left(t - \frac{d_0}{c}\right). \tag{3}$$

Here, A_r is the optical detector area, the distance between the transmitter and the receiver is d_0, and the speed of the light in free space is c. In addiation, ϕ_0 and θ_0 are assumed to be transmit angle and the receive angle, where $\phi_0 < 90°$, $\theta_0 < FOV$, and $d_0 >> \sqrt{A_r}$, respectively. The Dirac function $\delta\left(t - \frac{d_0}{c}\right)$ represents the signal propagation delay. To compute the length of propagation path between the reflections, let the angles of incidence and received be ϕ_1, ϕ_i and θ_1, θ_j, and d_ε be the direction generated by source element and destination, then the impulse response of the receiver with N transmitters and the k-th order reflections can be expressed as

$$h^k_{\text{NLoS}}(t) = \prod_{i=1}^{N}\int \frac{\cos^m(\phi_1)\prod_2^{k+1}\cos(\phi_i)\prod_1^{k+1}\cos(\theta_j)}{2\pi^{k+1}\prod_1^{k+1}{d_\varepsilon}^2} \\ \times {A_{\text{ref}}}^k A_r(m+1)\rho^k T_s(\theta_{k+1})\, g(\theta_{k+1}) \\ \times \text{rect}\left(\frac{\theta_{k+1}}{FOV}\right)\delta\left(t - \frac{d_1+d_2}{c}\right) dA_{\text{ref}}. \tag{4}$$

where ρ is the reflectance coefficient and $\text{rect}\left(\frac{\theta_{k+1}}{FOV}\right)$ is decision function.

TABLE I
The key parameters.

System Model Parameters	
Mining Roadway	
Dimensions	2 m × 5 m × 3.7 m
Radius	1 m
Coordinates of the transmitter	(0,0,1)
The location of Route 1	x=0 , z=−1
The location of Route 2	x=0.5 , z=−1
The location of Route 3	-0.6⩽x⩽0.6 , z=−1
Working Face	
Dimensions	2 m × 5 m × 4.7 m
Coordinates of the single transmitter	(0,0,-2)
Coordinates of the four transmitters with TP1	(-0.5,-1.25,1)
Coordinates of the four transmitters with TP2	(0.5,1.25,1)
Coordinates of the four transmitters with TP3	(0.5,-1.25,1)
Coordinates of the four transmitters with TP4	(-0.5,1.25,1)
The location of Route 1	x=0 , z=-2
The location of Route 2	x=0.5 , z=-2
The location of Route 3	-0.6⩽x⩽0.6 , z=-2
Other Parameters	
Height of receiving plane	1.7 m
Number of LEDs (N)	400
Semi-angle at half power	70°
Concentrator refractive index (n)	1.5
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

B. Path Loss Model

To mitigate the effect of fading, the large scale fading and small scale fading are commonly considered carefully in wireless communication. Unlike the previous radio frequency (RF) wireless communication, the effect of multipath fading is not considered in VLC, because the surface area of detectors of VLC receivers are typically millions of square wavelengths of visible light. In the underground mines VLC system, the path loss can be calculated as [9]

$$PL = -10\,\log_{10}\left(\int_0^\infty h(t)\,dt\right). \tag{5}$$

In a typical free space system, the logarithm distance path loss is a generic model in both RF communication and optical wireless communication. When the distance d between transmitter and receiver is larger than the reference distance d_r, the path loss can be expressed as [10]

$$PL = PL(d_r) + 10\,n\,\log_{10}\left(\frac{d}{d_r}\right) + \chi. \tag{6}$$

Here, n is the the path loss exponent and χ is the shadowing. In this paper, only path loss is considered.

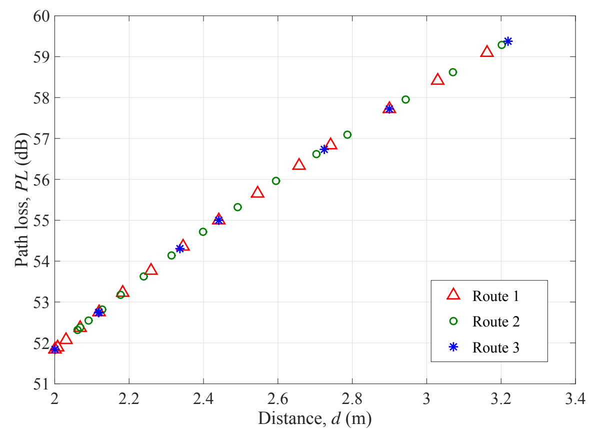

Fig. 2. LoS path loss estimation in mining roadway.

