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Conference Paper

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CISTER-TR-231204

2023/11/08

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Abstract

Visible Light Communication (VLC) has the potential to revolutionize various aspects of the healthcare industry. VLC 19s capability to achieve high data rates, reaching several megabits per second, renders it ideal for meeting strict communication requirements and ensuring dependable data transmission within healthcare environments. The Radio Frequency (RF) communication currently used in healthcare settings suffers from interference and high latency. In a VLC-enabled network, the information is transferred by modifying the visible light spectrum, which is used for lighting and ranges from 400 to 700 nm with no electromagnetic interference. The infrastructure to realise VLC communication includes light sources like Light Emitting Diodes (LEDs) that can improve the energy economy and also facilitate high-data-rate communication. This article aims to provide an in-depth literature survey towards important healthcare applications such as VLC-enabled patient monitoring systems and indoor localization and identifies some of the major challenges and some of the open issues in the field of VLC enabled healthcare.

VLC-enabled monitoring in a healthcare setting: Overview and Challenges

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***Abstract*—Visible Light Communication (VLC) has the potential to revolutionize various aspects of the healthcare industry. VLC's capability to achieve high data rates, reaching several megabits per second, renders it ideal for meeting strict communication requirements and ensuring dependable data transmission within healthcare environments. The Radio Frequency (RF) communication currently used in healthcare settings suffers from interference and high latency. In a VLC-enabled network, the information is transferred by modifying the visible light spectrum, which is used for lighting and ranges from 400 to 700 nm with no electromagnetic interference. The infrastructure to realise VLC communication includes light sources like Light Emitting Diodes (LEDs) that can improve the energy economy and also facilitate high-data-rate communication. This article aims to provide an in-depth literature survey towards important healthcare applications such as VLC-enabled patient monitoring systems and indoor localization and identifies some of the major challenges and some of the open issues in the field of VLC-enabled healthcare.**

***Index Terms*—VLC, Healthcare, LEDs**

I. Introduction

With the improvements in the domain of Wireless sensor networks (WSN) over the past decade, WSN has extended its reach into the development of several healthcare applications. Some of the prominent applications include patient monitoring where sensors are deployed over the patient's body to track physiological changes and send this information in real-time to a medical professional or a database [1]. RF-based technology is commonly used due to its wide adoption and capabilities to communicate with stringent latency. However, this kind of communication is susceptible to electromagnetic interference (EMI), compromising the precision and dependability of medical equipment [2]. Visible Light Communication (VLC) is a promising alternative form of communication to RF in a healthcare setting because of its capability to maintain integrity in communication without any vulnerability due to EMI. VLC operates in the visible region of the electromagnetic spectrum, which is visible to the human eye and ranges from roughly 380 nm to 780 THz [3]. In addition to its reliable communication, VLC also provides a sizable unlicensed bandwidth which can facilitate wireless high-speed communication. Table I presents some of the prominent differences between the VLC from the commonly adopted RF technology.

VLC technology's built-in security measures, such as directional light and line-of-sight communication, make it an excellent choice for transmitting sensitive medical information, such as patient records and real-time health monitoring data, with no risk of interception or unauthorized access [4].

Despite its many advantages, VLC in healthcare also can pose challenges such as line-of-sight requirements, signal interference, and infrastructure implementation costs [5], [6]. All these challenges must be clearly addressed for the widespread adoption of this technology. However, as technology advances with new research and time guarantees and bounds in VLC communication, it is expected to have a significant role in enabling several aspects of the healthcare industry.

VLC enables real-time transmission of health monitoring data from wearable devices or sensors to healthcare providers. In this paper, on one hand, we explore some of the state-of-the-art methodologies where VLC is utilized to aid in monitoring patient data. Some of the common biomedical sensor data include Electroencephalogram (EEG), Electrocardiogram (ECG), Photoplethysmography (PPG), temperature, and patient information, which can be transmitted to a healthcare provider using the IEEE 802.15.7 protocol [7]. On the other hand, we analyse the usage of VLC to realize indoor localization that is used in detecting the location of patients and medical professionals. Although healthcare applications were noted as a key application for VLC technology in the standard [8], the precise biological signals being carried out and the underlying methodologies were not clearly stated. It is necessary to comprehend the possible uses and advantages of VLC technology in the healthcare industry for its widespread adoption. This work aims to investigate the VLC technology in relation to healthcare applications to imply that this technology has the potential to revolutionize a number of healthcare delivery processes, from remote patient monitoring to real-time disease detection and diagnosis.

