Potential and challenges of VLC based IPS in underground mines

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Potential and Challenges of VLC based IPS in Underground Mines

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***Abstract*—Chile is the largest copper producer in the world. In the world, almost 40% of copper is produced underground and it is expected that the activity will reach the 60% of the total mining activity. Because of this, there will be new challenges in terms of safety and productivity. Visible Light Communications (VLC) is a new technology capable to provide illumination and communication at the same time. This technology has shown high accuracy in localization and tacking for indoor scenarios. Nevertheless, most of the applications that can be found in literature assumes square rooms, no tilt receivers, and Line of Sight (LOS) link. In this paper we will address the problem of enabling Visible Light Communications (VLC) based Indoor Positioning System (IPS) in underground mines. Feasible link configurations and positioning topologies are studied throughout this paper. In addition to this, different localization methods are classified in two groups, i.e., range based and range free methods. Their performance in terms of accuracy and robustness as well as the constraints of each method will be analyzed for its usage in underground mines.**

I. INTRODUCTION

Chile is the world leader producer of cooper. It is expected by 2020 that the largest open pit mine (Chuquicamata) will change its operation to underground. This, will pose new challenges in order to perform sustainable, safe and highly profitable mining process. To accomplish this purpose, industrial processes require reliable wireless communication systems for enabling mobility of dynamic actors and for transmission of different types of data equipment monitoring, maintenance labors, etc. Inside the tunnel, workers and machinery will be working together continuously. Localization and tracking of workers improves the safety of the operation since in case of an emergency, evacuation routes can be optimized in order to minimize the potential risks. Some countries, like the United States have already strengthened their safety standards and mine operators must have electronic tracking system [1]. Besides, localization and tracking of both, workers and mobile machinery, can lead to an optimization on the operation since its location information can be used by a central dispatch station to minimize the operation cost by sending the nearest idle worker or machine to the zone where it is required [2].

Since the traditional GPS system does not work on indoor scenarios because satellites signals cannot penetrate to confined places [3] some other alternatives has been proposed for localization in underground environments such as Radio frequency identification [4] and Zigbee [5] among others. Most of below named technologies uses the Radio Frequency (RF) portion of the Electro-magnetic (EM) spectrum to provide wireless communication. RF signals face some constraints when are used in underground mines. RF signals are affected by a large amounts of reflections, scattering, and shadowing. This, severely affect its propagation performance [6].

RF spectrum is just a small portion of the EM spectrum and, due to this, different frequency bands with different properties can be used to provide communication and localization. In particular, Visible Light Communications (VLC) technology has taken advantage among other types of optical wireless communications and it has found many applications. Visible light frequency is distributed in the range of 400 to 800 THz while the radio waves are placed in 3 kHz to 300 GHz. VLC technology transmits information by modulating the intensity of an optical source at a rate much more faster than the response time of human's eye making the change on the optical source unnoticeable. As a consequence, VLC technology is capable to provide illumination and wireless communication at the same time. In particular, in underground mines VLC based positioning systems can be installed inexpensively since this technology uses the existing lighting infrastructure with very few modifications [3].

To perform localization it is assumed that the wireless network contains a small number of special nodes with priory knowledge of their location called "Anchor Nodes". A second assumption is about topology edges, which is divided in two categories, *range based* and *range free*. Range based localization assumes that the device is equipped with extra hardware capable to determine precisely the range information. On the other hand, range free methods uses connectivity information to perform localization. Some of the range based techniques currently used on VLC applications are Receive Signal Strength (RSS) based, hybrid RSS-Angle of Arrival (AOA), AOA, Time of Arrival (TOA), hybrid TOA/RSS and Time Difference of Arrival (TDOA) among others which are summarized in few VLC localization surveys [3], [7]–[10]. On the other hand most of the range free methods has not been used in VLC based networks. Some of these methods are Distance-Vector Hop (DV-Hop) [11], Centroid [12] and Approximate Point in Triangulation (APIT) [13]. In this paper we will examine both localization schemes, i.e., range based and range free localization and their potential to perform localization in underground tunnels using the already deployed illumination infrastructure and considering the environmental constraints. The paper is organized as follows: In Section II the most commonly used VLC system configurations topologies as well as localization topologies will be described. In Section III range based and range free localization algorithms will be presented and detailed. In Section IV a comparative study between range based and range free localization algorithms for VLC based IPS in underground mines will be delivered. Finally, in Section V the main conclusions of the study as well as future research directions are shown.

