VISIBLE LIGHT COMMUNICATIONS FOR DOWNHOLE TELEMETRY SYSTEM: A MEASUREMENT BASED INVESTIGATION

A Thesis

by

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ABSTRACT

One of the critical components of the extracting and monitoring process in the gas and oil sector is the downhole telemetry system. As sensors resistant to high temperature and high pressure have been developed, more parameters can be monitored to increase safety and efficiency. Increased bandwidth demand for downhole communications necessitated the development of a novel, dependable, and low-cost communication network. By this, Visible Light Communications (VLC) have been suggested in the literature for downhole telemetry systems, since they can address the bandwidth needs by the availability of the huge spectrum. However, the gas types used in the literature so far are not sufficient enough to examine the real field conditions. In this research, after the challenges surrounding the use of VLC in downhole gas pipeline telemetry/monitoring systems are discussed, the performance of VLC is investigated by injecting a large variety of gas into the carbon steel covered gas pipeline, such as Methane, Ethane, and Carbon Dioxide. The effectiveness of the VLC system using a Non-Uniformly Clipped Optic Orthogonal Frequency Division Multiplexing (ACO-OFDM) modulation scheme with 128-FFT and guarding band is experimentally investigated. Furthermore, the impact of the Light-Emitting Diode (LED) colors on a VLC-based downhole telemetry system is also discussed. The measurement results indicate that the color of the LED affects the performance as the dominance of the noise decreases after the 7dB signal-to-noise ratio (SNR) region.

DEDICATION

I dedicated this thesis to my parents who have always supportive anywhere I needed their support, without them I have been unable to accomplish this competitive phase of education.

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Praise be to God, by whose grace good deeds are done. Thank you to my parents and family for all the support provided during my phase of education.

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Contributors

This work was supervised by a chair of committee Dr. Khalid Qaraqe from Electrical & Computer Engineering at TAMUQ and a thesis committee members consisting of Dr. Albertus Retnanto from Petroleum Engineering Department at TAMUQ and Dr. Nimir Elbashir from Chemical Engineering Department at TAMUQ.

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NOMENCLATURE

VLC	Visible Light Communication
ACO-OFDM	Asymmetrically Clipped Optic-Orthogonal Frequency Division Multiplexing
LED	Light Emitting Diode
SNR	Signal to Noise Ratio
MWD	Measurement While Drilling
LWD	Logging While Drilling
MPT	Mud Pulse Telemetry
PD	Photo Detector
ISI	Inter Symbol Interference
ICI	Inter Carrier Interference
IM/DD	Intensity Modulated/Direct Detection
APD	Avalanche Photo Diode
QPSK	Quadrature Phase Shift Key
CP	Cyclic Prefix

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CHAPTER I

INTRODUCTION

The oil and gas sectors are one of the most important sectors in globalization, with certain nations, such as Saudi Arabia, Russia, and Qatar, earning over half of their gross domestic product from it. Given the sector's current significant infrastructure expenditures, the demand for improved continuous supervision, data collecting, and communication networks for even more profitable and effective oil and gas monitoring and extracting is higher than ever. Monitoring and telemetry systems are essential for sustaining control performance and enhancing the productivity and efficiency of downstream and upstream operations.

The operations on drilling are amongst the most critical stage in the exploration and production activities of oil and gas reservoirs considering productivity and efficiency. Measurement-While-Drilling (MWD) and the Logging-While-Drilling (LWD) systems provide the required information to precisely execute and manage the operations. MWD and LWD systems are effective and capable technologies that allow the suitable management and monitoring of the processes associated with downhole by transmitting real-time drilling and logging the data. The LWD is used for measuring the geological developments, while MWD is for quantifying the performance of the drill strings, assessing the parameters of the drill bit and string operations such as torque, smoothness, bit rotation speed, and downhole vibrations associated with the drill bit [1], [2]. As a result, responsible units can use both techniques to manage downhole hardware, enhance productivity, reduce drill string and bit fatigue life, and modify borehole stress instantaneously. On the other hand, secure and reliable real-time data transfer forms the backbone of both systems. Until now, many wired and wireless methods have been tried for telemetry systems. Recently, fiber optic cables are one of the most used methods as a wired system [3]. However, the biggest disadvantage of wired systems is the necessity to stop the operation during data transfer, since the cable cannot withstand high temperature and pressure continuously. Thus, real-time measurement cannot be provided in wired transmission scenario. Therefore, wireless communication is more advantageous in terms of both time and financial expenses. Acoustic, electromagnetic and mud-pulse methods systems have been proposed as wireless methods for downhole telemetry systems [4]-[6]. Mud-Pulse-Telemetry (MPT) uses drilling mud as a communication medium by utilizing parameters such as rotation speed of drill string, and mudflow rate. Although MPT allows a controlled medium [7], desired data rates cannot be reached due to dominant noise caused by the drilling process, such as bit vibrations, and stalled drilling motors, and drill bit contact [4], [8]. Low-frequency electromagnetic waves (in the range of 2–12Hz) have also been used as an alternative to MPT [5], [9]. In addition to not meeting the desired data rates, the low-frequency electromagnetic waves method has practical problems such as requiring large antenna sizes and being too sensitive to environmental conditions.

