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A Review of Downhole Communication Technologies

Augustus E. Ibhaze[1], Deborah O. Akinola[1], Agbotiname Lucky Imoize[1,2], Patience E. Orukpe[3], Frederick O. Edeko[3]
[1]Department of Electrical and Electronics Engineering, University of Lagos, Akoka, Lagos 100213, Nigeria
[2]Department of Electrical Engineering and Information Technology, Institute of Digital Communication, Ruhr University, 44801 Bochum, Germany.
[3]Department of Electrical and Electronics Engineering, University of Benin, Benin City 300283, Nigeria.
aimoize@unilag.edu.ng

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Abstract

Different telemetry techniques have been tested and used in the oil and gas industry to acquire data via downhole monitoring. However, the rate at which conventional telemetry systems transmit data is low. In order to address this problem, some telemetry techniques have been proposed. The wired and wireless drill pipes are among the contending classifications of telemetry techniques used in downhole monitoring. This review provides an in-depth overview of the existing and researched methods of downhole monitoring by highlighting their particular challenges and innovations for which the wireless drill pipe based on visible light communication techniques proves to be promising as an optimal telemetry technique. The review will guide future research studies in the common area of interest in downhole monitoring. The study will contribute significantly to the oil and gas industry by investigating the effectiveness of emerging technologies such as visible light communication technology in transmitting data at a very high rate compared to the existing telemetry techniques.

I. INTRODUCTION

A communication system connotes the transfer of information between the transmitter and the receiver. The signal or information transferred passes through the wireless channel to the receiver [1]. A downhole communication system communicates between a downhole region inside a wellbore and a surface position. A downhole tool, a telemetry module, and an interface electrically linking the downhole device to the telemetry modules are all part of the system. The telemetry module is connected to a string and receives signals based on the telemetry technique [2]. The optical spectrum is a portion of the electromagnetic spectrum that varies from infrared to visible and ultraviolet regions. In contrast, the optical communication system uses light to transmit a message from one medium to another by transforming the message between optical and electrical signals [3]-[5]. Visible light communication (VLC) is a form of optical wireless communication (OWC) known for the transmission of unguided optical signals, which in turn makes it possible to transmit data at high speed with visible light [6].

In downhole communication, signals are sent from a device at the bottom of the drill string (a drill pipe column that transmits drilling fluid to the drill bit) to a processing screen on the surface in real-time (during drilling) [7]–[8]. Currently, communication with downhole tools during drilling is achievable with techniques such as mud-pulse telemetry (MPT), which is the most commonly used following its ease of implementation and the electromagnetic telemetry (EMT), acoustic telemetry, and wired drill pipe telemetry [9]-[10]. The mud-pulse telemetry gives an average data rate of about 5 to 10 bps [11]. Electromagnetic telemetry (EMT) provides data rates higher than MPT, acoustic telemetry gives a higher data rate than MPT and EMT, and wired drill pipe telemetry offers the highest data rates (up to 57Mbps) [12] among the techniques.

With more diverse and advancing technologies, there is a need to transmit data at greater and higher rates. One of the biggest concerns in obtaining data for real-time monitoring has been the average data transmission speed [9]. Another is providing and adopting a more efficient communication system between downhole and surface instruments for maximum production efficiency and improved good performance [13]. Reliable data acquisition and transmission for downhole communication, especially in controlled spaces, remains a problem in the field [14]. Using the VLC system as a telemetry technique will be one of the most reliable, cost-effective and fastest methods for obtaining downhole data [15]. The invention of the photophone brought about the concept of VLC reported by Alexander Graham around 1880 [16]. The photophone was a method that relayed speech over a long distance using modulated sunlight. His invention was a guiding line for fibre optic communication [16]. Later in 1995, a few Universidad de Buenos Aires students used the photophone concept to develop a laser diode [16]. It was used to detect photodiodes. In 2003, three undergraduates at Keio University, Japan, developed more on the concept and began new works using LED lighting [16]. VLC is a new revolutionary high-speed communication technology that uses visible light for communication. It makes technology the fastest means of communication utilizing light. The VLC technology as a telemetry technique could achieve a data rate of up to or more than 1Gb/s [15], [17], [18], [19].

Downhole data acquisition is a crucial part of the oil and gas industry. Over the decades, different telemetry techniques have been tested and used to acquire data via downhole monitoring. By using other propagation methods, each telemetry technique transmits downhole data from the well to the surface. Each method has diverse advantages and disadvantages, resulting in unreliability and temporary efficiency [9], thus requiring technological improvement and advancement. Wireless drill pipe telemetry (WDPT) currently transmits data at the highest rate compared to the other techniques. Its effectiveness ranges from having little or no signal attenuation, interference, and unlimited depth. It is also the most expensive among the methods used [9].

The limitations of the existing telemetry technologies used in the industry, such as high signal attenuation, low data rates, power and distance trade-offs etc., require a much more reliable and cost-effective solution for the acquisition of downhole data for downhole monitoring in real-time [20]-[22]. Therefore, alternate wireless telemetry based on VLC is proposed for further investigations as a possible solution. Works exploring VLC as a telemetry technique for downhole data acquisition are demonstrated in [23]-[24]. Both works have very usable results highlighting the clear advantages of using VLC as a telemetry technique. Maximizing production from deep hydrocarbons or petroleum reservoirs requires real-time two-way communication for up-linking and down-linking. Telemetry channels are necessary to maintain continuous interaction with the downhole environment while drilling occurs [25]. The contributions made in this article encompass the investigation of gaps in existing telemetry techniques in relation to their transmission techniques, coding, modulation and throughput performances. The visible light communication technique is equally proposed as a possible solution to the throughput limitations inherent in the existing telemetry techniques.

The remainder of the article is organized as follows. Section 2 presents the methods covering the various telemetry systems used in the oil and gas industry. Section 3 covers the deployment of VLC and the market penetration of visible light communication. The progress made in wired and wireless telemetry technology is discussed in Section 4. The conclusions and directions for further work are presented in Section 5.

II. TELEMETRY METHODS

There is a requirement for telemetry channels to maintain a consistent connection with the downhole environment while drilling takes place. Generally, the importance of a telemetry channel stems from its usefulness in transmitting information from the surface to the bottom hole assembly (BHA) so that the necessary trajectory control can be achieved. It is also helpful in navigating the tools and transmitting the information from the sensors close to the drill bit (the cutting equipment used to create holes) to the surface [25].