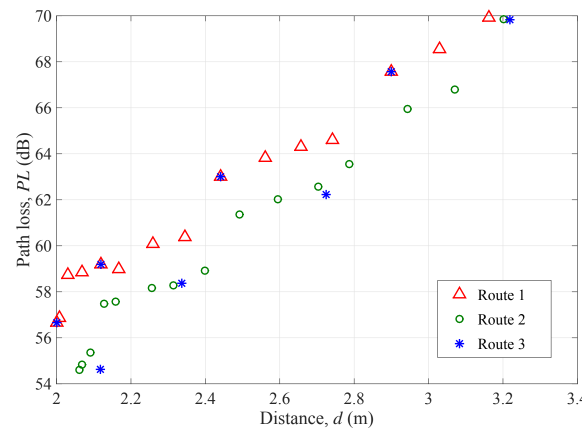

Fig. 4. NLoS path loss estimation in mining roadway.

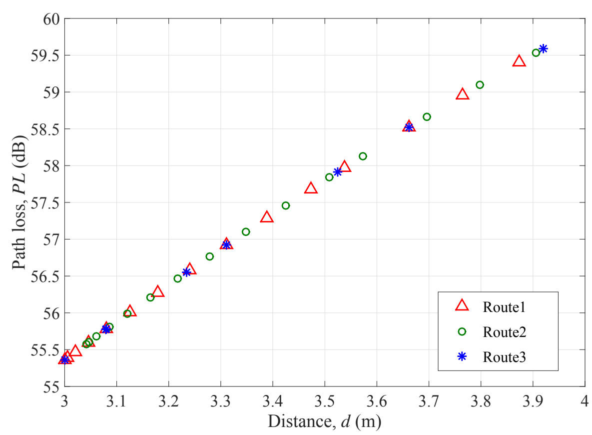

Fig. 3. LoS path loss estimation in working face.

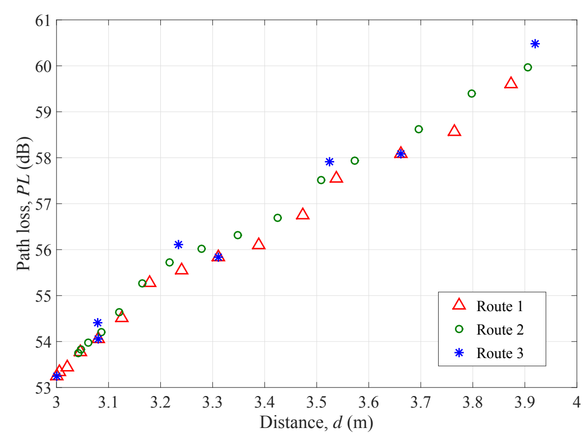

Fig. 5. NLoS path loss estimation in working face.

C. RMS Delay Spread

The aim of this part is to characterize the multipath dispersion and find the delay spread of VLC channels in underground mines. Inter-symbol interference (ISI) induced by multipath dispersion has a significant impact on channel capacity. The mean excess delay μ_τ can be calculated from the channel impulse response as

$$\mu_\tau = \frac{\sum_i \tau_i \; h_i^2(t)}{\sum_i h_i^2(t)}. \tag{7}$$

Then the channel RMS delay spread is given by σ_τ [8]

$$\sigma_\tau = \sqrt{\frac{\sum_i (\tau_i - \mu_\tau)^2 h_i^2(t)}{\sum_i h_i^2(t)}}. \tag{8}$$

III. Results and Discussions

To evaluate the performance of different communication scenarios in underground mines, Matlab is applied to analyse the channel characteristic differences. The results are obtained as presented in Table II by applying the curve fitting techniques for the 12 routes in mining roadway and working face.

A. Path Loss

In this subsection, the path loss of VLC channel is computed in both mining roadway and working face. For ease, we choose three movement trajectories in underground mines to calculate the LoS path loss and NLoS path loss, as presented in Fig. 1. Moreover, we get the path loss exponent n from (6) by applying the curve fitting technique on the simulation values of path loss results which are obtained from (5).

1) LoS Path Loss : The simulation results of LoS path loss under three movement trajectories in mining roadway and working face are presented in Fig. 2 and Fig. 3, respectively. As expected, the path loss exhibits a linear behavior in log-domain via the curve fitting techniques which are applied in the Fig. 2 and Fig. 3. In addition, the values of the norm of residuals are small on Route 1, Route 2, and Route 3 which are 10.24×10^{-5}, 10.65×10^{-5}, and 31.24×10^{-5} in mining roadway. Meanwhile, the values of norm of residuals in working face which approximately equal 8.4974×10^{-5}, 7.768×10^{-5}, and 23.58×10^{-5} are smaller than that in mining roadway, respectively. Moreover, it is presented in Table II that the path loss exponent amounts are the same value which is equal to 3.64 on Routes 1, Route 2, and Route