Therefore, the acoustic wave method, which offers relatively higher data rates, has been proposed in the literature [10], [11]. However, due to the short communication range of the acoustic wave method, data transfer is carried via relays, which increases the cost and complexity of the operation. Considering all the limitations mentioned, the Visible

Light Communications (VLC) method seems to be a natural candidate for downhole telemetry systems in search of a novel, dependable, and low-cost wireless solution [12], [13]. Since VLC has a huge available spectrum (430THz to 770THz), the required data rates can be provided. Therefore, studies on the VLC method in downhole systems have started to gain momentum recently. In [14] considered diffuse reflections for the first time while analyzing the route model on the optimal Lambertian Light-Emitting Diode (LED) transmitter for an empty pipe. Furthermore, a channel model based on ray-tracing which contains crucial characteristics such as the pipeline's inner coating's reflecting qualities and gas requirements is investigated in [15]. Moreover, in [12], [13], the gas pipe surroundings are patterned using Zemax software that simulates the gas pipeline environment shape while considering the interior coating reflections and LED and photodetector (PD) characteristics. In [16], nitrogen and air are used and real field conditions are emulated by providing gas flow with a circulating pump. In [17] besides carbon dioxide measurement, air measurement was also made as a benchmark. Many aspects still need to be considered for VLC to be implemented on downhole systems. The main contributions of this research can be summarized as follows. The used VLC for a gas pipeline environment is only studied from a conceptual viewpoint. In this study, in order to fulfill the gap in the literature, the performance of VLC is investigated experimentally by filling the pipeline with Methane, Ethane, and Carbon Dioxide gases. Especially considering the high percentage of Methane and Ethane in downhole systems, which is the closest results to real field conditions. The applicability of the proposed VLC-based telemetry system on the gas pipeline channels is proved and established to be useful via Bit-Error-Performance analysis on a real data setup. In addition, to the effect of various LED colors on communication performance.

Case Study

The requirement to communicate between surface instrumentation and downhole equipment has aroused the interest of many activists and academics, and as a result, a variety of practical and thought-provoking solutions have been developed. As a result, it has become a critical need as administrators prioritize high levels of process performance and well optimization methods in the Oil and Gas sector.

A downhole monitoring system in the oil and gas sector measures numerous characteristics. Amount, location, materials, lubricant level, and mass are all geologic properties. Environmental and trustworthy measures, such as downhole concentration, flow rate, and water cut tracking, are also taken. This metric assists reservoir designers in enhancing well effectiveness. Temperature and pressure have been the most crucial and required factors in offshore wells. These measurements may be used to determine the depth of the well. The limits of existing methodologies and technology demand the creation of an innovative and robust wireless solution for real-time-downhole monitoring.

Visible Light Communications (VLC) is a promising competitor for this sort of application due to its growing energy economy and advancement. VLCs constitute the advantageous conditions of having visible lights that function in a spectrum resources, have a wide throughput, do not necessitate a license, are low cost, must not have any radio frequency intervention difficulties, use simple receivers such as PDs and transmitters such as LEDs, are stable and secure, have a greater standard of spatial reutilization, and most importantly, the component of fault location is convenient and effective when visible lights are used. Therefore, the use of VLC systems can reduce energy consumption, bring considerable environmental advantages, and aid in the security of operations.

The primary aim of the present research is to examine and create a novel approach, model, and methodology related to the field of visible light communications, which has also been highlighted as an increasing issue of interest. VLC is recognized to have the ability to significantly boost the effectiveness of future generations in the domain of telemetry systems inside the domain of downhole assessment or monitoring in the gas and oil sectors.

Problem Statement

In the present academic and industrial fields, there is a significant interest laid upon creating technology that is effective when communicating amid surface instruments and downhole in the gas and oil industry. Presently, it has not only become a field of interest, it has come to a point of being a key necessity as operators push effectiveness of product and well performances to improve to stay afloat in the competitive and cut throat market environment. Presently, wirelines systems are utilized for this purpose in the industry, nevertheless, such installations are known to create numerous inefficacies such as the need for high maintenance which renders higher costs and need for manpower, as well as concerns with reliability and dependability. Moreover, wireline systems have substantial installation expenses, and pauses in production that leads to downtime which is a wastage of resources, time and money [18].

The main objective of this research is to investigate and develop a new technique, model and method associated with the field of visible light communications which is also identified as an emerging area of concern. VLC is known to have the potential towards improving the performances of future generations in a significant manner pertaining to telemetry systems in the area of downhole assessing or tracking in the gas and oil sector.