Much of this is done to further one's understanding and understanding of the formation (rocks around the borehole) and also to make sure that the wellbore follows its previous designated (well) path [25]. It is good to know that the sensors established downhole close to the drill bit give formation evaluation data and drilling data. Notably, the rate or speed at which telemetry systems can carry information is crucial [25].

The telemetry techniques currently used in the industry can be classified mainly into wireless and wired telemetry. The wireless telemetry techniques used are known as mud pulse telemetry (MPT), electromagnetic telemetry (EMT) and acoustic telemetry (AT). The wired telemetry method used is the wired drill pipe telemetry (WDPT). The mud pulse and acoustic telemetry both use pressure waves to propagate information. In comparison, electromagnetic and wired drill pipe telemetry makes use of electromagnetic waves [9] - [10], [25]-[27].

The mud pulse telemetry (MPT) is the most common and widely used telemetry method, and the wired drill pipe telemetry (WDPT), although not as common and used as the MPT, achieves the highest data rate transmission compared to the other telemetry methods [15], [25]–[26]. Due to this observation, the MPT and WDPT are discussed more considerably than electromagnetic and acoustic telemetry in this section.

These current telemetry systems suffer from several disadvantages like very low data rates, high signal attenuation, low channel reliability and so on [9] – [10], [20] and [27]. This section considers the existing telemetry techniques and discusses each telemetry method and its basic information like general designs, methods, and theories.

A. Mud Pulse Telemetry

Mud pulse telemetry (MPT) was introduced commercially in the 1970s. Mud pulse telemetry (MPT) is the oldest telemetry technique to transmit borehole data. This discovery was a milestone in the industry, especially in directional drilling. It gave the directional driller real-time details on the steering system’s output and the wellbore’s geometric location. In addition, this caused significant improvement in directional drilling’s performance and accuracy while minimizing risk [10], [25].

Like any communication system, a telemetry system needs a transmitter and a receiver to transfer information or data effectively. The two primary processes of a telemetry system are the uplink and downlink [25]. The drill string achieves downlink communication by changing the rotation rate, usually used for trajectory regulation or steering. It can also be achieved by intermittent mud flow rate changes [25]. Here, the flow rate variance or rotational motion identifies and reacts to the sensors in the downhole measurement while drilling (MWD) [25]. For up-link communication, data is transmitted via the MWD instrument in the bottom-hole assembly (BHA) by producing pressure pulses in the mud stream, including the support of a mud pulser, a pressure-inducing pressure system. Here, the sensors in the receiving system determine pressure fluctuations at the surface, and signal processing units analyze the readings. This technique is known as decoding [25].

It transmits data via coded pressure waves through several digital and analogue modulation methods using positive or negative pulses. Alternatively, it uses an oscillating shear valve or mud siren [10]. The valve producing these pressure waves or pulses can be of various configurations and outlines and be divided into various operating system forms. Positive pulse, negative pulse and continuous pulse are the three primary forms. In practice, any of the three forms can be used if there is the possibility of the valve creating easily enough exists (in the order of ms). Based on the drilling system parameters, the pulse length will range from 80ms to about 400ms [9]. The equipment causes a constraint in the positive pulse, which causes the pressure of the standpipe to rise. It was observed that a portion of the flow leaks through the annulus for the negative pulse. The equipment causes that, and that results in a decrease in pressure. Lastly, for the continuous pulse, continuous constraints and reliefs are created by a modulator and stator [25].

Its transmission channel is based on the drilled mud inside the drill string. Its receiver is a standpipe-mounted pressure sensor that converts the pressure waves to voltages that embedded processors and operators would decode and use during the processing of directional drilling [10].

The mud pulse telemetry system consists of multiple parts: the downhole transmitter, the surface receiving system, the transmission channel, and associated downhole surface processing units [25]. The downhole and surface modules are engineered to achieve the highest data rate and reliability level. Several additional components are interfaced with the surface system to account for signal alterations during transmission [25].

It should be noted that the frequency of the pressure wave (to be propagated) and the properties of the drilling mud and the drill string determine how much the pressure wave propagates [27]. In order to express mathematically, the wave equation suitable for pressure wave propagation considering a continuous flow of pressure is given by equation (1) [27]:

$$\nabla^2 p = \frac{\rho_0 \partial^2 p}{B \partial t^2} \tag{1}$$

where:

ρ_0 = the drilling mud's density

B = the drilling mud's bulk modulus

p = wave pressure

The pressure's wave time and spatial relationship to the drilling mud density are related by equation (1). Pressure, depth, and temperature often affect density fluctuations in drilling mud. An analytical model relating temperature, pressure, and density has been established and is given by equation (2) [27]:

$$\rho = \rho_{sf} e^{\Gamma \rho_0 T} \tag{2}$$

where:

ρ_{sf} = drilling mud static density (at the surface)

$\Gamma \rho_0 T$ = temperature and pressure differentials define the analytical function

T = mud temperature

With an increase in depth, temperature and pressure also rise, causing a decrease in density because of thermal expansion and increased density due to the drilling mud's compressibility. While the drilling mud's density changes influence the pressure wave's attenuation, the wave will be further attenuated by the radiative losses, the stiffness of the tool joints, and the moment of inertia [27].

Another characteristic of the mud channel is its signal attenuation. The distance determines the signal's attenuation as it passes across the mud channel, the mud signals travel, and the mud properties used, are defined by [28] using lamb's law. Equations (3) - (6) give a mathematical expression to prove that with increasing distance, the mud pulse's attenuation also increases exponentially [25].

$$P(x) = P_0 e^{-x/L} \tag{3}$$

with,

$$L = \frac{d_i c}{2} \sqrt{\frac{2}{vw}} \tag{4}$$

where:

$P(x)$ = pressure wave's amplitude at a distance x from the source, measured in Pascal (Pa) or psi

P_0 = pressure wave's amplitude at the source, measured in Pascal (Pa) or psi

d_i = pipe's internal diameter measured in feet or meters

v = kinematic viscosity, measured in ft^2/s or m^2/s

c = velocity of the wave in ft/s or m/s

w = angular velocity in radians per second

By ignoring the pipe modulus effects, wave velocity (c) can be mathematically expressed as [25]:

$$c = \sqrt{\frac{B}{\rho}} \tag{5}$$

where:

ρ = drilling mud or fluid density, measured in kg/m^3

B = mud bulk modulus, measured in Pascal (Pa)

Substituting (5) into (4), we have the mathematical expression as [25]:

$$L = \frac{d_i c}{2} \sqrt{\frac{2B}{\eta w}} \tag{6}$$

where:

$\eta = \rho v$ = plastic viscosity

Notable, equation (3) holds only for high-frequency telemetry systems more significant than 10 Hertz. For a low-frequency system, equation (7) is more suitable to be used or applied, and R is defined in equation (8) and C in (9) [25]:

$$P(x) = P_0 (1 - e^{R/C}) \tag{7}$$

$$R = \frac{P}{Q} \tag{8}$$

$$C = \frac{V}{B} \tag{9}$$

where:

R = mechanical resistance, measured in Pascal

Q = volumetric flow rate in m^3/s

C = mechanical compliance in m^3/Pa

V = mud's volume above MWD instrument (m^3)

The MPT is only usable during the drilling process [27]. It is a highly dependable and stable method with a regulated medium for transmission, low signal attenuation, and the capacity to transmit data over a long distance. However, it achieves low data rates. The low data rate is due to signal interference and signal attenuation, as an increase in length causes an increase in pulse length, which is necessary to acquire the signals reliably. So, the data rate reduces [25]-[26]. The reduction in data rates is affected by the properties of the drilling mud (which affects the signal attenuation), which is not approvable for underbalanced drilling. Because of the hardware's long-term stability, MPT has been restricted to MWD systems [27]. In addition, the signal in the fluid can only propagate at the speed of sound, which in turn causes latency [26].

B. Electromagnetic Telemetry

The electromagnetic telemetry (EMT) system was introduced in the 1980s. It consists of a transmitter that transmits data via coded EM waves, using an installed electrical insulating sub (the transmitter) [10]. This installation is possible as the drill string is made used as a dipole electrode which produces a voltage difference that is altered [10]. The rest of its communication parts are the channel / propagating medium that uses the formation (which is) adjacent to the wellbore. The receiver receives the data transmitted as a measured voltage difference between the wellhead and an antenna anchored on the earth's surface. In addition to the system, a casing antenna can also be included for operation [10]. Maxwell's equations relate to the electric and magnetic fields and can calculate how the EM waves propagate across conductive media. The EMT system works in the near field because the electric field's wavelength has higher magnitude orders greater than the good casting's measurement. Relatively, an estimation of the circuit can be obtained during transmission (i.e. the channel) [27]. By using Maxwell's Equation: Ampere's Law, we have equation (10), whose components are defined in (11) and (12) in [29]:

$$\nabla x H = J + \frac{\partial D}{\partial t} \tag{10}$$

with,

$$D = \varepsilon E \tag{11}$$

$$J = \sigma E \tag{12}$$

where:

H = magnetic field intensity

D = electric flux density

J = current density

ε = permittivity of the material

σ = conductivity of the material

The density of the electric flux **D** can be proportionally related to the material's permittivity ϵ, and electric field **E,** which relates to the movement of **E** across the medium. The medium's conductivity (σ) and electric field **E** are proportionally related to the current density, representing current transmission. The magnetic field **H** that relates to the electric field lines propagates perpendicularly.

Good conductors where the conductivity of the material is far greater than 1, lossy media where the conductivity of the material is incredibly approximate to 1, and low-loss media where the conductivity is far lesser than 1, make up the bulk geological media's bulk [27]. Equation (10) would be governed by **D** as a low-loss geological medium. Here, no current will flow with the movement of the electric field in the medium [27]. The current will flow in the same direction as the electric field for a lossy geological medium. J would govern equation (10) for an excellent conducting geological medium, and current will flow through the medium with attenuation occurring intensely in the electric field [27]. These theories can be portrayed by comparing them to the workings of a circuit system [27]. As a result, it can be concluded that the geological medium decides the mode of transmission, and the best antenna arrangement for inserting current into the formation should be selected appropriately [27]. Some of the other theories guiding the workings of the EMT system are listed following the relation in (13) [27]:

$$E(z) \approx E_0 e^{-z} \bullet \sqrt{\frac{w\mu\sigma}{2}} \tag{13}$$

Equation (14) shows the relation of the attenuation constant with the transmission of the electric field's attenuation.

$$E(r) = iw\mu \int_{v} dr' J(r') \bullet \frac{1}{4\pi} \left[I + \frac{\nabla\nabla}{k^2} \right] G(r, r') \tag{14}$$

where equation (14) is used to calculate E numerically [27].

It should be noted that radio frequency (RF) communication can also be used as a telemetry method [20], [26]. According to [20], either of the two systems can achieve data at exceptional high-speed and large bandwidths, allowing either to be perfect for operations meant for digital oilfields. Although, inside downhole fluids, the signal can be easily attenuated, particularly at high data rates [20]. However, with repeaters, transmission length increases at low data speeds. Additionally, because of the negotiation between distance and power, EMT / RF are suited better for short-hop communications.

Some advantages of the EMT are its low failure rate, not including rotating pieces in the downhole, is also a two-way communication technology and can be used in underbalanced drilling (far more suitable and dependable than MPT) [10]. However, the EMT has high signal attenuation and interference. One of the reasons is the elevation of the water in the formation, which causes the reduction of signal intensity (strength) [20], [26]. For the EMT, as stated above, the signal must pass through the ground, making multiple formations at each drill site. The signal transmitted to the surface from the downhole is (generally) affected by conductivity and permittivity. Based on the formation's material properties, there can be hardly any usable signal at the surface because of extremely high signal attenuation [26]. It is also relatively costly, achieves low data rates and can only be applied in wells with shallow depths. Although when applied in deeper wells, its performance is dependent on a fairly low formation resistivity [10], [20] and [26].

C. Acoustic Telemetry

The acoustic telemetry (AT) system was first established commercially in the industry in 2000. Using an acoustic transmitter transmits data in acoustic waves via the metallic drill string. An example of an acoustic transmitter is the PZT stack which operates by changing the length of the stack. This operation causes the generation of additional (acoustic) waves and, thus, transmits to the surface device through the drill string. Its receiving system can be located at the wellhead [10], [20].

Acoustic telemetry is ideal for underbalanced drilling (UBD) because AT is mainly untouched by the formation properties as it is focused on stress wave propagation via the metallic drill string [27]. It achieves a higher data rate than EMT and MPT due to the wide spectrum of carrier frequencies available, varying from 400 to 2000 Hertz, unlike the low carrier frequencies of EMT and MPT [30]. It also attenuates heavily and cannot be used for transmission over a long distance. Long-distance transmission causes the system to constantly need repeaters, usually 500 meters apart [10], [20]. Like the EMT system, it provides a negotiation between propagation length and power use and its load demand and durability is dependent on the outflow of temperature [20].

