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Visible Light Channel Modeling for High-data Transmission in the Oil and Gas Industry

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Abstract: High-speed communication has been a major concern in the oil and gas field for downhole data acquisition, transmission and exploration. This has necessitated this investigation of the promising license-free broadband visible light spectrum for improved communication reliability in the oil and gas field. A Visible Light Communication (VLC) Multiple Input Multiple Output (MIMO) communication link is proposed as the drill pipe wireless communication link. The proposed model was seen to perform more optimally using the maximum likelihood detection technique in comparison with zero forcing at reduced bit error rates and improved throughput relative to increasing values of the Signal to Noise Ratio (SNR). Although this investigation proposes a novel design of the wireless drill pipe, its adoption will greatly reduce exploration time thereby increasing the return on investment as data transmission speed increases.

Keywords: Electromagnetic telemetry, MIMO, mud pulse telemetry, Visible Light Communication, wired drill pipe

1. Introduction

The oil and gas industry have been a global source of revenue generation for quite some time and as such requires new innovative trends in maintaining its industrial processes among many other industry-based concerns. A major industry and academic research concern have been geared towards providing a more efficient communication mechanism between down-holes and surface equipment's for optimum production efficiency as well as improving oil well performance [1]. While long range communication mediums have been adapted for downhole communication especially in restricted areas, reliable high-speed communication mechanism for data acquisition, transmission and processing still remains a research problem. Communication techniques ranging from wired technologies to wireless techniques have been deployed invariably in the oil and gas industry encumbered by diverse merits and challenges. Attainment of efficient communication system cannot be overemphasized in the oil and gas industry with the advent of smart wells and the prevalent Internet of Things ideologies which is envisioned to interconnect everything over the Internet. This will definitely require high speed data driving technology for which other industrial processes such as drilling, monitoring, data transmission and management will thrive.

The evolution of the economic global market-place is gradually altering the way in which we carry out intended practices with the idea of having an eventual smart and converged ecosystem. This has also influenced the industry as processes are now becoming smarter with the development of smart wells. The communication channel between

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downhole and surface equipment's more than ever before now requires new and reliable wireless real time monitoring systems. A new innovative high-speed communication field – visible light communication system is proposed in this research undertaking. It is intended that high data rate technique suitable for diverse oil and gas communication using visible light spectrum be modeled and deployed for reliable and performance driven oil and gas industrial processes [2].

According to [3], diverse techniques have been researched, validated and deployed for communication with downhole tools in time past. Concerns have been on the average data transmission speed within the communication link. Some of the techniques used for communicating with downhole equipment's are mud pulse telemetry being about the most commonly used [4], electromagnetic telemetry [5] and wired drill pipe telemetry [6]. Using diverse forms of mud telemetry, the average data transmission rate obtainable is about 5 to 10bps. With electromagnetic telemetry, data rates up to 100bps have been achieved while wired drill pipes have recorded up to 57Mbps [7]. Following directly from the evolving and emerging technologies, is the need to transmit at much higher data rates. Despite the progress made in this research area, overall performance is still adjudged by the time difference in receiving and processing downhole related data. The problem this research intends to address is to investigate and proffer solution to the data rate challenge such that techniques for data transmission up to 1Gbps is achieved for communication in the oil and gas field thereby optimizing overall performance.

1.1 Related Work

The oil and gas field has been in demand of techniques for reliable permanent real time monitoring and control infrastructure of oil wells for reliable production in the sector. Diverse techniques for communication have been investigated and deployed ranging from wired architectures, to sensor, wireless sensor infrastructure and wireless communication deployments. The challenges and merits of differing communication systems have provided the need for continuous improvement in view of productivity in the sector. Deployed monitoring systems transmitting data to surface equipment's among other downhole tools using optical fiber or electrical cables interfacing with surface data acquisition, transmission and processing devices have been well validated in the literatures [8, 9]. Reservoir monitoring and control remains a critical metric for efficient optimization and development of oil and gas reservoirs and as such wireless communication technique can be used to resolve wired communication challenges such as installation rigors, cost and maintenance [10].

Wireless communication has become the mainstay for global integration across diverse metrics of technology, economies, governance and institutions to mention a few. With a quick overview of the existing wireless communication infrastructure, earliest wireless technologies could achieve 2.4kbps data rate [11] in comparison with the existing wireless communication technology model with the data rate of 30Mbps [12]. In view of the increasing growth rate of the present data hungry society, data rate revolution is envisaged to achieve at least 1Gbps [13] which will completely alter the communication pathway in increasing communication efficiency by well over 3,000%. This will not only improve the performance metric in the oil and gas industry but will absolutely transform the nation as much more could be achieved in less time.