The main contributions of this survey are as follows:

- We provide an in-depth literature review on the state-of-the-art of VLC enabled patient monitoring system
- We also discuss the usage of VLC in the context of indoor localization in a healthcare setting
- We provide an in-depth discussion on the challenges and open issues of the VLC-enabled healthcare systems.

The rest of this paper is structured as follows, in Section II, we provide an overview of indoor localization in a healthcare setting. In section III, we present the state-of-the-art of VLC-enabled patient monitoring system where we group the literature based on static, mobile and hybrid transceiver models. In Section IV, we discuss the open challenges and possible

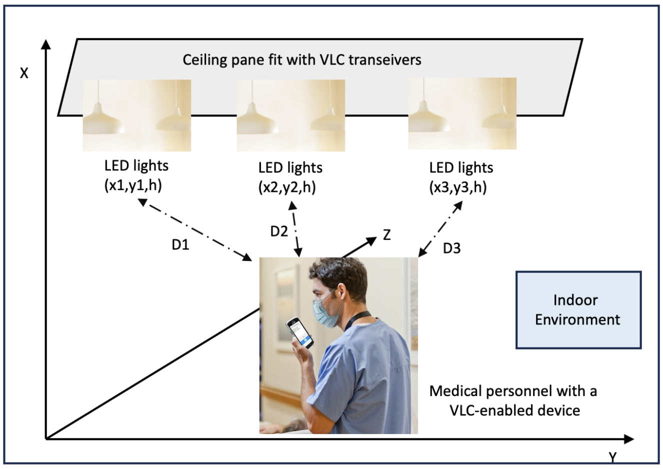

Fig. 1. An example of a VLC-enabled indoor localization where a ceiling is fit with VLC-enabled transceivers used to locate medical personnel carrying a VLC-enabled device in an indoor environment

TABLE I
KEY DIFFERENCES BETWEEN VLC AND RF COMMUNICATION IN HEALTHCARE SETTINGS

Property	VLC	RF
Line-of-sight	Strict LoS	No LoS needed
Bandwidth	380 THz to 780 THz	3 Hz to 3000 GHz
EM interference	No interference	with nearby RF devices devices
Penetration	Cannot move through opaque obstacles	Can move through walls
Noise sources	Ambient light	EM devices
Communication range	Short	Short/Long

research scopes for this novel technology. We wrap up with the final discussion in Section V.

II. INDOOR LOCALIZATION IN HEALTHCARE

Indoor localization is one of the fundamental capabilities for indoor applications on mobile devices. They can help in determining the real-time position of patients, medical staff, and equipment (Figure 1). One of the major advantages of indoor localization through VLC is its ability to be non-intrusive. Localization through this technology can be considered passive, as it is using the existing lighting infrastructure without the need for additional sensors or devices on individuals.

Researchers in [9] propose a low-cost localization solution based on VLC in indoor environments. In this method, modulated LED lights are used as beacons to aid indoor localization. Gaussian Process (GP) is used in modelling the intensity distributions of the light sources. Bayesian localization framework is constructed based on the outcomes of the GP, resulting in precise localization. Such indoor localization can be implemented in a healthcare setting to locate the location of the patients in real-time.

Researchers in [10] propose indoor localization using commercial off-the-shelf technology (COTS). In this hardware VLC system, they use an Android APP to configure the signal pattern for each beacon. VLC beacons are used in indoor localization, where a dedicated low-cost photonic sensor and a rolling-shutter camera are used in decoding the signal as an analogue input. It was found that the system had a high recognition rate on the beacon signal when the luminance is bright enough. This work showed one of the prerequisites of having high luminance for the effective functioning of the VLC system.

A multi-colour sensor has been used to realise an indoor localization system based on the light fingerprint in [11], which is suitable for healthcare centres and hospitals. Three algorithms, namely KNN, neural network and decision tree were used for this localization. Based on their experiment results the localization was found to be much more effective for neural networks with mean localization errors of ten centimeters. It has been stated in this work that this precision can be improved further by advancing the system setup and hardware devices.

A robust indoor localization system (ILS), called VLC-Bounding box is proposed in [12]. By this method, the position can be calculated using the received signal strength (RSS) technique. This reduces the localization error and maintains stability. Monte Carlo simulations were used in evaluating the distribution of mean localization error. The VLC-Bounding box achieves a good performance in terms of localization even when the noise power rises up to 0.03 mW.