CHAPTER II

LITERATURE REVIEW

Challenges with Various Types of Downhole Monitoring Technologies

Modern VLC systems often make advantage of illuminance supplies, including such luminaires positioned in a ceiling of rooms. Aside from such different lighting and ambience sources, sources identified as secondary light could be present, that includes, yet is not limited towards, task lighting, for instance office task light luminaries, standard lamp fixtures, and table lamp fixtures. There are also the accent lights which are utilized for art highlighting and highlighting other artifacts. The light sources that are identified as secondary are able to serve as possible relay terminals when considering a network of VLC. This is done by relaying the data from a light source that is primary to a designated location, for instance a computer or mobile device, by using secondary light sources that operate as possible relay terminals [25].

VLCs encompass the favorable circumstances of having visible lights that operate in a spectrum that is unlicensed, that has a bandwidth which is quite high, does not require a license, is of low cost, does not have any radio frequency interference challenges, us simple receivers such as PDs and transmitters such as LEDs, it is secure and safe, it has a high level of spatial reusage and most noteworthily the aspect of fault finding is simple when visible lights are utilized. As a result, the usage of VLC networks can minimize energy usage, provide significant ecological benefits, and assist with securing applications [26].

Methods and Techniques Presently Used with VLC Technology for Downhole Gas Pipeline Monitoring

Wirelines are utilized in the oil and gas sector for the said purpose, although such installation efforts offer dependability and maintenance concerns. Moreover, wireline systems are known to comprise of substantial expenses attributable to installation and their operations necessitate a pause in production activity, which incurs additional expenses to the operator as a result of downtime.

A number of wireless technologies pertaining to communication exists. There are also a number of methodologies that could be employed in downhole monitoring; yet every wireless technology used for monitoring has their unique implementation issues [10]. One technology that has long been utilized in the oil and gas sector is the mud-pulse telemetry as a primitive method to monitor wirelessly. This entails using drilling mud as a transmitter side while changing drilling settings (for instance rotation drill string speed, mud flow rate. A generic system pertaining to mud-pulse throughput is limited to quite low rate (which is only a few bits per second), especially if the well is deep [27]. These issues involve reduced impulses as a result of the tough drilling conditions, as well as high temperature and pressure levels that add distortion to the transmission. Other technique is to employ low-frequency electromagnetic radiation (e.g., 212 Hz) as the data transmission method, with the good metallic structure (tubing string) as the variable [28]. Nevertheless, this approach is not a robust approach in principle and is vulnerable to environmental development.

For instance, if particular types of formations (as a result of influences pertaining to resistivity of the earth). For example, in particular formations (because to the influence of earth resistivity), the pulse might quickly lose power, turning undetected at only a few hundred meters of depth. Because of this dispersion, large antennas are required to identify low frequency signals; yet, a tiny pipeline system would not be capable of accommodating such an antenna. Another technique is to employ acoustic waves, which give a rather more reliable system at larger data speeds [10].

Present acoustic telemetry equipment is primarily designed for producing tubing with diameters of up to 4 inches and can work at well levels of up to 2000 meters. The specifications for wells in Qatar, on the other hand, vary markedly, with depths of roughly 5000m and the use of production tubing with a thickness of 7 inches. Additionally, the below portion of their tube is covered in cement and spans 6000m, poses a substantial mechanical problem for acoustic signaling.

Several parameters are measured in an oil and gas sector downhole monitoring system [25]. The geologic characteristics include amount, position, materials, lubrication level, and mass. Ecological and dependable measures, such as downhole density, flow rate, as well as water cut tracking, are also taken. This measurement aids reservoir engineers in improving well efficiency. The most critical and necessary characteristics in offshore wells are pressure and temperature. The depth of the well may be determined based on these measures.

The limitations of existing techniques and technology, as described above, necessitate the development of a novel and dependable wireless solution for real-time downhole observation. As a result of its increasing energy economy and development, Visible Light Communications (VLC) is a hopeful contender for this type of application.

CHAPTER III

SYSTEM MODELS

ACO-OFDM based VLC System Model

Orthogonal Frequency Division Multiplexing (OFDM) is a very well-known and widely used technique in most communication systems to achieve a high data rate and mitigate Inter-Symbol-Interference (ISI) and Inter-Carrier-Interference (ICI). Since the conventional OFDM cannot be used in optical communication systems due to the need for non-negative Intensity-Modulated/Direct-Detection (IM/DD), asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing (ACO-OFDM) is considered. The block diagram of the ACO-OFDM system is shown in Figure 1. ACO-OFDM parameters [19].