The increasing demand for oil and gas produce has led to advancements in oil and gas exploration in attempts to increase production efficiency. Common connections and interactions between oil well, sensors and other control devices utilizes optical fiber cables and hydraulically operated well valves to collate measurements from oil wells in view of optimizing production efficiency. Despite the sensor based optical fiber deployment and high temperature and pressure electronic devices, a reliable wireless telemetry technique that can be deployed permanently over the life time of the well is still an open research area [14]. Moving forward from wired to wireless technologies, the basic state of the art wireless technologies deployed for wireless downhole communication are pressure-wave telemetry and electromagnetic telemetry [14, 15, 16]. In pressure-wave telemetry, pressures pulses are made to propagate through the drilling or production fluid while in electromagnetic telemetry, well castings or drill strings are employed as the transmission medium through which electromagnetic waves can propagate to the surface. The basic limitations of these existing wireless systems remain low data rates, high attenuation and low reliability of the telemetry channel. As efforts are being made towards achieving high data rates over the entire downhole infrastructure within the wireless framework, this research is intended to achieve high data rates over surface device communication within the downhole domain.

In order to make the ecosystem a more amiable place with effective and efficient communication infrastructure for seamless integration, this research undertaking is therefore dosed with the motive of proposing a possible solution for high data rate integration within the oil and gas field. The actualization of a high-speed two-way communication system capable of improving the transmission data rate between drilling, evaluation service providers and surface equipment's will enable the instantaneous and immediate real time availability of evaluation and drilling data. This will increase safety as continuous downhole pressure, high rate drilling string energy transmission data monitoring will be achieved with improved efficiency, reliability and productivity as processing time will reduce drastically.

2. Design Method

In order to achieve high throughput/data rates, single carrier schemes in time past were not able to mitigate the frequency selective related issues of the transmission process [17, 18, 19] from the highly dispersive and multipath driven wireless channel. This made multicarrier schemes such as the Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) techniques ideal for mitigating frequency selectivity [20, 21] while improving transmission data rate through the use of equalizers [22] and spatial diversity techniques [23]. Alternatively, the multiple links in the MIMO configuration could be separately modulated digitally to achieve the multicarrier equivalent of the OFDM scheme due to hardware support and design complexity of the OFDM scheme for real-time applications. In the work of [24], a single carrier single channel VLC model was proposed for wireless gas pipelines using different constellations of pulse amplitude modulation (PAM) scheme. In recent past, single carrier with frequency domain equalization (SC-FDE) has been investigated to have similar properties with OFDM as it eliminates the high peak-to-average power ratio (PAPR) associated with OFDM [25, 26]. To adapt these techniques to the visible light spectrum for improved data rates, a multichannel VLC MIMO-based technique using space division multiplexing has been adopted [27, 28]. The system modeling was achieved using the setup shown in Fig. 1. The setup consists of both hardware and software interface such that a novel signal conditioning module is prototyped for high data rate. Since the drill pipe consist of devices used for sensing physical quantities, the custom protocol and multichannel MIMO module is used to process, transform, modulate and map the analog quantities into the required digital format for spatial multiplexing. The digital-to-analog converter (DAC) is then used to obtain the analog equivalent of the digital data whose voltage levels are converted to the required output current using the transconductance amplifier (TCA). The output current is used to drive the light emitting diode (LED) for signal transmission. At the receiving end, the emitted photons are directly detected by the photodiode (PD) which converts the photon energy to current. The transimpedance amplifier then acts as the current-to-voltage converter with its output fed into the analog-to-digital converter (ADC) for further processing, demapping and data recovery using the custom protocol multichannel MIMO module. In this work, a 15x15 MIMO configuration is deployed using 15 LEDs and 15 PDs $\forall k = 1,2,\cdots,15$ respectively.