II. Visible Light Communications and Indoor Positioning Systems

In this section VLC system configuration as well as indoor positioning topologies will be described. In order to provide wireless communication as well as positioning different system configurations of VLC link will be analyzed for it usage in underground mines in terms of users' mobility, robustness and coverage. In addition to this, based on the application, different indoor positioning systems topologies will be examined and their link requirements will be summarized in order to determine if VLC system is applicable on each topology and underground mines IPS requirements will be shown.

A. Visible Light Communications System Configuration

There are great number of considerations which must be taken into account when designing VLC networks. When VLC is used for confined environments, light will be reflected by the ceiling, walls and most of the objects inside the room. In addition to this, the optical signal will not pass through opaque barriers. Due to this, there are numerous ways to physically configure an optical link. Typically, They are grouped into four system configurations as shown in Figure 1.

Direct LOS path is commonly used in point-to-point communication links. The link is concentrated in a very narrow beam, this leads to a low power requirement. In addition to this, LOS link offers higher data rates with a transmission range from few meters to kilometers. LOS link is almost not affected by multipath signal distortion. Its usage for indoor applications could be limited because of its small coverage area [15]. Direct LOS path needs the alignment between emitter a receiver, because of this, this link configuration cannot be used in mobile applications.

On the other hand, nondirect LOS is commonly used for indoor applications. This link configuration is considered as the most flexible configuration. A combination of a wide light beam transmitters and a wide Field of View (FOV) receiver is used. Signal scattered from surfaces ca be used to increase the coverage area. This link configuration is suitable for point to multipoint broadcast applications because it offers robustness against shadowing and blockage. Transmitter must not be necessarily aligned with the receiver to perform the communication. Nevertheless, this type of link can may be affected by a high path loss and multipath distortion which leads to a detrimental effect on the performance of the system when dealing with high data rates. Besides, inter-cell interference increases when multiple sources are arranged in a small area due to the wide light beam of the transmitters. Nondirect LOS link is not suitable to operate in environments with intense ambient light [14], nevertheless, underground mines are far from being intensively illuminated.

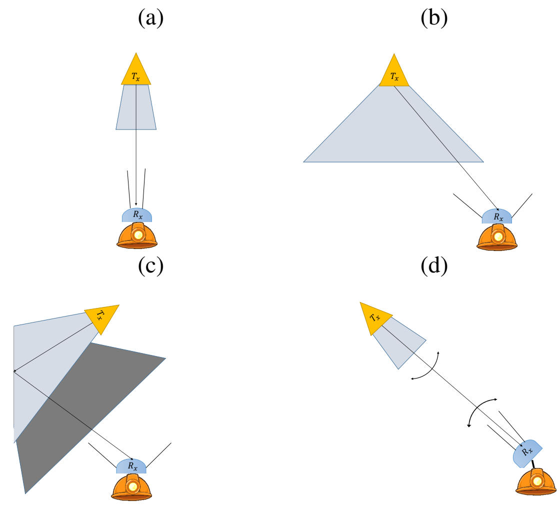

Fig. 1: Different systems configurations for VLC link, Photo detector (PD) is placed in the miner's helmet: (a) directed LOS, (b) nondirected LOS, (c) diffuse, and (d) tracked [14]

Diffuse configuration proposed in [16] consists on a transmitter pointing directly towards the ceiling or any surface within the room as shown in Figure 1 c). This link is the most suitable for optical Wireless Local Area Network (WLAN) and optical ad-hoc networks. Alignment between emitter and receiver is not necessary and is immune to blockage. It suffers from a multipath distortion and a high path loss which is increased by temporary obstructions [17]. The bit rate is limited and its performance is severely affected by ambient light.

TABLE I: Comparison of different VLC system configurations

System Configuration	Mobility	Coverage	Cost
Directed LOS	none	low	low
Nondirected LOS	high	high	low
Diffuse	very high	very high	low
Tracked	high	high	high

In tracked systems emitter and receiver are aligned automatically by an electro-mechanical device. Nevertheless, these electro-mechanical devices are expensive. Electronic tracking schemes for this type of communication scheme has been previously proposed in [18]. In table I the main characteristics of each link configuration for enabling VLC based IPS are presented, i.e., mobility, coverage and cost. Diffuse and nondirected LOS link configurations have higher mobility and coverage compared to others configurations. Moreover, the cost of implementing a VLC system using nondirected LOS or diffuse link is low.