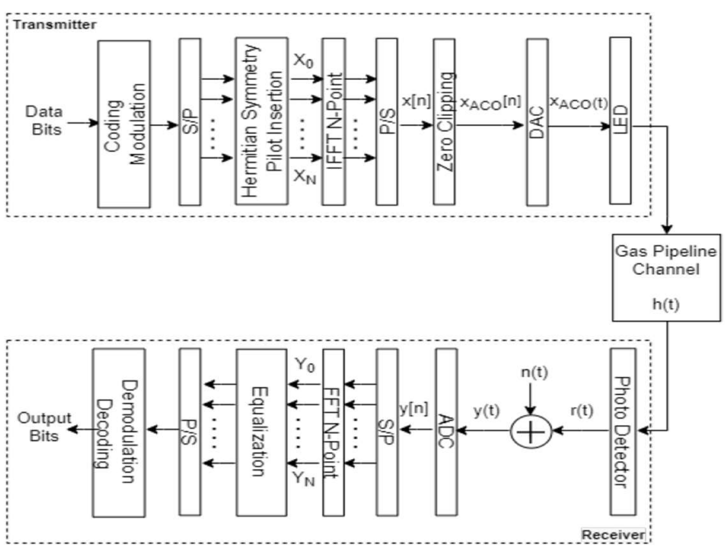

Figure 1 Block Diagram of the ACO-OFDM System

Channel Model for Gas Pipelines

There have been specific intermittent efforts rendered towards addressing the VLC channel modelling [20], [21]. Particularly, the Monte Carlo Ray tracing was utilized towards calculating the CIR pertaining to a room that was empty at the VL wavelengths [20], however, the dependance pertaining to the wavelength was avoided since surface materials have constant reflectance values. The recursive approach presented by [22], was utilized in [21] studies to get CIR in the VL band. However stable reactance is maintained once more. The reflectance parameters are extracted as the mean of frequency dependent coefficient over through the VL band in order to capture the impact of wavelength dependence in channel estimation. Thus far, very limited studies have specifically taken wavelength dependence into consideration is described in [23], where a recursion technique is employed to calculate the CIR of an evacuated chamber. Nevertheless, the requirements of only solely diffuse reflections and a perfect Lambertian supply, which may not be applicable in many real circumstances.

This research, provides numerous CIRs for diverse indoor situations based on a realistic VLC channel modeling technique that solves the constraints. Zemax, a commercial optical and lighting design program [24], serves as the foundation for our modeling. Even though the primary goal of such program is optical system development, which uses its ray tracing characteristics to accurately describe the interplay of rays emanating from a lighting source inside a defined limited region. The test scenario is generated in Zemax, and it allows us to determine the shape of the system, the items inside it, and the specifications of the receivers (i.e., photodiodes) and generators (i.e., LEDs). The non-sequential ray tracing tool estimates the observed power and route distances from sources to detectors for every ray for a specified number of rays and number of reflections. Thereafter, these readings are then input into MATLAB and analyzed to get the CIR with totally diffuse reflections and a perfect Lambertian source. This method may also get CIRs for additional (non-ideal) data sources, and also specular and mixed specular-diffuse reflections.

CHAPTER IV

MEASUREMENT SETUPS

The measurement was conducted at the premises of the Texas A&M University situated in Qatar. Measurements are carried out under generic room lighting conditions without the use of optical filters.

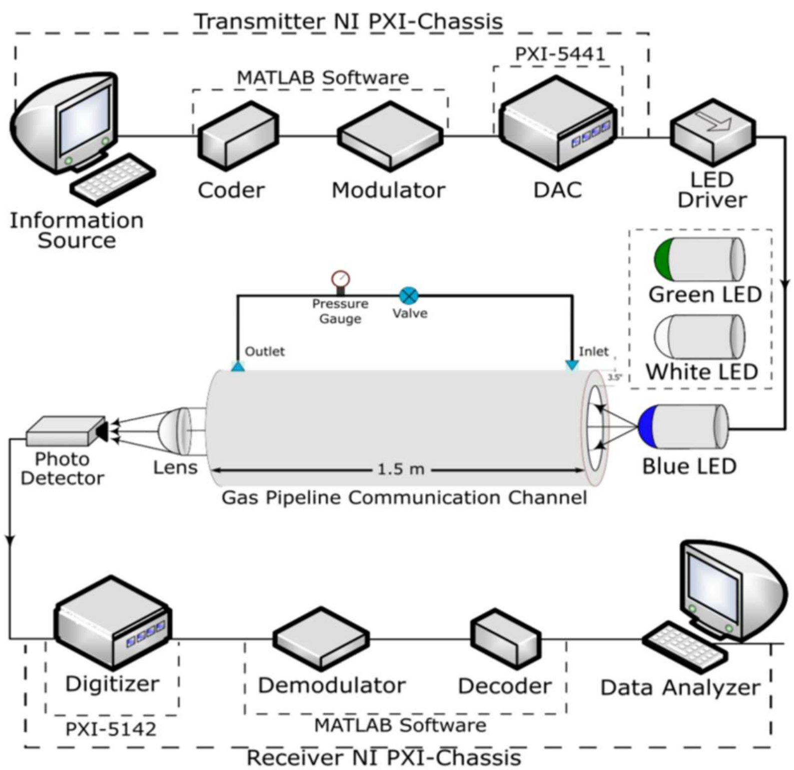

Figure 2 Block Diagram of the Measurement Setups

The measurement setup is shown in Figure. 3 below as well as the block diagram in Figure. 2 above. As shown from the figures, the measurement setup consists of three parts: the transmitter, the gas pipeline and the receiver.