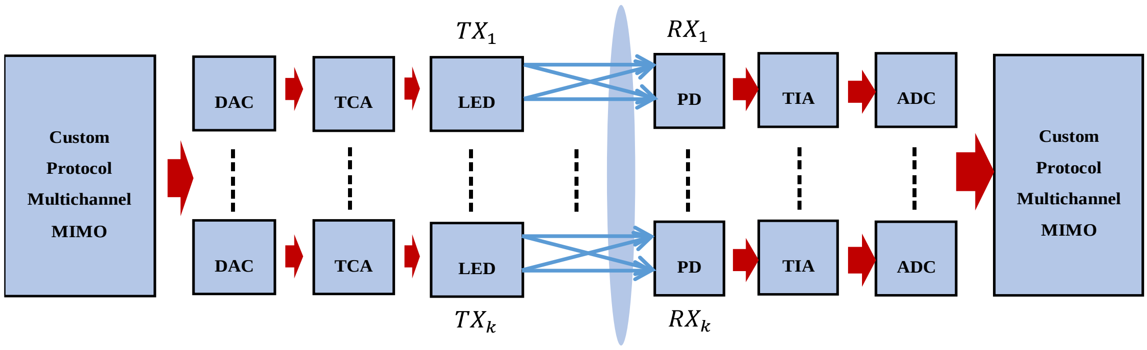

Fig. 1 - Visible Light Spectrum data rate prototyping system

Fig. 2 depicts a typical multichannel VLC MIMO drill pipe model where d_{trx} is the separation distance between the VLC-MIMO transceivers installed across the drill pipe width d_w, over the wireless drill pipe of length d_l. The transceiver setup is replicated after traversing the distance d_{trx} so as to prevent attenuation of the communication coverage. The transceiver units therefore act as signal repeaters along the drill pipe length. The broadband wireless communication link provided by the VLC-MIMO link provides the interface for high data rate interaction between the sensor network, bottom-hole assembly (BHA) and the surface equipment for efficient logging while drilling (LWD), measurement while drilling (MWD) and other performance checks.

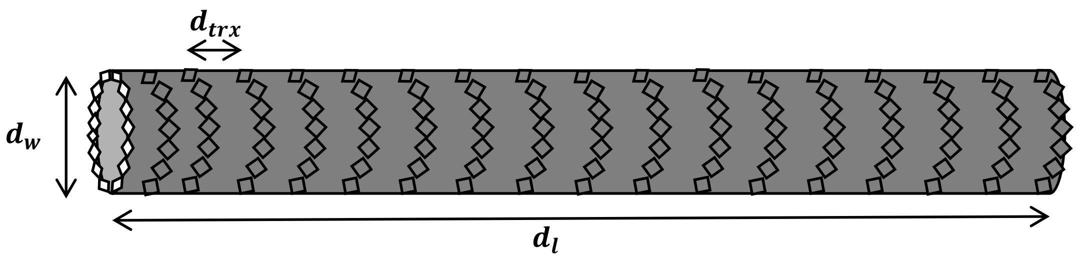

Fig. 2 - VLC MIMO drill pipe model

The channel model of the VLC-MIMO link follows directly from a cross section of Fig. 2 shown in Fig. 3. The multiple LEDs and PDs form the VLC-MIMO transceiver link.

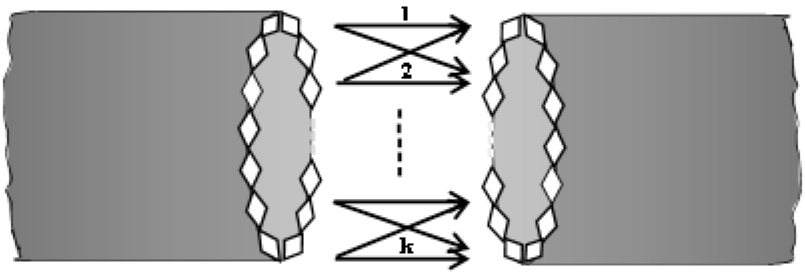

Fig. 3 - A typical in-pipe multichannel VLC MIMO configuration

Considering the multipath channel formed by the multiple LEDs and PDs, the channel performance can be improved by the spatial diversity formed by the multiple links denoted as $1,2,...,k$. The channel model of the k^{th} link is given by:

$$y_k = h_k x_k + n_k \tag{1}$$

where x_k is the k^{th} transmitted signal, y_k is the k^{th} received signal, h_k is the fading coefficient of the k^{th} link and n_k is the noise in the k^{th} link.

The received signal at the k^{th} PD receiver becomes $y_1, y_2, \cdots, y_k$. In order to detect the transmitted signals, the received signals are linearly combined by weighting the individual received signal such that:

$$b_1^* y_1 + b_2^* y_2 + \cdots + b_k^* y_k \tag{2}$$

where b_k^* is the conjugate of b_k and $b_k^* y_k$ is y_k weighted by b_k^*

From the foregoing, (2) is of the form:

$$\begin{bmatrix} b_1^* & b_2^* & \cdots & b_k^* \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} \equiv \bar{b}^H \bar{y} \tag{3}$$

where $\bar{b}$ is the vector describing the weight whose Hermitian transpose is $\bar{b}^H$.

The linear combination of the received signal $\bar{b}^H \bar{y}$ is referred to as beamforming where $\bar{b}$ is the beamforming vector.