D. Wired Drill Pipe Telemetry

In 2006, the wired drill pipe telemetry (WDPT) as drilling activity was commercialized in the oil and gas industry. It transmits downhole data in electrical signals via a coaxial cable that supplies data at a high rate [10]. The coaxial cable is placed inside the drill pipe wall, and inductive coils are used to retransmit data from one pipe to the next. Furthermore, sensors mounted on various sections of the drill string aid in acquiring readings at various stages [25].

The wired drill pipe telemetry achieves and offers data rates far greater than the other existing telemetry systems (currently able to achieve data rates of 57.6 Mb/s) in both transmission directions, i.e. surface to downhole transmission and downhole to surface transmission [12], [31]. It can reach reasonable distances for transmissions and retains a constant data rate regardless of the size of the data, width, and range acquired.

Since each drill pipe on the rig must be replaced, and major rig tool adjustments can be needed, it is an expensive telemetry option. Additionally, the system's longevity declines due to the degradation of the coils through consistent pipe management, deterioration of the inductive coupling, and constant over-torquing. It also lacks signal intensity and thus, needs downhole booster subs (signal repeaters) at every 400 or 500 meters [25].

Two additional components of the WDPT system are the data sub, also known as the interface sub [25]. It allows logs and commands to be communicated as it connects the drill pipe (wired) to the measurement while drilling (MWD) or logging while drilling (LWD) tool and rotary steerable system (RSS) equipment. The other is the top drive swivel, which comprises a sub that carries network traffic and a swivel that connects the cable to the receiving system [25]. It is mounted by removing a saver sub on the lower part of the top drive unit. Thus, with small variations between tools and devices from different manufacturers, the wired drill pipe telemetry system is typically made up of four components: a telemetry pipe, signal repeaters, data sub and top drive swivel [10], [25], and [31].

III. DEPLOYMENT OF VLC TECHNOLOGY

VLC is among the most suitable alternatives for reliable, safe and fast communication [32]. With its wide bandwidth range, exemption from electromagnetic signal interference and low power consumption, VLC surpasses many communication techniques in both applications and advantages. This feature is due mainly to the continuous advancement of solid-state lighting. Despite the challenges in VLC adoption, some of which are the limited coverage, signal absorption by obstacles and illumination control requirements, VLC standardization has been initiated by the IEEE and the Visible Light Communication Consortium (VLCC) in Japan. The VLCC has published the Japan Electronics and Information Technology Industries Association (JEITA) CP-1221 standard, presenting the necessary specifications and the acceptable indication level to avoid and minimize interference between different VLC systems JEITA CP-1222 and JEITA CP-1223 [33]. IEEE published the 802.15.7 standard, establishing a minimum standard for new product design. It is also used for MAC and physical layers [34].

VLC development has achieved traction since around 2011, aided by the IEEE 802.15.7 draft publication [34]. Moreover, several researchers have demonstrated that VLC can achieve up to and even more than gigabits per second transmission using commercially available RGB and phosphorescent white LEDs [35] – [38]. The increased interest in VLC technology has received widespread popularity from the science community and the public in past years. One of the essential VLC specifications is that the system design must be made of lighting-grade LEDs and meet the illumination requirements and safety guidelines [39]. Additionally, the transmission of data should have little effect on the LED efficiency [40]-[41].

VLC can be used across different applications such as indoor wireless communication, transportation and hospitals [42]. Although, it is highly implemented for providing high-speed connectivity in indoor areas. Technology is a significant driving force for the wireless communication industry. It is a promising advancement in 5G visual light communication systems, downhole exploration, inside tunnels/ mines communication, and the prospect of wireless connectivity [42] – [43]. The vast distribution of LED light bulbs is estimated to accelerate potential connectivity ubiquity and offer industry leaders a plethora of opportunities [42].

North America is predicted to play a significant role in the deployment of VLC as it is the market‘s main player, following along with the United States (US) and Canada: contributing significantly to the market’s total sales. The global visible light communication market consists of sections such as the type of transmission, i.e. one-way or two-way directional transmission, and the components used, i.e. LEDs, software, microcontrollers, etc., and applications listed in [42]. Visible light communication-based wireless telemetry design has been investigated in [15] where the limited coverage (travel distance) of the emitted photons was circumvented through the deployment of multiple lights emitting diodes and photodetectors repeating stations for high throughput transmission.

IV. DISCUSSION OF RELATED WORK

There has been much progress in advancing the technologies used in monitoring and acquiring downhole data. Some of these advancements and improvements will be discussed according to their mode of operation. The authors of [14] developed a new method of transmitting data downhole, with its carrier as vibration waves and casings and tubings as its medium for transmission. Based on a test system developed, the design's feasibility was confirmed to be workable and operational in solving some traditional (currently used) telemetry limitations, such as transmission over a short distance, slow data transfer speed, and complexity. The authors of [21] investigated the application of acoustic waves for downhole telemetry by creating a testbed to study acoustic wave propagation over the pipes used for production, which significantly reduced the channel's attenuation using signal processing algorithms and dispersion of the system.

In 2017, the authors of [44] introduced a modern wireless downhole real-time telemetry tool and its usage of three separate deepwater completions activities, emphasizing the implementation of a novel telemetry network and downhole data use. Fracpack optimization, fluid loss management, and downhole weight tracking were the system's advantages. According to the findings, later on, the same authors suggested a modern wireless acoustic device that could transmit right through the good construction operating envelope while also providing operators with access to downhole data during the entire well construction phase [45].

The authors in [46] developed an acoustic telemetry system that uses drill strings as its medium and non-contiguous orthogonal frequency division multiplexing (NC-OFDM). The telemetry system achieves high data transmission with a data rate of more than 500 bits per second using a compressional acoustic wave. In [47], the authors used a validated bi-directional gravel pack approach to reduce completion time, sand control, and monitor the system in real time, increasing the overall system's reliability. Similarly, to solve the difficulties of acoustic vibration of pipe strings for sensor-based tracking and measurements of a given parameter, a stable and effective downhole acoustic communication system using two separate media was developed in [48].