On the transmitter side, the NI PXI-5441 16-bit 100 MS/s arbitrary waveform generator is connected to the driver circuit that makes the analog signal suitable for the LED. The LED driver consists of a high bandwidth buffer and current limiter resistors that adjust the power of the signal. In order to investigate the effect of colors on downhole telemetry systems THORLABS M470L4 blue, THORLABS MCWHL5-C1 white, and THORLABS M530L4 green LEDs with central nominal wavelengths of 470 nm, 440 nm, and 530 nm are used.

The gas pipeline communication channel is emulated with a 1.5-meter-long, 3.5-inch diameter metal pipeline. Two endpoints of the pipeline are equipped with METAGLAS 2-inch NPT threaded sight glasses that are connected to the hexagonal-based sight glasses in order to allow transmitting the light through the pipeline. By extending the safety conditions in the setup, more realistic measurements are made than in previous studies by examining methane, ethane and carbon dioxide, which constitute more than 95% of the gases in the real field downhole systems [15]. It should be noted that; the gases are put into the pipeline separately at atmospheric pressure using CONCOA regulator and soda siphon charger.

In the receiver, Hamamatsu C12702-04 Avalanche Photodiode (APD) modules and NI PXI-5142 14 bit 100 MSamples/s PXI digitizer is used. The PD has a peak response at a wavelength of 800nm with a 3dB bandwidth of 4kHz to 80MHz. By placing a lens between the PD and the pipeline, the light is focused on the active area of the photodiode.

The measurement consists of four software parts: preprocessing, transmission, reception, and post-processing. In the pre-processing block, the data produced with a random number generator with a predefined seed in MATLAB software is modulated with Quadrature-Phase-Shift-Keying (QPSK) modulation. After the data is converted from serial to parallel, pre-generated pilot sequences are placed for channel estimation. A Cyclic Prefix (CP) and synchronization signal are added to the transmission after IFFT procedure. Finally, the ready-to-send signal is saved in binary format.

For the transmission, the produced data is sent to the NIPXIe-1082 device and forwarded to the NI PXI-5441 DAC by using NI LabVIEW software. The output is transferred to the LED driver that is designated that generates an intensity modulated signal. The signal is transferred to the LED via the LED driver with a data rate of 2Mbps.

For the reception, the transmitted intensity-modulated signal is captured with Hamamatsu C12702-04 APD. The NI PXI-5541 digitizer processes the output of APD. The received data is saved on the hard drive to be given to the post-processing stage.

All the steps in the post-processing stage are performed in the MATLAB software. Firstly, the synchronization signal is detected and then the CP is removed. FFT operation is applied after the data is converted from serial to parallel. After the equalization is performed, the SNR value is determined.