In relation to (1), the beamformer output becomes

$$\bar{b}^H \bar{y} = \bar{b}^H \bar{h}x + \bar{b}^H \bar{n} \quad (4)$$

where $\bar{b}^H \bar{h}x$ is the signal component and $\bar{b}^H \bar{n}$ is the noise component

The estimation of the signal to noise ratio (SNR) follows directly from (4) which enable the selection of the beamformer $\bar{b}$ that will maximize the SNR in the design process. While beamforming contributes in making the communication link more robust, the spatial diversity (multiple transmit LEDs and multiple receive PDs) boost the achievable data rate of the VLC system. To estimate the SNR, the received signal power is given as the product of the transmitted power and the channel gain:

$$p_r = \left|h_k\right|^2 x_k \quad (5)$$

where $\left|h_k\right|^2$ is the channel gain which accounts for the signal path loss.

Comparing (4) and (5), the signal power becomes

$$p_r = \left|\bar{b}^H \bar{h}\right|^2 x \quad (6)$$

The received noise power is given as the expectation of the noise component. It is the same as the noise variance given as:

$$n_r = E\left\{\left|n_k\right|^2\right\} = \sigma_k^2 \quad (7)$$

Comparing (4) and (7) yields:

$$n_r = E\left\{\left|\bar{b}^H \bar{n}\right|^2\right\} \quad (8)$$

Since the magnitude of a quantity is the same as the product of the quantity and its conjugate, (8) becomes:

$$n_r = E\left(\left(\bar{b}^H \bar{n}\right)\left(\bar{b}^H \bar{n}\right)^*\right) \quad (9)$$

$$n_r = E\left(\bar{n}\bar{n}^H \bar{b}\right) \quad (10)$$

$$n_r = \bar{b}^H \bar{b} E\left(\bar{n}\bar{n}^H\right) \quad (11)$$

Since the expectation of the noise component is the same as the noise variance, combining (7) and (11) yields:

$$n_r = \bar{b}^H \bar{b} \sigma_k^2 \quad (12)$$

Note that $\bar{b}^H \bar{b}$ is the beamforming component and it is the same as the sum of the beamforming vector of the individual link for all the links $1,2,...,k$. It is the magnitude of the beamformer and it implies the square of the beamforming component $\left|b_k\right|^2$. Hence, the summation of the magnitude is the same as the norm of the vector whose squared value is the same as the length squared of the vector given as:

$$\bar{b}^H \bar{b} = \left\|\bar{b}\right\|^2 \quad (13)$$

The noise power of (12) follows directly from (13) and it defines the noise power at the beamformer's output as:

$$n_r = \bar{b}^H \bar{b}\sigma_k^2 = \sigma_k^2\left\|\bar{b}\right\|^2 \quad (14)$$

Hence, the SNR derives directly from (6) and (14) as the ratio of the received signal and noise powers:

$$SNR = \frac{\left|\bar{b}^H \bar{h}\right|^2 x}{\bar{b}^H \bar{b}\sigma_n^2} \quad (15)$$

For reliable signal detection, the effects of zero forcing (ZF) and maximum likelihood (ML) detection techniques [2] were compared for the VLC MIMO system. ZF detects and nullifies interfering signals by imposing a weight whose effect is to invert the effect of the multipath channel such that:

$$\tilde{x}_{ZF} = x + \tilde{n}_{ZF} \quad (16)$$

where $\tilde{x}_{ZF}$ is the detected signal, x is the desired signal, $\tilde{n}_{ZF}$ is the product of the ZF imposed weight b_{ZF} and channel noise n given by [29]:

$$\tilde{n}_{ZF} = \left(h^H h\right)^{-1} h^H n = b_{ZF} n \quad (17)$$

where h^H is the Hermitian transpose of the channel gain.

ML estimates the received signal by computing the Euclidean distance between the received signal vector and the product of the interfering signal vectors and the channel gain. The preferred signal is the one with the minimum distance. For a given signal constellation χ and k number of transmit antennas, the estimated transmitted signal vector using ML is given by [30]:

$$\hat{x}_{ML} = \underset{x \in \chi^k}{\arg\min} \left\|y - \mathbf{hx}\right\|^2 \quad (18)$$

3. Results

The BER and throughput performances relative to the detection techniques are shown in Fig. 4 and 5 respectively. Fig. 4 compares the error performance of ZF and ML of the VLC-MIMO link. The ML detection is seen to outperform the ZF technique with lower bit error rates at increasing SNR. At 25dB, ZF and ML achieved BER of 0.014 and $1x10^{-4}$ respectively. The throughput performance further showed the superiority of the VLC-MIMO based configuration with an average throughput of 1.38Gbps and 640Mbps using ML and ZF detection techniques respectively. At increasing SNR values, the throughput performance is seen to measure up to 1Gpbs at 35dB using ZF detection while ML was seen to achieve about 3Gbps which further typifies an improvement in transmission speed.