B. Indoor Positioning Systems Topologies

The architecture of the deployed network has an important effect on the performance of localization algorithm. Localization can be arranged in three different topologies [19] depending on where the localization is performed and the communication direction.

- Remote positioning: In remote positioning receivers at one or more localizations measure the signal provided by or reflected from the object to be positioned. Measurements performed by the receiver are communicated to a central station and the position is determined by combining this information. This topology of localization system is useful when there is another system running an application on a central site.
- Self Positioning: In self positioning systems the receiver measures the signal from the anchor nodes and uses the measurements to determine its own position.
- Indirect: A self-positioning receiver sends the information about the location to a remote site or vice versa. If the information is sent from the self-positioning receiver to the central station the system is known as *Indirect remote-positioning* and if the central station sent the information about the localization to the object to be positioned the system is known as *Indirect self-positioning*.

To perform remote positioning uplink is required since Mobile Nodes (MN) send information to the fixed Access Point (AP). On the other hand, to perform self-positioning only downlink is required. Finally, to perform indirect positioning both, uplink and downlink are required. Since VLC has been proposed mainly as downlink technology [20], [21] self-positioning or indirect self-positioning are feasible alternatives to perform positioning in underground mines using VLC. In table II a summary of link requirements, suitable technologies as well as the main issues to be overcome for implementing IPS in underground tunnels for the above mentioned topologies are shown. There is still many issues to be solved for using VLC

TABLE II: Topologies for VLC based IPS in underground mines

Topology	Link Requirements	Technology	Issues
Remote Positioning	Uplink	RF or IR	Low performance of RF systems. IR needs fixed PD devices placed inside the tunnel
Self Positioning	Downlink	VLC	No information about positioning in central station
Indirect	Uplink and Downlink	VLC for downlink and RF or IR for uplink	Full duplex communication is required

for uplink since visible light can cause disturbance to users. Due to this, uplink is mainly provided by infrared or RF [22]–[24] and visible light is mainly used for downlink.

C. Underground mines positioning systems requirements

Based on the US safety standard for underground mines of 2006 [25] some IPS requirements have to be met in order to provide information about the position of workers inside the underground tunnel. The system must have a minimum accuracy of $60.96(m)$ relative to a fixed point. In addition to this, it must have an update rate up to 60 seconds and it has to be used for maximum possible number of persons, including visitors, expected to be inside the tunnel.

III. Topology edges

Most of the work done so far in the literature about range free VLC based IPS assume that there exist a high anchor node's density (LED lights) and MN can perceive more than 3 sources at each time. In this section, commonly used methods for VLC based IPS will be described and examined.

A. Range based methods

Range based methods assumes that the device is equipped with extra hardware capable to determine precisely the range information. The mainly used range based localization methods for VLC systems will be presented in this section, i.e., RSS, TDOA, AOA and TOA.

1) Received signal strength: The signal of VLC link gradually falls of in strength as the receiver moves further away from the light transmitter. If the relationship between distance and signal strength is known, i.e., $d_{sr} = f(P_r)$, where d_{sr} is the distance between transmitter and receiver, P_r is the received power and $f(.)$ is a function that relates distance and received power, then, the RSS can be used to determine the distance d_{sr}. If there is signal strength information about several different based stations or targets, trilateration can be used to determine the position of the MN. This method mostly assume that there exist LOS link between emitter and receiver because it suffers detrimental effects when the reflected light is considered [26]. In addition to this, the received power depends also on the signal's received angle. In order to solve this problem a scaling factor RSS method was proposed in [27] when no other devices such as gyroscopes or accelerometers are incorporated at the receiver. Some other methods use PD arrays [28] and cross correlation function between transmitter and receiver [29] in order to deal with angle diversity in the receiver side. In general, RSS based method increases their accuracy when a large number of LEDs are perceived [30], multipath effects are neglected and non-tilt receivers are considered.