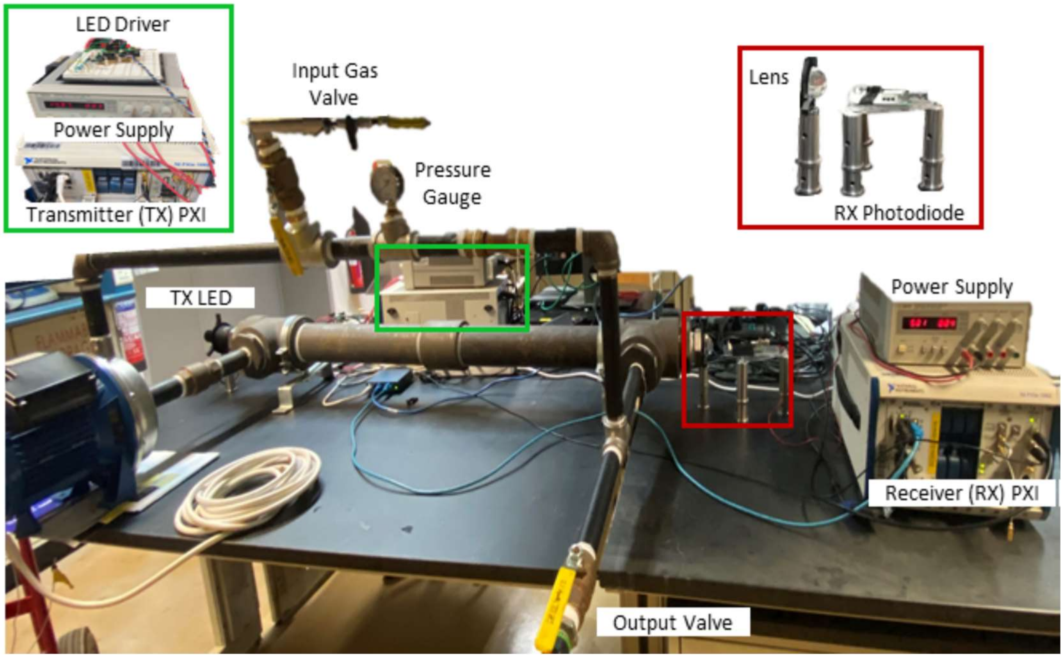

Figure 3 Illustration of the Gas Pipeline Measurement Setup

CHAPTER V

RESULTS & DISCUSSION

The Bit-Error-Rate (BER) versus Signal-to-Noise-Ratio (SNR) performance of VLC based ACO-OFDM transmission with blue, green and white led colors in Methane, Ethane, and Carbon Dioxide filled pipeline is shown in Figure. 4, Figure. 5 and Figure. 6, respectively. As a benchmark for this research, the air measurements in [17], can be taken into account.

As can be seen from the below figures, VLC ACO-OFDM communication showed promising results in all three different gases scenarios. It is observed that color differences affect the communication performance in the 7dB to 15dB SNR region. After many repeated measurements, it is concluded that BER values do not form a certain pattern at SNR levels less than 7dB since the noise is much more dominant in communication than the effect of colors. In addition, after 15dB, the BER is unable to go lower than a certain value as the system becomes saturated. When the results are analyzed from this perspective, it is observed that blue color performs better than white and green colors. Especially in the methane scenario, blue performed much better than the other colors since as stated in [15], the maximum transmittance of Methane gas is in the range of 464nm-478nm. Besides, in the investigation of BER performance according to different gas types, it is concluded that Ethane gas with larger particle diameter and density affects communication more negatively than Methane and Carbon Dioxide.

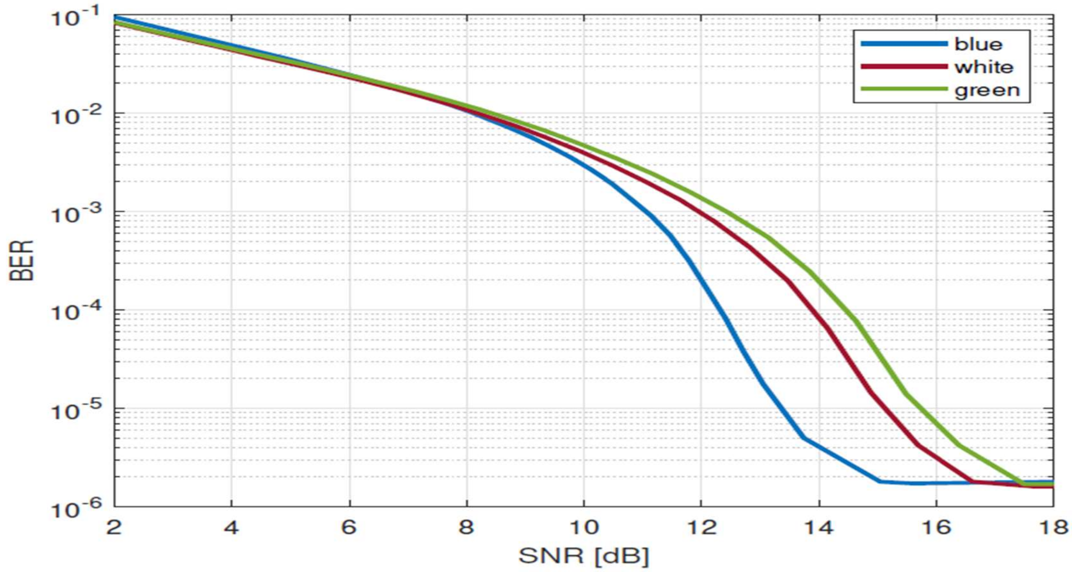

Figure 4 BER Performance Versus SNRs with Different Colors of LEDs Over the Methane Filled Gas Pipeline Channel