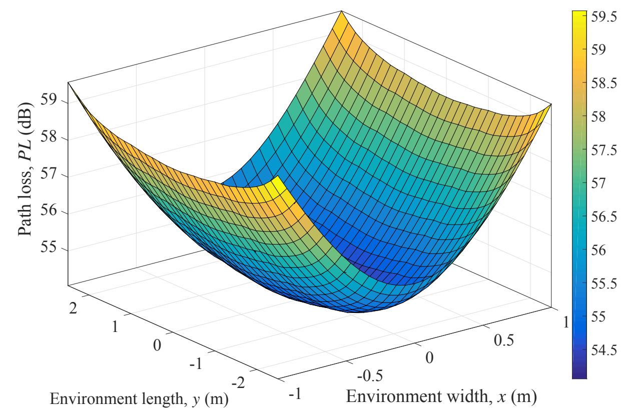

Fig. 6. Path loss distribution for a single transmitter in working face.

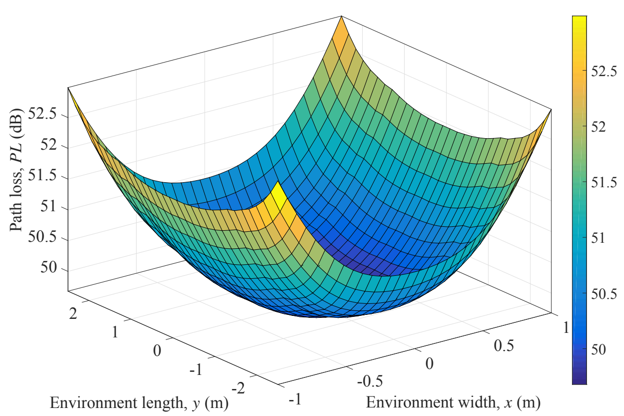

Fig. 7. Path loss distribution for four transmitters in working face.

3 with the different reference distance. Hence, the shape of communication scenarios and the different reference distance have no influence on the value of path loss exponent. One obvious phenomenon that some discrete points of Route 1 and Route 3 are coincident in Fig. 2 and Fig. 3 can be explained that the Route 3 of the polylines is partly going through the Route 1 which is in the middle of mine. Since Route 1 exhibits a higher linear behavior, it is used to develop the model for LoS path loss in mining roadway and working face.Thus the LoS path loss equations as a function of separation distance d in mining roadway and working face can be written as follows:

$$PL^{\mathrm{LoS}}_{\mathrm{Mining\ Roadway}} = 51.84 + 36.46\ \log_{10}\left(\frac{d_1}{2}\right) + \chi \quad (9)$$

and

$$PL^{\mathrm{LoS}}_{\mathrm{Working\ Face}} = 55.36 + 36.46\ \log_{10}\left(\frac{d_2}{3}\right) + \chi. \quad (10)$$

Here, $d_1 \geqslant 2\ m$ and $d_2 \geqslant 3\ m$.

B. NLoS Path Loss Estimation

The simulation results in Fig. 4 and Fig. 5 are related to NLoS path loss with three movement trajectories which are correspondingly estimated for distances from 2 m to 3.2191 m and 3 m to 3.9195 m away from the respective operational transmitter in mining roadway and working face. To simplify the calculation, only first reflection is considered. It can be seen that the LoS path loss estimation is better than NLoS path loss estimation obviously on the linear behavior in log-domain in Fig. 2 and Fig. 4. However, because of the increasing reflection walls, the path loss exponent of mining roadway is larger than that of working face. Therefore, the NLoS path loss equation along Route 1 in mining roadway and working face are determined as follows:

$$PL^{\mathrm{NLoS}}_{\mathrm{Mining\ Roadway}} = 57.18 + 61.55\ \log_{10}\left(\frac{d_1}{2}\right) + \chi \quad (11)$$

and

$$PL^{\mathrm{NLoS}}_{\mathrm{Working\ Face}} = 53.44 + 54.47\ \log_{10}\left(\frac{d_2}{3}\right) + \chi. \quad (12)$$

Here, $d_1 \geqslant 2\ m$ and $d_2 \geqslant 3\ m$.

As observed from Fig. 6 and Fig. 7, the path loss varies as the change of the number of transmitters and user location. Here, the maximum values and minimum values of path loss in received plane are 59.5730 dB and 54.0603 dB with a single transmitter in working face, which are 6.5843 dB and 4.3814 dB larger than that with four transmitters, respectively. As shown in Fig. 6, the path loss increases obviously as receiver away from transmitter. Thus, the middle of received plane has the minimum path loss compared with the other positions in Fig. 6 and Fig. 7. Increasing the number of transmitters, the value of path loss will decrease correspondingly.