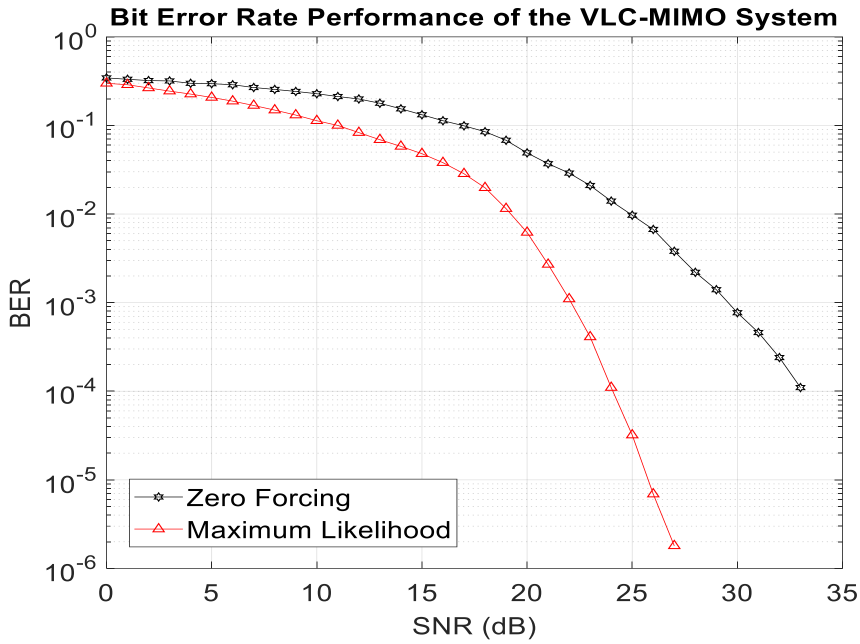

Fig. 4 - BER performance comparison of the VLC-MIMO system

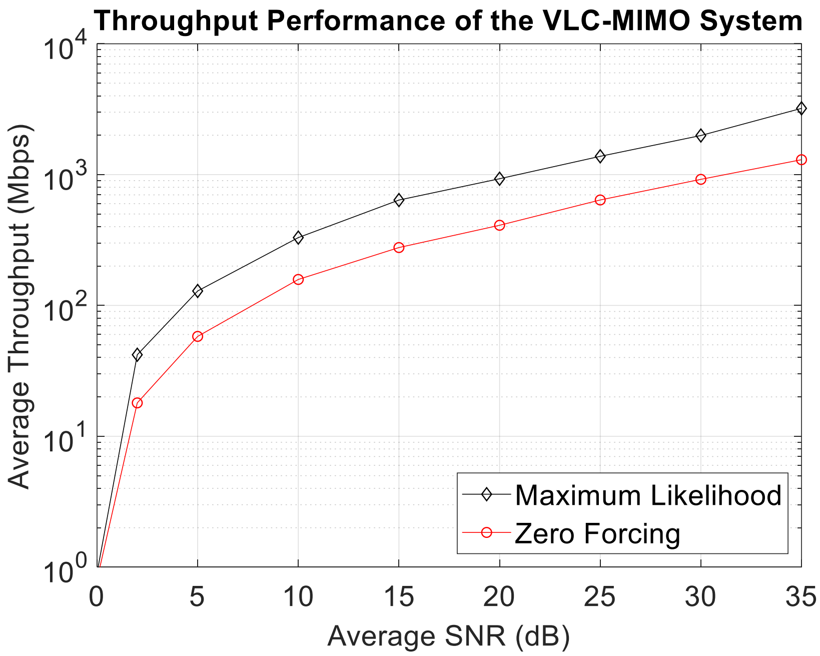

Fig. 5 - Throughput performance comparison of the VLC-MIMO system

4. Conclusion

High-speed wireless drill pipe technology has been proposed using spatially multiplexed visible light communication MIMO technique. Throughput up to 3Gbps and 1Gbps were achieved using maximum likelihood and zero forcing detection technique at 35dB respectively. This model could be adopted in the design of high performance wireless drill pipes for downhole exploration in the oil and gas field as the transmitting and receiving nodes are replaced by multiple light emitting diodes and photodetectors respectively.

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