Another similar VLC-beacon-based indoor localization has been performed in [13]. In their proposed method, signal decomposition is the fundamental module for global localization. It was used to provide global reference information similar to GPS technology. In their method, they realized signal decomposition based on an asynchronous assumption of the LED beacons. Their experiments achieved an accuracy of around 0.56 m. Researchers in [14] use a combinational approach

TABLE II
DIFFERENT VLC TECHNOLOGIES AND METHODOLOGIES USED IN THE LITERATURE TO REALISE INDOOR LOCALIZATION

Paper	Methodology	VLC technology
[9]	Gaussian Process (GP)	Modulated LED lights
[10]	COTS	Photonic sensor Rolling-shutter camera
[11]	KNN, NN, Decision tree	Light fingerprint
[12]	Monte Carlo simulations	LED RSS
[12]	Signal decomposition	Async LED beacons
[14]	Combinational approach	Modulated LED lights

of using hardware-conditioned signals, Gaussian filtering, and weighted Bayesian models to triangulate the position of the nodes in the system. Despite their work designed for the indoor positioning of robots, the travel space is minimal. Considering a larger environment like a hospital, more light sources have to be installed, thus dramatically increasing the cost and the complexity of the system. In Table II, we tabulate different VLC technologies and methodologies used in the literature to realise Indoor localization. It is noticed that most of these methods involve a small area and mostly static nodes. In the case of patients of medical personnel in a hospital setting, there is a need for mobile localization.

III. VLC IN PATIENT MONITORING SYSTEM

VLC can be used to enable an extensive patient monitoring system that leverages visible light to transmit medical data between devices in a healthcare setting. In a medical facility, LED transmitters can be installed on various monitoring devices, such as bedside monitors, infusion pumps, and other medical equipment to collect patient data and transmit them using data transceivers. As shown in Figure 2, data from the monitoring devices, such as the heart rate, blood pressure, and oxygen saturation, can be converted into digital information and encoded onto the light signals to be emitted by the LED transmitters. As presented in the previous section, communication through VLC will be possible by either static or mobile transceivers. Having this in mind, this section provides an overview of the VLC-based MBSN (Medical Body Sensor Networks) monitoring systems based on static and mobile transceivers.

A. Static transceiver Models

For the transmission and monitoring of biomedical data, a novel visible light communication method using a commercial white LED display is proposed in [15]. Without the use of a collimating lens, the biological data has been transmitted at a rate of 56 kbps with a bit error rate (BER) of 106 at a distance of 0.5 meters by using the On–off keying (OOK) modulation scheme. Their experiments achieved an accuracy of 90% of the nominal optical power of the LED transmitter.

Multiple sensors also have been employed in the literature [16], where the data was transmitted as a single combined signal from a VLC transmitter to a receiver. Thin film corner cube retroreflectors (TCCR) were used in the passive transmission to modulate and reflect the measured information from sensors to a central node. The transmitted power and the user's position are taken into account while analyzing the absorbed reflected power at TCCR, and SNR (signal-to-noise ratio) at the image sensor.

LED illumination has been used in conveying healthcare data like patient information and biological signs [17]. In this research, a compact and portable receiver module was developed and attached to a mobile device. Using a single-channel VLC, three different types of healthcare data, such as ECG, PPG signals, and HL7 text information, were communicated simultaneously in real-time. A reduced packet error rate was achieved by carefully calculating the data packet size. In their research, simultaneous monitoring and evaluation of arterial blood pressure and heart rate was feasible.

Space diversity of photodetectors has been utilized for multiple patient data transfer uplink [18]. In this proposed system, ambient lighting provides the least interference for properly positioned photodetectors. In their proposed model, OOK modulation yields a transmission rate of 10 bps at a 1:2 scaled distance and a 5 times greater power LED can be used for real-time applications. Despite being efficient in a fixed environment setting, this kind of communication can only be efficient where there is less movement of the patient like in the ICU wards of the hospitals. It will be a tough challenge when the data has to be communicated when the transceivers are mobile. To address this, there have been some solutions in the literature where the transceivers are mobile, this will be discussed in the following subsection.

B. Mobile transceiver models

A mobile-health home-based rehabilitation is facilitated through A mobile-visible Light Communication [19]. The proposed strategy utilizes visible light as a hazardless communication medium between wearable sensors and a smartphone. A smartphone camera receives clinical data such as PPG, ECG, and respiration signals through an LED. The smartphone also acts as a local interface to transmit the data to the cloud so that a physician can continue to monitor it.