C. RMS Delay Spread

RMS delay spread for the cases of a single transmitter and four transmitters are illustrated in Fig. 8 and Fig. 9, respectivley. It can be noticed that the maximum values are 0.4500 ns and 1.6546 ns for a single transmitter and four transmitters, respectively. Likewise, the minimum values are 0.1781 ns and 0.2381 ns, respectively. As shown in Fig. 8 and Fig. 9, the RMS delay spread distribution is not uniform because the model of the working face is not closed cuboid which leads to the reflections from the right wall and left wall are not counted. However, taken LoS and NLoS components into consideration, the RMS delay spread decreases as receiver goes away from transmitter as illustrated in Fig. 8 and Fig. 9.

IV. Conclusions

In this paper, the recursive channel model for VLC has been employed to determine the path loss of VLC channels in underground mines. Both mining roadway and working face with different numbers of transmitters have been considered. Specifically, the path loss exponent has been calculated for particular LoS and NLoS scenarios over three different trajectories. Simulation results have shown that the path loss acts a linear behavior in log-domain. Furthermore, the results have indicated that the value of path loss exponent of NLoS is larger than that of LoS in both mining roadway and working face.

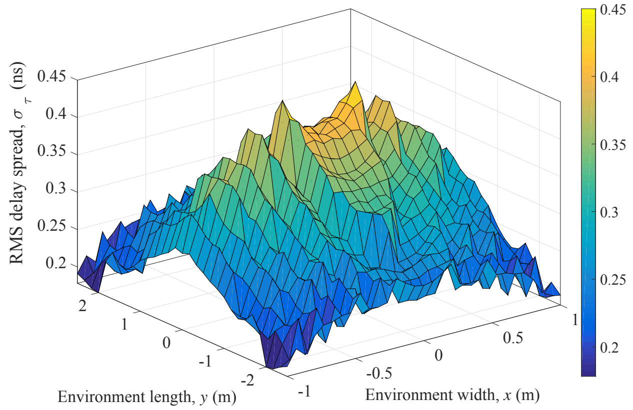

Fig. 8. RMS delay spread distribution for a single transmitter in working face.

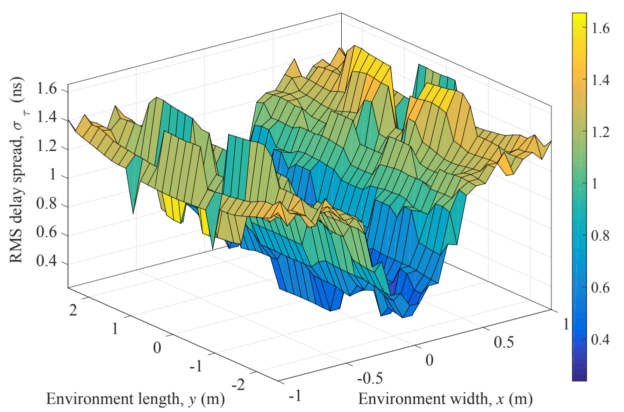

Fig. 9. RMS delay spread distribution for four transmitters in working face.

Besides, in consideration of LoS and NLoS components, the RMS delay spread decreases as receiver moves away from the transmitter.

TABLE II
Estimated parameters for the path Loss model.

LoS path loss estimation in mining roadway		
Route	Fitting equation	Norm of residuals
1	$= 51.84 + 36.46 \log_{10}\left(\frac{d}{2}\right)$	1.025×10^{-4}
2	$= 52.32 + 36.46 \log_{10}\left(\frac{d}{2}\right)$	1.065×10^{-4}
3	$= 51.84 + 36.46 \log_{10}\left(\frac{d}{2}\right)$	3.124×10^{-4}
NLoS path loss estimation in mining roadway		
Route	Fitting equation	Norm of residuals
1	$= 57.18 + 61.55 \log_{10}\left(\frac{d}{2}\right)$	2.442
2	$= 55.17 + 69.72 \log_{10}\left(\frac{d}{2}\right)$	2.799
3	$= 55.50 + 67.20 \log_{10}\left(\frac{d}{2}\right)$	4.935
LoS path loss estimation in working face		
Route	Fitting equation	Norm of residuals
1	$= 55.36 + 36.46 \log_{10}\left(\frac{d}{3}\right)$	0.8497×10^{-4}
2	$= 55.68 + 36.46 \log_{10}\left(\frac{d}{3}\right)$	0.7768×10^{-4}
3	$= 55.36 + 36.46 \log_{10}\left(\frac{d}{3}\right)$	2.358×10^{-4}
NLoS path loss estimation in working face		
Route	Fitting equation	Norm of residuals
1	$= 53.44 + 54.47 \log_{10}\left(\frac{d}{3}\right)$	0.7795
2	$= 54.13 + 56.13 \log_{10}\left(\frac{d}{3}\right)$	0.6885
3	$= 53.56 + 58.43 \log_{10}\left(\frac{d}{3}\right)$	0.9971

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