The work in [49] created and analyzed a simulation of acoustic telemetry signal attenuation in directional drilling with a viscous dissipation term, which offered a better theoretical basis for acoustic wave attenuation. At the same time, the work in [50] used data from previous experiments to study the use of a strain receiver and a multi-channel receiver to implement acoustic borehole communication. The results showed low bit error rates. The authors of [51] and [52] worked on similar topics that focused on creating and observing an improved and automated high-speed mud pulse telemetry (MPT) system with the capacity to supply data rates higher than the conventional MPT. In [53], the authors created a new continuous-wave mud pulse generator that can send data via hydraulic pressure waves was proposed. With the assistance of a novel data processing system, a study in [54] engineered a hybrid mud pulse telemetry system that uses two transmitters for data transmission, resulting in a 10 - 30 per cent increase in overall transfer speed.

The authors in [55] developed a downhole framework for multiple parameter monitoring based on an existing loop data transfer process for consistent and precise tracking. The two circuits operate efficiently with the current loop process, with the system divided into two. Electromagnetic telemetry (EMT) has undergone several improvements to overcome the system's limitations, like high attenuation and low data rates. To address the issues raised earlier, the authors of [22] developed an EMT system capable of transmitting over a long distance using an advanced casing antenna system. This technology was created to prevent significant signal attenuation, resulting in higher data speeds.

In [26], a system based on guided wave propagation in a fluid-filled drill pipe was developed to produce 10s of megabits per second using a wireless radio frequency (RF) signal. For air-filled tubing, the system proved to be the most successful. A control and approach downhole EM transmitter for the EM MWD model was built in [56] for further improvement. The system's efficacy was shown by modelling and experimental findings with a laboratory prototype.

The wired drill pipe (WDP) proved to be the most effective telemetry device for achieving high data speeds. But it has undeniable drawbacks such as complex settings, maintenance, and the potential for high costs. The authors of [57] developed a solution for the problem of evaluating and retrieving real-time downhole data and intangible variables using wired drill pipe telemetry. In [13], the authors studied and analyzed the work of an operator who used WDP together with a real-time, closed-loop downhole automation system (DHAS). The outcomes demonstrated that the method is robust and reliable. Furthermore, the study [58] discussed the reliability and usability of the data obtained from WDPT and the sensors installed downhole in the rig fleet, which proved highly accurate and useful for future testing. The work [59] examined the output of a bi-directional high-speed WDP system that provides power to downhole devices.

The authors of [15], [23], [24], [60] and [61] have made progress in analyzing the feasibility of using visible light communication (VLC) as a means of wirelessly transmitting downhole data. [62], discussed the existing telemetry systems, and gave an overview of the VLC system. [23] Investigated the use of VLC for wireless gas pipeline monitoring, the propagation characteristics of the VLC channel, which is dependent on ray tracing, and the maximum achievable link scale to maintain a specified bit error rate. Instead of photodetectors, [24] used a single-photon avalanche diode (SPAD) as the receiver. This decision was made because of the probability of long-distance transmission, later realized in the paper.

The authors of [15] developed a telemetry model based on visible light. They used a spatially multiplexed multiple in multiple out (MIMO) method for high-speed data transfer, achieving data speeds of up to one gigabit per second. The VLC was also investigated as a wireless telemetry solution for reliable and fast downhole data transmission [61]. The authors' architecture was somewhat similar to that of [23]. Still, the main distinction between the two works is that the authors of [61] used a non-sequential ray-tracing approach to achieve the properties of the light-emitting diodes (LEDs). A summary of related work is given in Table 1.

Table 1
Summary of Related Works

Author	Telemetry Method	Telemetry Parameter	Implementation	Software	Problem Solved	Remarks
Farraj et al., 2013 [21]	Acoustic	Acoustic Waves	Testbed	Not specified	Channel propagation	Helpful in the adoption of acoustic wave propagation.
Miaoxin et al., 2013 [55]	Monitoring	Multi-parameter	Implemented	Not specified	Data transmission	An intelligent system capable of accurately transmitting and monitoring data.
Emmerich et al., 2015 [51]	Mud pulse	Pressure waves	Implemented	Not specified	High-speed data transmission	Automated system. High data transmission.
Chen et al., 2015 [22]	Electromagnetic	Electromagnetic waves	Model design	Not specified	Signal attenuation	A casing antenna was used in the setup, which provided the required gain for mitigating and compensating for the harmful effects of signal attenuation.
Li et al., 2014 [24]	Visible-light communication	Light waves	Simulation	Not specified	Downhole monitoring	Unlike traditional VLC systems, this design used single-photon avalanche diodes (SPADs) as the receiver.
Zhao et al., 2015 [57]	Wired drill pipe	Downhole parameters	Simulation	Integrated Drilling Simulator (IDS)	Downhole data quality control	The system used data validation and reconciliation (DVR) to evaluate the downhole data and parameters.
Emmerich et al., 2016 [52]	Mud pulse	Pressure waves	Implemented	None	Reliable high-speed data transmission	The use of signal processing and adaptive filters allowed the device to reach higher data rates than average, based on the efficiency of the field reviewed.
Trichel et al., 2016 [13]	Wired drill pipe	Electrical signals	Implemented	Not specified	Data transmission and system automation	A downhole automation system (DHAS) was used in the construction, which resulted in improved well performance and data transmission.
Zheng et al., 2017 [14]	Vibration	Vibration waves	Model design	Not specified	Reliable communication system for downhole communication	Transmission of downhole data is feasible using this technique.
Hawthorn et al., 2017 [45]	Acoustic	Acoustic waves	Implemented	Not specified	Downhole data transmission	The system used a measurement network that amplified the system’s performance.
Aguilar et al., 2017 [44]	Acoustic	Acoustic waves	Implemented	Not specified	Downhole data transmission	A fail-safe mechanism that allows operations to continue even though a tool fails.
Yan et al., 2018 [53]	Continuous-wave mud pulse	Hydraulic pressure waves	Simulation	FLUENT environment	Data transmission	The findings promote more system development, which can be accomplished by building a prototype that can operate in the field and transmit downhole data.
Ma et al., 2018 [46]	Acoustic	Acoustic waves	Simulation and model design	Not specified	Channel propagation	The description of the acoustic channel