Researchers in [20] investigate the effect of random receiver orientation on line-of-sight links for mobile users over VLC downlink channels. To realise this objective, the patient wearing the receiver was made to move around the room and the receiver location's axes were distributed uniformly over a 2D plane. They experimented with a uniform distribution which was used to mimic the receiver's random orientation based on the patient's movements. It was found that the impact of the LoS (Line of Sight) rays on the channel impulse response (CIR) is greater than that of the reflected rays when the orientation angle is equal to zero or perpendicular. It was also learned that for data rates up to 30 Mbps, the effect of receiver orientation does not have a major impact on the channel model performance. A site-specific channel modelling approach based on ray tracing has been used to characterize the channel parameters of VLC-based MBSNs in

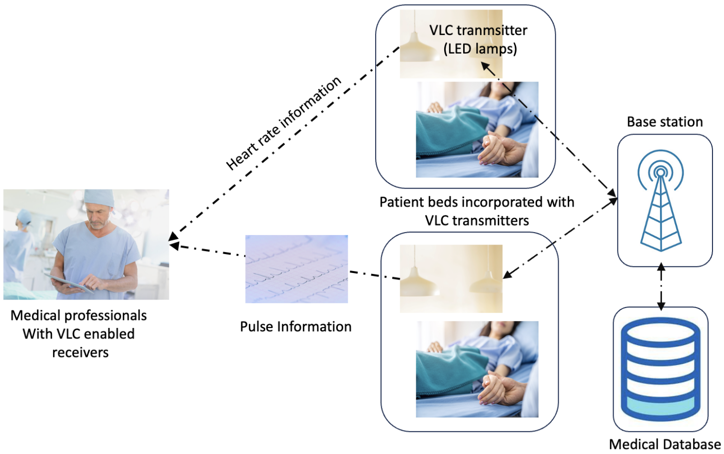

Fig. 2. An example of a VLC-enabled patient monitoring system where the information from the patient beds is transmitted through LED lamps that act as VLC transmitters to the medical professionals. Also, the data from the patients are relayed onto the medical database for future reference

[21]. A Root Mean Square (RMS) delay spread in a realistic Intensive Care Unit (ICU) ward and Family-Type Patient Room (FTPR) where three MBSN nodes move along realistic random trajectories has been considered in this model. Based on their simulation results, the route loss and RMS delay spread both exhibit a linear impact on the communication of the monitoring system.

The location of the transceivers has an impact on communication as they are the direct counterparts of antennas in RF-enabled communication. In [22], the transmitter was pointed towards the floor and fixed to the ceiling. A 2D statistical model was also used to predict the location of a mobile receiver pointed upward. Configurations such as ordinary and hospital bedrooms and their respective 2D and 3D models were tested. The results of this study show that the impact of geometrical orientations of the transceiver outweighs the effects of furniture and human presence in a typical bedroom. Additionally, it was found that as data flow increases, the impact of the geometrical detail of the model grows.

With the dominant growth of the smart-tech wearable market, there have been many medical devices that monitor human health on a daily basis. One such low-power wearable ECG acquisition device has been proposed in [23]. The conventional multi-lead-wired ECG detector restricts the patient's movements and activities. In this proposed method, a perpendicularly oriented VLC receiver is built within a tablet that is held in front of the moving patient at a set height of 1.2 meters. At a fixed height of 1.2 m, an IR transmitter with a perpendicular orientation was mounted for the uplink channel. Thanks to its ability to communicate through water, VLC has been used in the realisation of a diving health monitoring system [24]. The proposed system detects health parameters such as Panic, temperature and body position of the diver. In case of any emergency, the system sends critical information to an adjacent diver and submarine. Further, the detected health parameters are also stored in a memory chip as a database.

A lossless ECG data compression technique based on variable-word length coding has been used for enhancing the sampling rate of the device [25]. This work proposes an algorithm that handles both data compression and power savings. Experimental outcomes show that the compression ratio of the device can reach 2.38 when the sampling rate is 400 Hz, and the operating current is only 3.64 mA. The results also revealed that uplink IR channels with optimal orientation perform better than downlink VLC channels.

VLC has the capability to stop the spread of new diseases in an Intensive Care (IC) medical environment. The work in [26] presents a low-cost, reliable VLC transceiver system and is incorporated into real-world characterizations of an IC setting. Transmission of Manchester-based on-off keying signals and the Eye Opening Penalty (EOP) metric have been utilized to provide an assessment of the VLC system. Defining factors such as line-of-sight link distance, modulation frequency, LED bias current, and signal pattern have been examined in this work. Vital parameters like heart rate, Oxygen saturation, pulse rate, respiration rate, and non-intrusive blood pressure signals were transmitted by VLC links ranging to 15 meters.