2) Time of arrival: This method uses the time it takes to Electro-magnetic (EM) waves to travel the distance between anchor node and receiver. Since the velocity of EM waves can be considered as constant the distance is determined by $d_sj = c\Delta t$ where c is the speed of light, Δt is the time it takes to the signal to travel between transmitter and receiver. In TOA the receiver's clock is somehow synchronized to the transmitter's clock in order to determine Δt as shown in [31]. This system also assumes direct LOS communication and unlike RSS based methods it does not suffer detrimental effect

TABLE III: Summary of VLC based IPS and their constraints in underground mines application

Parameter	Range based				Range free	
Method	RSS	TOA	TDOA	AOA	Hop count	Neighborhood
Acuraccy	From 0.01 when LOS link and no multipath effect is considered and up to 1[m] with tilt receivers, multipath and noise	0.02-0.06[m] when transmitter and receiver are assumed to be perfectly synchronized. LOS link and no multipath effects are considered	0.01[m] when LOS link and noise free communication are considered. Up to $\approx$ 0.7[m] when multipath, noise and rising-falling time of LED lights are considered	0.05 [m] when no tilt PD or multiple PD array, no multipath and LOS link are considered, and up to 0.3 [m] when tilt receiver with accelerometers is used on tilt circular PD array	From several meters up to few centimeters can be achieved assuming full connectivity of the Ad-Hoc network	0.1 [m] using angular diversity of the transmitting LED lights is exploited to create coverage area up to 2.5[m] when Cell ID is used
Robustness	Strongly decreases when multipath effects and tilt receivers are considered. Diffuse link configuration is not feasible since precise ranging information is required	Strongly decreases when multipath effects. Tilt receivers has no effect on the performance. Diffuse link configuration is not feasible since precise ranging information is required	Strongly decreases when multipath effects is considered. Tilt receivers has no effect on the performance. Diffuse link configuration is not feasible since precise ranging information is required	Strongly decreases when multipath effects and tilt receivers are considered. Diffuse link configuration is not feasible since precise ranging information is required	Only connectivity information is required. Tilt receivers as well as Non-Directed LOS and diffuse links can be used. Accuracy strongly depends on the node density and connectivity of the network	Only connectivity information is required. Tilt receivers as well as Non-Directed LOS and diffuse links can be used. Accuracy strongly depends on the transmitter's node density of the network
Cost	low since no additional hardware is required in the receiver	medium since special hardware for synchronization and time measurement is required	medium since special hardware for time measurement is required	medium since special hardware for angle measurement is required	medium since special hardware for note-to-node communication is required	low since no additional hardware is required in the receiver

when tilt receivers are considered. Nevertheless, synchronization between transmitter and receiver is a difficult task.

3) Time difference of arrival: TDOA uses the difference on the arrival's time of the signals transmitted by fixed lights to the MN or by measuring a single or multiple sources in a multiple PD array at the receiver. If the distance between transmitters is known then, the distance between each transmitter and the receiver can be obtained and, subsequently, the position of the mobile node. Some methods assume a single PD receiver who measures the difference on the arrival time from multiple light sources with known positions. In order to differentiate the signals Time Division Multiplexing (TDM) or Frequency Division Multiplexing (FDM) techniques are used. The considered method assumes that there exist LOS link between transmitter and receiver. In addition to this, at least three sources has to be sensed by the MN to perform localization [32]–[34]. An interesting localization method is proposed in [35] where a 2-PD receivers and two light sources are used to perform localization in a infrastructure to vehicle network. Another advantage over TOA method is that TDOA does not need synchronization between transmitter and receiver.

4) Angle of arrival: For using AOA method the angle in which different optical signals arrive to a single PD receiver have to be measured or alternatively, the AOA of a single or multiple sources to a multiple PD array. For doing this, LOS link is considered as de-facto system configuration in VLC. Positioning using AOA can be obtained by using a minimum of 2 LED lights for 2-D localization unlike above mentioned methods where at least 3 sources are required. The difference on the AOA can be inferred from the difference of the received power from multiple sources in a single PD or by using a PD array. Besides considering LOS link, some applications assumes that the transmitter and receiver are aligned in the same X-Y plane, thus, incidence angles and irradiance angles are equal. Other sensors such as accelerometers can be used to compensate the effect of tilt receivers in combination with multiple PD array [36]. Nevertheless, using these sensors at the receiver side will reduce the battery lifetime in mobile devices. In addition to this, AOA methods suffer high detrimental effect when non-LOS link and reflections are considered.