						in this study may be used for further studies on acoustic telemetry.
Miramirkhani et al., 2018 [23]	VLC	Light waves	Simulation	Zemax®	Channel propagation	The VLC channel's measurable data was successfully obtained by considering the link ranges required.
Geoffroy et al., 2018 [47]	Acoustic	Acoustic waves	Model design		Real-time control and monitoring	It can be considered for other drilling operation modes like water-based operations.
Redissi, 2019 [48]	Acoustic	Acoustic vibrations	Simulation	Not specified	Short packets synchronization	The system used two distinct modes of communication, one for low data transmission and the other for high data transmission.
Cote, 2019 [26]	RF	Guided electromagnetic waves	Simulation	VectorVu ANSYS	Channel propagation	Signal repeaters were also used in the design.
Shin, 2019 [49]	Acoustic	Acoustic waves	Simulation	Not specified	Signal attenuation	It can be used as a testbed for designing acoustic telemetry communication algorithms.
Berro et al., 2019 [54]	Mud pulse	Pressure waves	Simulation	LabVIEW MATLAB	Data transmission	The data rates were successfully increased by 10 to 30% over the standard MPT scheme.
Giltner et al., 2019 [58]	Wired drill pipe	Electrical signals	Simulation	Not specified	Downhole data control, transmission and monitoring	Useful for an in-depth understanding of wired drill pipe drilling performance.
Tokgoz et al., 2020 [61]	VLC	Light waves	Simulation	Zemax® MATLAB	Channel propagation	The model design is currently being implemented.
Liu, 2020 [56]	Electromagnetic	Electromagnetic waves	Simulation	MATLAB Simulink	Downhole electromagnetic transmitter topology	A good resource to further understand the estimated load model and the layout of an electromagnetic transmitter control algorithm.
Morapitiya et al., 2020 [62]	VLC	Light waves	Review	None	Overview of the visible light communication (VLC) system	Present telemetry solutions are briefly discussed, and the benefits of VLC systems over RF systems.
Ibhaze et al., 2020 [15]	VLC	Light waves	Model design	MATLAB	Channel propagation	Long-distance transmission can be achieved with this design.
Silvester et al., 2020 [59]	Wired drill pipe	Electrical signals	Implemented and tested	Not specified	Reliable the bi-directional downhole communication system	The system is highly dependable and well-suited to good activities.
Alenezi, 2018 [50]	Acoustic	Acoustic waves	Implemented	MATLAB	Reflections due to mismatch between the drill pipe and downhole joints	The concept centred on using two separate receivers for the acoustic telemetry system, which resulted in spatial diversity issues.

V. CONCLUSION

The major role of the downhole telemetry system is to transmit downhole data from the bottom hole assembly (BHA) to the surface and vice versa. Different methods and techniques are used to accomplish reliable and effective transmission. Various hardware modules like casing antennas, photodetectors, LEDs, repeaters etc., and software packages like MATLAB, Zemax® etc., are used to develop new systems to improve the current systems used in the oil and gas field. The review of related works showed the advancements in the telemetry systems, and that data transmission remains a major problem in the oil field. Most telemetry systems transmit data at a low rate following the problem of signal attenuation, signal interference, low bandwidth and more. For these reasons, the visible light communication (VLC) based wireless telemetry techniques presented in Table 1 will be more convenient for deployment in the oil and gas field due to the reliability, high data rates, flexibility and low-cost of VLC techniques and based on the fact that VLC based telemetry can fulfil the critical needs of operators in maintaining production efficiency and the optimization of gas well performance. Therefore, research efforts should be given more to wireless telemetric technologies utilizing visible light communication. With the convergence of VLC with established connectivity protocols, interference with natural light sources, consideration of mobility problems in VLC to facilitate seamless connectivity between VLC repeater stations within drill pipes, review and specification of forward error correction schemes for performance improvement, consideration of interference among the various systems making use of VLC, there will most likely be an increase of VLC systems in the near future, especially beyond the 5G and 6G era.

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REFERENCES

[1] E. S. A. Ahmed, (2015). Introduction to Communication Systems: Communication Model, transmitting Line, and Data Communication, Ed. Port Sudan: CreateSpace Independent Publishing Platform.

[2] E. Lemenager, D. Merlau, A. Mohan, (2013). Downhole Communication System, JUSTIA Patents, 20130128697

[3] A. E. Ibhaze, P. E. Orukpe and F. O. Edeko, (2020). High Capacity Data Rate System: Review of Visible Light Communications Technology," Journal of Electronic Science and Technology, Vol. 18, No.3, https://doi.org/10.1016/j.jnlest.2020.100055.

[4] P.H. Pathak, X.-T. Feng, P.-F. Hu, P. Mohapatra, (2015). Visible light communication, networking, and sensing: a survey, potential and challenges, IEEE Commun. Survey Tutorial vol. 17 no. 4, pp. 2047–2077.

[5] H. Bhasin, (2021). Communication Systems – Types and Elements, marketing91.com, 2021. [Online]. Available: https://www.marketing91.com/communication-systems/. [Accessed: 11-Jan-2022].

[6] J. Lian, Z. Vatansever, M. Noshad and M. Brandt-Pearce, (2019). Indoor visible light communications, networking, and applications, Journal of Physics: Photonics, vol. 1, no. 1, pp. 1 – 28.

[7] International Association of Drilling Contractors (IADC), (2022). Downhole telemetry," drillingmatters.iadc.org. [Online]. Available: https://drillingmatters.iadc.org/glossary/downhole-telemetry/. [Accessed: 27-Jan-2022].

[8] W. C. Lyons, J. H. Stanley, F. J. Sinisterra and T. Weller, (2020). Air and Gas Drilling Manual - Applications for Oil, Gas, Geothermal Fluid Recovery Wells, Specialized Construction Boreholes, and the History and Advent of the Directional DTH," Elsevier Inc., https://doi.org/10.1016/C2017-0-02316-9.

[9] I. N. de Almeida. Jr., P. D. Antunes, F. O. C. Gonzalez, R. A. Yamachita, A. Nascimento, and J. L. Goncalves, (2015). A Review of Telemetry Data Transmission in Unconventional Petroleum Environments Focused on Information Density and Reliability, Journal of Software Engineering and Applications, vol. 8, no. 9, pp. 455–462, doi: 10.4236/jsea.2015.89043.

[10] M. J. Berro and M. Reich, (2016). Review of Commercial Telemetry Systems for Real Time Data Transmission in Boreholes, SPE International-German Section. Student Technical Conference, Wietze, Germany, 3rd -4th November, 2016,

[11] I. Wasserman, D. Hahn, D. H. Nguyen, H. Reckmann, and J. Macpherson, (2008). Mud-pulse telemetry sees step-change improvement with oscillating shear valves, Oil and gas Journal, vol. 106, no. 24, pp. 39–40.

[12] K. Bybee, (2008). High-Speed Wired-Drillstring Telemetry, Journal of Petroleum Technology, vol. 60, no. 12, pp. 76–78, doi: 10.2118/1208-0076-JPT.