C. *Hybrid transceiver models*

Some of the recent models like in [27] use hybrid channels that use both VLC and RF to satisfy the needs of the MBSN. In this work, Pareto-simulated annealing was used to efficiently select either a VLC link or an RF link to satisfy the underlying system constraints. In comparison with the standard VLC system, their hybrid RF/VLC scheme was able to outperform in terms of SNR. Researchers in [28] propose an integration of an LED array and Bluetooth transmitter chip in a patch to send health data. This patch collects the ECG data based on the health condition of the patient to minimize power consumption. Researchers in [29] also stress the need for hybrid VLC architectures to meet the needs of MBSN.

Table III presents the comparison of all the discussed monitoring techniques in a nutshell view.

TABLE III
COMPARISON OF VLC TECHNOLOGIES IN A MONITORING SETTING

Paper	Transceiver model	VLC technology	Inference
[15]	static	white LED	LED power has an impact over the accuracy of the system
[16]	static	TCRR	Transmission power of LED affects the SNR of the system
[17]	static	LED illumination	Reduced packet error rate by adjusting the data packet size
[18]	static	Photodetectors	Positioning of the sensors greatly affect the interference
[19]	mobile	LED	VLC communication through wearables
[20]	mobile	LED	Line-of-sight connection has a dire impact on CIR
[21]	mobile	Ray tracing LED	Route loss and RMS delay spread have a linear impact on communication
[22]	mobile	2D, 3D statistical models	The geometrical detail of the model had a direct impact on the dataflow
[23]	mobile	VLC-enabled wearable	Orientation of the wearable impacts the communication strength
[24]	mobile	Underwater VLC	Length of the communication impacts the energy efficiency
[26]	mobile	IC - VLC	Link distance, modulation frequency, LED bias current, and signal pattern have an impact on the communication
[27]	hybrid	VLC - RF	Hybrid models satisfy the communication demands of MBSN
[28]	hybrid	LED-BLE	Hybrid models can also be more energy efficient

IV. CHALLENGES AND OPEN ISSUES

Despite VLC having a steep potential to realise several healthcare applications, it also faces several challenges. Some of those are listed as follows:

- **Interference from ambient lighting:** VLC highly relies on the modulation of visible light for its data transmission. When there is any form of interference from other light sources, such as sunlight or artificial lighting in healthcare facilities it can lead to severe attenuation in the signal resulting in data loss or degradation of the communication signal. When considering critical applications like healthcare, such degradation can be catastrophic.
- **Limited coverage and line-of-sight requirement:** In an application like healthcare monitoring, VLC demands a direct line of sight between the transmitter and receiver. In a healthcare setting, this can be challenging because obstacles can obstruct the communication path. Further, the optical signals transmitted through the air experience scattering due to humidity, dust, or other airborne particles present in healthcare environments. VLC does not facilitate communication through signals that can reflect from surfaces. This further reduces the coverage of the range of communication which restricts the practical implementation of VLC in healthcare facilities.
- **Interoperability with existing technology:** The entirety of communication in healthcare applications relies on RF waves. Incorporating VLC now into the existing healthcare systems can pose a major challenge, reasoning the costs involved in the deployment of the technology as well as the necessary change in the infrastructure to be made to accommodate VLC. The adoption of VLC also sometimes requires the use of high-intensity light sources for communication compared to the RF counterpart. Hence, there is a need for low-power VLC technologies for widespread adoption in healthcare settings.
- **Security and Privacy concerns:** VLC-enabled communication is very secure because of its limited range and its operation in confined indoor spaces. However, there can be events like light leakage or transparent partitions that can eventually compromise privacy if sensitive information is inadvertently leaked [30]. It is also vital to ensure network segmentation and isolation to prevent any unauthorized access to sensitive data transmitted through VLC networks.

- **Mobility and positioning of patients:** In line with the indoor localization health setting, the patients usually move around and constantly change positions. This makes it possible to maintain a stable connection of the VLC devices in the system. Movements of the patients result in disruption of the line-of-sight communication leading to eventual data loss. The possibility of mobile transmitters or good switching mechanisms has to be explored to resolve this challenge.

V. CONCLUSION

In this work, we provide an in-depth literature review on the state-of-the-art of VLC-enabled patient monitoring system. We discuss the monitoring system in terms of the static and mobile transceiver models and provide some insights into the literature. Then, we also discuss the usage of VLC in the context of indoor localization in a healthcare setting. In this line, discuss some of the techniques used for this domain and their results. Finally, we provide an in-depth discussion on the open challenges of the VLC-enabled healthcare systems and future scopes. Despite having the potential to be one of the de-facto standards in enabling health care, there is a need to avoid interference due to ambient lighting and methods to secure communication more efficiently.

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