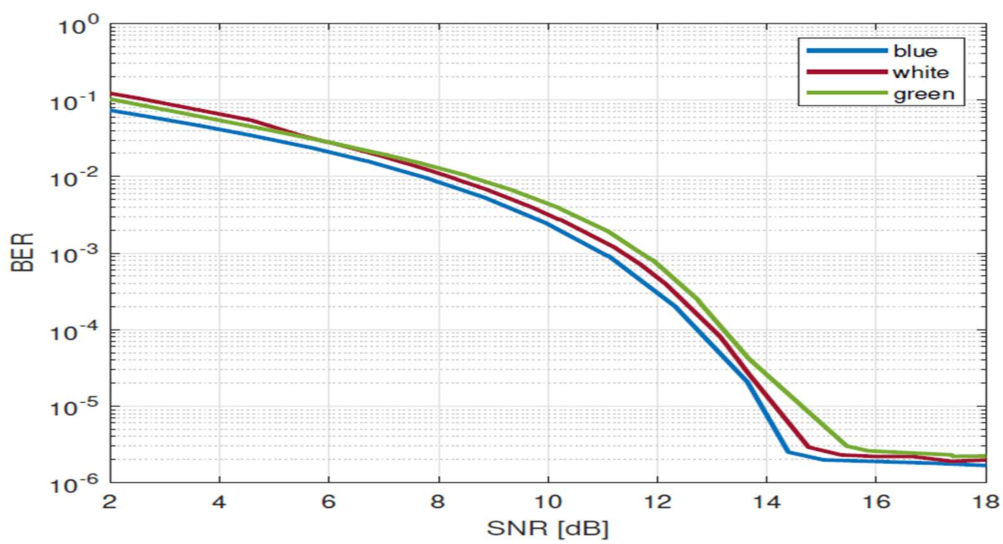

Figure 5 BER Performance Versus SNRs with Different Colors of LEDs Over the Ethane Filled Gas Pipeline Channel

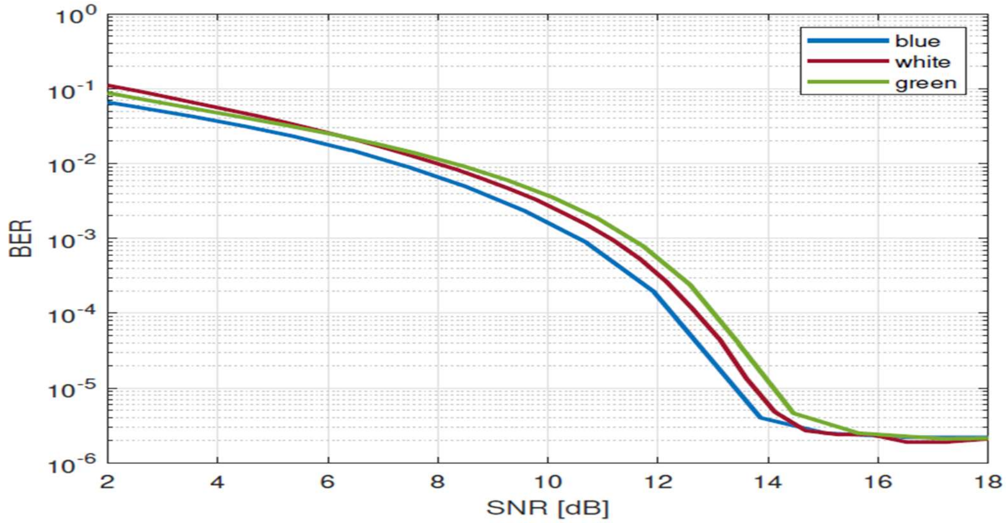

Figure 6 BER Performance Versus SNRs with Different Colors of LEDs Over the Carbon Dioxide Filled Gas Pipeline Channel

CHAPTER VI

CONCLUSIONS & FUTURE WORK

After the development of the downhole application-specific VLC ACO-OFDM system, the communication performance of LED colors on VLC is investigated by filling the pipeline with the different gases types constituting the majority of gases in downhole systems such as Methane, Ethane and Carbon Dioxide. The pipeline is filled with gases separately under atmospheric pressure conditions. Measurement results show that the blue LED color performs better than other LED colors such as white and green. In addition, the results showed that during the system design process, it is necessary to focus on the SNR region from 7dB to 15dB. Consequently, it is stated that VLC is an important candidate for downhole gas pipeline monitoring systems where a reliable, flexible, and low-cost solution is sought.

One of the challenges with VLC downhole systems is the alignment problem that encountered many times during the measurements. In future research, the measurements can be repeated by taking into account the gases as a real field percentage to examine the performance of VLC downhole telemetry systems in real field conditions. In addition to that, the best performing color for the VLC downhole telemetry system can be determined by increasing the variety of LED colors.

REFERENCES

[1] R. Desbrandes and R. Clayton, “Measurement while drilling,” in Developments in Petroleum Science. Elsevier, 1994, vol. 38, pp. 251–279.

[2] A. W. Kamp, “Downhole telemetry from the user’s point of view,” Journal of Petroleum Technology, vol. 35, no. 10, pp. 1792–1796, 1983.

[3] T. Jacobs, “Downhole fiber-optic monitoring: An evolving technology,” Journal of Petroleum Technology, vol. 66, no. 08, pp. 44–53, 2014.

[4] C. Klotz, P. R. Bond, I. Wassermann, and S. Priegnitz, “A new mud pulse telemetry system for enhanced mwd/lwd applications,” in IADC/SPE drilling conference. OnePetro, 2008.

[5] K. Tietze, O. Ritter, and P. Veeken, “Controlled-source electromagnetic monitoring of reservoir oil saturation using a novel borehole-to-surface configuration,” Geophysical Prospecting, vol. 63, no. 6, pp. 1468–1490, 2015.

[6] A. K. Farraj, S. L. Miller, and K. A. Qaraqe, “Propagation measurements for acoustic downhole telemetry systems,” in SPE Annual Technical Conference and Exhibition. OnePetro, 2013.