[13] D. K. Trichel, M. Isbell, B. Brown, M. Flash, M. McRay, J. Nieto, I. Fonseca, (2016). Using wired drill pipe, high-speed downhole data, and closed loop drilling automation technology to drive performance improvement across multiple wells in the Bakken, IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas, USA, doi: 10.2118/178870-ms.

[14] L. Zheng, J. Yu, Q. Yang, Y. Gao, and F. Sun, (2017). Vibration wave downhole communication technique, Petroleum Exploration and Development, vol. 44, no. 2, pp. 321–327, doi: 10.1016/S1876-3804(17)30037-X.

[15] A. E. Ibhaze, P. E. Orukpe and F. O. Edeko, (2020). Visible Light Channel Modeling for High-data Transmission in the Oil and Gas Industry, Journal of Science and Technology, Vol. 12, No. 2, pp.46 - 54.

[16] C. John, (2021). Visible Light Communication-History, Working & Applications, www.circuitstoday.com. [Online]. Available: https://www.circuitstoday.com/visible-light-communication. [Accessed: 13-Mar-2021].

[17] L. Zeng, D. C. O'Brien, H. L. Minh, G. E. Faulkner, K. Lee, D. Jung, Y. Oh, and E. T. Won, (2009). High data rate Multiple Input Multiple Output (MIMO) optical wireless communications using white LED lighting, IEEE Journal on Selected Areas in Communications, vol. 27, no. 9, pp. 1654–1662, doi: 10.1109/JSAC.2009.091215.

[18] D. Tsonev, H. Chun, S. Rajbhandari, J. J. D. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. E. Kelly, G. Faulkner, M. D. Dawson, H. Haas, and D. O'Brien, (2014). A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μ LED, IEEE Photonics Technology Letter, vol. 26, no. 7, pp. 637–640, doi: 10.1109/LPT.2013.2297621.

[19] R. X. G. Ferreira, E. Xie, J. J. D. McKendry, Member, S. Rajbhandari, H. Chun, G. Faulkner, S. Watson, A. E. Kelly, E. Gu, R. V. Penty, I. H. White, D. C. O'Brien, and M. D. Dawson, (2016). High Bandwidth GaN-Based Micro-LEDs for Multi-Gb/s Visible Light Communications, IEEE Photonics Technology Letter, vol. 28, no. 19, pp. 2023–2026, doi: 10.1109/LPT.2016.2581318.

[20] John Hunter, (2017). Comparison of Current Wireless Downhole Telemetry, www.tendeka.com, [Online]. Available: https://www.tendeka.com/news/comparison-of-current-wireless-downhole-telemetry/. [Accessed: 11-Oct-2021].

[21] A. K. Farraj, S. L. Miller, and K. A. Qaraqe, (2013). Propagation measurements for acoustic downhole telemetry systems, SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 2013, doi: 10.2118/166131-ms.

[22] J. Chen, S. Li, C. MacMillan, G. Cortes, and D. Wood, (2015). Long range electromagnetic telemetry using an innovative casing antenna system, SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, September 2015, doi: 10.2118/174821-ms.

[23] F. Miramirkhani, M. Uysal, O. Narmanlioglu, M. Abdallah, and K. Qaraqe, (2018). Visible Light Channel Modeling for Gas Pipelines, IEEE Photonics Journal., vol. 10, no. 2, pp. 1–10, doi: 10.1109/JPHOT.2018.2819723.

[24] Y. Li, S. Videv, M. Abdallah, K. Qaraqe, M. Uysal, and H. Haas, (2014). Single photon avalanche diode (SPAD) VLC system and application to downhole monitoring, in IEEE Global Communications Conference, pp. 2108–2113, doi: 10.1109/GLOCOM.2014.7037119.

[25] M. S. Nithin, (2015). Enhancing Directional Drilling using Wired Drill Pipe Telemetry, Teesside University.

[26] P. Cote, (2019). Downhole RF Communication: Characterization and Modeling of Waveguide Propagation in a Fluid-Filled Drill Pipe, Montana Technological University.

[27] N. G. Franconi, A. P. Bunger, E. Sejdić, and M. H. Mickle, (2014). Wireless Communication in Oil and Gas Wells, Energy Technology, vol. 2, no. 12, pp. 996–1005, doi: 10.1002/ente.201402067.

[28] R. Desbrandes, (1988). Status report: MWD technology. Part 2. Data transmission, Pet. Eng. Int., vol. 60, no. 10, pp. 48–54.

[29] R. F. Harrington, (2001). Time-Harmonic Electromagnetic Fields, Wiley-IEEE Press

[30] W. R. Gardner, R. E. Hyden, E. J. Linyaev, L. Gao, C. Robbins, and J. Moore, (2006). Acoustic Telemetry Delivers More Real-Time Downhole Data in Underbalanced Drilling Operations, in IADC/SPE Drilling Conference, Miami, Florida, USA, February 2006, doi: 10.2118/98948-MS.

[31] A. Rodriguez, C. MacMillan, C. Maranuk, and J. Watson, (2013). Innovative Technology to Extend EM-M/LWD Drilling Depth, in SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 2013, doi: 10.2118/166190-MS.

[32] L. U. Khan, (2017). Visible light communication: Applications, architecture, standardization and research challenges, Digital Communications and Networks, vol. 3, no. 2, pp. 78–88, doi: 10.1016/j.dcan.2016.07.004.

[33] S. Hranilovic, L. Lampe, and S. Hosur, (2013). Visible light communications: the road to standardization and commercialization (Part 1), IEEE Communications Magazine., vol. 51, no. 12, pp. 24–25, doi: 10.1109/MCOM.2013.6685753.

[34] IEEE-SA Standards Board, (2019). 802.15.7-2018 - IEEE Standard for Local and metropolitan area networks--Part 15.7: Short-Range Optical Wireless Communications, IEEE.

[35] C. Hongda, W. Chunhui, L. Honglei, C. Xiongbin, G. Zongyu, C. Shigang, and W. Qin, (2016). Advances and prospects in visible light communications, Journal of Semiconductors, vol. 37, no. 1, pp. 011001-1 - 011001-10. doi: 10.1088/1674-4926/37/1/011001.

[36] A. E. Ibhaze, F. O. Edeko and P. E. Orukpe, (2021). Comparative Analysis of Optical Multicarrier Modulations: An Insight into Machine Learning-based Multicarrier Modulation, Gazi University Journal of Science, Vol. 34, No. 4, pp.1016-1033.