B. Range free methods

Range free localization uses the connectivity information between the nodes. The Anchor nodes with prior knowledge of their own position are commonly fixed nodes of the network while mobile nodes uses the information to estimate their position. In this scheme ranging measurements are not needed, due to this, range free localization has a lower cost and higher robustness since connectivity information is not easily affected by the environment. Range free methods can be divided mainly in two groups, hop-count methods and neighborhood methods.

1) Hop count methods: In order to determine the position of a mobile node, hop count method propagates the anchor node information throughout the network. By doing this, MN that are not directly communicated with the anchor node can have a rough estimation of their distance to the nearest anchor nodes by counting the number of hops between them. Ad-hoc wireless network is a mandatory requirement for this type of algorithms since mobiles nodes must to be able to communicate between them. Hybrid VLC-RF techniques has been studied where VLC anchor nodes are considered and communication between MN is performed by using a RF method such as Zigbee or Bluetooth [37]–[39]. This method is affected by node density because communication between MN and anchor nodes has to be ensured.

2) Neighborhood: Neighborhood methods does not use ranging information to determine MN position. In addition to this, this type of methods do not require an ad-hoc network or WSN implementation since they use the received anchor node's information to perform localization. This, pose a constraint to the system since the MN has to be aware about the position of one or more anchors to perform localization. Coarse grained localization can be obtained when a large number of anchor nodes is considered. The most used neighborhood methods are Centroid [12], Approximate Point in Triangulation (APIT) [13]. A neighborhood method for underground mines was proposed in [40]. LOS link was considered. Higher accuracy is obtained by increasing the overlapping regions of LED lights.

IV. Discussion

When using range based methods for localization in underground mines tunnels tilt transmitters and receivers, multipath effects, low anchor node's density and diffuse link has to be considered as shown in Figure 2 (a). Luminaries deployed inside the tunnel can be placed in the top of the tunnel or in the walls in order to facilitate maintenance labors. When luminaries are placed in the tunnel's walls tilt transmitters has to be considered. In addition to this, machinery inside the mine can cause shadowing as shown in Figure 2 (b). Due to this, the signal received by workers inside the mine will be provided by the reflection of the light inside the tunnel (diffuse link). RSS, TOA, TDOA and AOA based methods suffer detrimental effects when multipath or diffuse link is considered. These methods are unfeasible to be deployed in working zones inside the tunnel since machinery and workers co-exist and the VLC link will suffer from shadowing. Tilt receivers have to be considered since workers will be performing labors inside the tunnel. This, will reduce the accuracy of AOA and RSS based methods. Inside the tunnel, low anchor node's density exists and RSS, TDOA and TOA methods need at least 3 LED to perform localization. On the other hand, when using AOA based method only two transmitters are required to be sensed to perform 2-D localization.

Range free algorithms are not susceptible to multipath effect, diffuse link conditions and tilt transmitters or receivers. Nevertheless, for implementing hop-based localization there must be connection between the MN in order to increase the accuracy of the system. On the other hand, neighborhood methods uses only anchor nodes to estimate the position of the mobile nodes. Higher accuracy can be achieves by increasing the number of LED lights. Nevertheless, an accuracy of at least $60.96(m)$ is required for underground mines. A brief summary of each technique is shown in Table III where accuracy, robustness and cost for each localization method is presented.

(a)

(b)

Fig. 2: El Teniente underground mine light deployment (a) Transportation tunnel (b) Machinery working inside the tunnel

V. Conclusions and Future work

Throughout this paper different considerations for enabling VLC based IPS systems in underground mines where pointed out and discussed. Mainly, three subjects where studied, i.e., VLC system configuration, IPS topologies and localization methods. Since in underground mines workers and machinery works alongside mainly two VLC system configuration have to be considered, nondirected LOS and diffuse links. When this type of system configuration is assumed, range based localization algorithms lacks of accuracy since they suffer from diffuse link on ranging measurements.

Two different IPS topologies can be considered for using VLC systems in underground mines, these are, self-positioning and indirect positioning. In particular indirect positioning is the one that has to be addressed to increase the safety by sending position information to a central station. Finally, we conclude that range free algorithms can be a suitable method for VLC based IPS system in underground mines since these methods are robust to LOS link shadowing, multipath effects and the cost is lower since they do not require additional hardware infrastructure to perform ranging measurements. In future work a novel VLC channel in underground mines will be proposed, power distribution, channel impulse response and time delay spread will be obtained. In addition to this, performance of range based algorithms under this VLC channel will be evaluated.

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