[7] N. G. Franconi, A. P. Bunger, E. Sejdi´c, and M. H. Mickle, “Wireless communication in oil and gas wells,” Energy Technology, vol. 2, no. 12, pp. 996–1005, 2014.

[8] S. M. Mwachaka, A. Wu, and Q. Fu, “A review of mud pulse telemetry signal impairments modeling and suppression methods,” Journal of Petroleum Exploration and Production Technology, vol. 9, no. 1, pp. 779–792, 2019.

[9] N. Shoaib, A. Bouchalkha, and K. Alhammadi, “Electromagnetic wave propagation in underground oil pipelines,” in 2016 16th Mediterranean Microwave Symposium (MMS). IEEE, 2016, pp. 1–4.

[10] T. J. Ahmad, M. Noui-Mehidi, and M. Arsalan, “Performance analysis of downhole acoustic communication in multiphase flow,” in IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society. IEEE, 2014, pp. 3909–3913.

[11] A. Redissi and S. Miller, “Communication through acoustic vibration of pipe strings,” The Journal of the Acoustical Society of America, vol. 146, no. 2, pp. 1416–1426, 2019.

[12] S. C. Tokgoz, S. L. Miller, and K. A. Qaraqe, “On the investigation of achievable links for vlc based wireless downhole telemetry systems,” in 2020 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom). IEEE, 2020, pp. 1–6.

[13] K. Dalle, J. Medina, S. C. Tokgoz, S. L. Miller, and K. A. Qaraqe,“Visible light communications for downhole gas pipeline monitoring systems,” in 2020 28th Signal Processing and Communications Applications Conference (SIU). IEEE, 2020, pp. 1–4.

[14] Y. Li, S. Videv, M. Abdallah, K. Qaraqe, M. Uysal, and H. Haas, “Single photon avalanche diode (spad) vlc system and application to downhole monitoring,”in 2014 IEEE Global Communications Conference. IEEE, 2014, pp. 2108–2113.

[15] F. Miramirkhani, M. Uysal, O. Narmanlioglu, M. Abdallah, and K. Qaraqe, “Visible light channel modeling for gas pipelines,” IEEE Photonics Journal, vol. 10, no. 2, pp. 1–10, 2018.

[16] O. Alaca, S. C. Tokgoz, A. Retnanto, S. L. Miller, and K. A. Qaraqe,“Experimental demonstration of visible light communication based downhole telemetry system,” in 2021 IEEE International Mediterranean Conference on Communications and Networking (MeditCom). IEEE, 2021, pp. 366–371.

[17] O. Alaca, S. Tokgoz, A. Retnanto, S. Miller, and K. Qaraqe, “On the investigation of carbon dioxide medium for vlc based downhole telemetry system,” in 2022 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom) (IEEE BlackSeaCom 2022), Sofia Bulgaria, jun 2022.

[18] Cevik, T. & Yilmaz, S., 2015. An overview of visible light ccommunication systems. International Journal of Computer Networks & Communications (IJCNC) , 7(6), pp. 1-12.

[19] S. C. Tokgoz, R. Boluda-Ruiz, S. Yarkan, and K. A. Qaraqe, “Aco-ofdm transmission over underwater pipeline for vlc-based systems,” in 2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). IEEE, 2019, pp. 1–7.

[20] Chun, H., Chiang, C. & O'Brien, D. C., 2012. Visible light communication using OLEDs. Illuminating and channel Modelling. International workshop on optical wireless communications (IWOW), pp. 1-3.

[21] Komine, T. & Nakagawa, M., 2004. Performance evaluation of visible-light wireless communication system using white led lightings. Proceedings. ISCC 2004. Ninth International Symposium on Computers And Communications, 1(1), p. 258.

[22] Barry, J. R. et al., 1993. Simulation of multipath impulse response for indoor wireless optical channels. IEEE Journal on Selected Areas in Communications, 11(3), pp. 367-379.

[23] Lee, K., Park, H. & Barry, J. R., 2011. Indoor channel characteristics for visible light communications. IEEE Communications Letters, 15(2), pp. 217-219.

[24] Zemax, 2022. Zemax 13 Release 2. Radiant Zemax LLC.. [Online] Available at: http://www.radiantzemax.com/zemax [Accessed 14 April 2022].

[25] Morapitiya, S. S., Jayakody, D. N. K. & Weerasuriya, R. U., 2020. Visible Light Communication for Downhole Monitoring. 12 th International Research Conference, pp. 1-15.

[26] Haigh, P. A., 2014. 1-Mb/s visible light communications link with low bandwidth organic components. IEEE Photonics Technol. Lett., Volume 26, pp. 1295-1298.

[27] Stokka, S., Andersen, J., Freyer, J. & Welde, J., 1993. Gas kick warners - an early gas influx detection method. SPE/IADC Drilling conference.

[28] Wilt, M. et al., 1995. Crosshole electromagnetic tomography: A new technologue for oil field characterizaation. The Leading Edge, 14(3), pp. 173-177.