[37] A. E. Ibhaze, F. O. Edeko and P. E. Orukpe, (2020). A Signal Amplification-based Transceiver for Visible Light Communication, Journal of Engineering, Vol. 11, No. 26, pp.123 - 132.

[38] A. E. Ibhaze, P. E. Orukpe and F. O. Edeko, (2020). A Simplified Approach for Single Carrier Visible Light Communication Transceiver using off-the-shelf Components, Applied Research and Smart Technology, Vol. 1, No. 2, pp.64-70.

[39] Y. Ohno, (2017). Solid State Lighting Annex: Task 1: Application Study of CIE S 025/E: 2015, Energy Efficient End-use Equipment (4E) International Energy Agency.

[40] W. O. Popoola, (2016). Impact of VLC on Light Emission Quality of White LEDs, Journal of Lightwave Technology, vol. 34, no. 10, pp. 2526–2532, doi: 10.1109/JLT.2016.2542110.

[41] M. Figueiredo, L. N. Alves, and C. Ribeiro, (2017). Lighting the Wireless World: The Promise and Challenges of Visible Light Communication, IEEE Consumer Electronics Magazine, vol. 6, no. 4, pp. 28–37, doi: 10.1109/MCE.2017.2714721.

[42] Infinium, (2022). Visible Light Communication Market, www.infiniumglobalresearch.com [Online]. Available: https://www.infiniumglobalresearch.com/automotive/global-visible-light-communication-market. [Accessed: 04-February-2022].

[43] A. E. Ibhaze, F. O. Edeko and P. E. Orukpe, (2021). A Novel Adaptive OFO-OFDM Modulation for Visible Light Communication, Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi, Vol. 25, No. 2, pp.269-282.

[44] S. Aguilar and A. Hawthorn, (2017). Downhole real time wireless telemetry system applications in deepwater completions in the Gulf of Mexico, Offshore Technology Conference, Houston, Texas, USA, May 2017, doi: 10.4043/27836-ms.

[45] A. Hawthorn and S. Aguilar, (2017). New wireless acoustic telemetry system allows real-time downhole data transmission through regular drillpipe, SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, October 2017, doi: 10.2118/187082-ms.

[46] D. Ma, Y. Shi, W. Zhang, and G. Liu, (2018). Design of acoustic transmission along drill strings for logging while drilling data based on adaptive NC-OFDM, AEU - International Journal of Electronics and Communications, vol. 83, pp. 329–338, doi: 10.1016/j.aeue.2017.08.035.

[47] G. Geoffroy, G. Werkheiser, M. Coffin, K. King, and T. Frosell, (2018). Two-way acoustic telemetry for completion installation, control, and monitoring, SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, September 2018, doi: 10.2118/191439-ms.

[48] A. Redissi, (2019). Communication Systems Design for Downhole Acoustic, Texas A&M University.

[49] Y. Shin, (2019). Signal attenuation simulation of acoustic telemetry in directional drilling, Journal of Mechanical Science and Technology, vol. 33, no. 11, pp. 5189–5197, doi: 10.1007/s12206-019-1008-4.

[50] A. H. Alenezi, (2018). Borehole communication via drill strings in oil, New Jersey Institute of Technology.

[51] W. Emmerich, O. Akimov, I. B. Brahim, and A. Greten, (2015). Reliable high-speed mud pulse telemetry, SPE/IADC Drilling Conference and Exhibition, London, England, UK, March 2015, doi: 10.2118/173032-ms.

[52] W. Emmerich, O. Akimov, I. B. Brahim, and A. Greten, (2016). Field performance of automated high-speed mud pulse telemetry system, IADC/SPE Drilling Conference and Exhibition, January 2016, doi: 10.2118/178871-ms.

[53] Z. Yan, Y. Geng, C. Wei, T. Wang, T. Gao, J. Shao, X. Hu, and M. Yuan, (2018). Design of a continuous wave mud pulse generator for data transmission by fluid pressure fluctuation, Flow Measurement and Instrumentation, vol. 59, pp. 28–36, doi: 10.1016/j.flowmeasinst.2017.11.008.

[54] M. J. Berro and M. Reich, (2019). Laboratory investigations of a hybrid mud pulse telemetry (HMPT) – A new approach for speeding up the transmitting of MWD/LWD data in deep boreholes, Journal of Petroleum Science and Engineering, vol. 183, doi: 10.1016/j.petrol.2019.106374.

[55] J. Miaoxin, G. Qiang, and X. Dianguo, (2013). A downhole multi-parameter monitoring system, Proc. - 3rd International Conference on Instrumentation, Measurement, Computer, Communication and Control, pp. 1660–1663, doi: 10.1109/IMCCC.2013.367.

[56] K. Liu, (2020). Model and control method of a downhole electromagnetic transmitter for EM-MWD system, Journal of Petroleum Science and Engineering, vol. 192, pp. 107210, doi: 10.1016/j.petrol.2020.107210.

[57] K. Zhao and D. Sui, (2015). Drilling data quality control via wired drill pipe technology, Chinese Control Conference, pp. 7883–7888, doi: 10.1109/ChiCC.2015.7260892.

[58] M. Giltner, L. Earle, J. Willis, D. Tellez, and R. Neel, (2019). Performance impact of downhole data from wired drill pipe and downhole sensors, SPE/IADC International Drilling Conference and Exhibition, The Hague, The Netherlands, March 2019, doi: 10.2118/194093-ms.

[59] I. Silvester, T. Høgset, S. Torvund, and S. Saxena, (2020). Qualification & testing of a powered wired drill pipe solution, IADC/SPE International Drilling Conference and Exhibition, Galveston, Texas, USA, March 2020, doi: 10.2118/199604-ms.

[60] A.E. Ibhaze, A. L. Imoize, O. Okoyeig-bo, (2022). A brief Overview of Energy Efficiency Resources in Wireless Communication Systems, Telecom, vol. 3, pp. 281–300.

[61] S. C. Tokgoz, S. L. Miller, and K. A. Qaraqe, (2020). On the Investigation of Achievable Links for VLC based Wireless Downhole Telemetry Systems, IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), doi: 10.1109/BlackSeaCom48709.2020.9234990.

[62] S. S. Morapitiya, D. N. K. Jayakody, and R. U. Weerasuriya, (2020). Visible Light Communication for Downhole Monitoring Visible Light Communication for Downhole Monitoring View project Visible Light Communication for Downhole Monitoring, 12th International Research Conference- General Sir John Kotelawala Defence University, pp. 1–6.