Journal of the Nigerian Association of Mathematical Physics
***Volume 59* (January – March *2021 Issue*), pp165 – 178**
© J. of NAMP

RECEIVED SIGNAL QUALITY EVALUATION IN DIGITAL TRANSMISSION NETWORKS BASED ON BIT ERROR RATE PERFORMANCE

Daniel Asuquo,[1] Imeh Umoren[2] and Daniel Effiang[3]

[1]Department of Computer Science, Faculty of Science, University of Uyo, PMB 1017, 520003, Uyo, Nigeria
[2,3]Department of Computer Science, Faculty of Science, Akwa Ibom State University, Mkpat Enin, Nigeria

Abstract

The advancement on communication and file transfer over the Internet has been achieved through digital techniques for traffic propagation along transmission channels. To sustain desired reception signal quality requires swift adjustment in telecommunication services and downlink transmission in robust modulation schemes. However, the problem of bit error rate (BER) generates large scale fading of wireless communication channel thereby reducing throughput and spectral efficiency experienced in beyond third generation (B3G) networks. This paper presents a framework that uses inputs on the receiver to ensure efficient correlation of signal and overall improvement in system performance on fading channels. Comparative performance analysis of three modulation techniques - Phase Shift Keying (PSK), Differential PSK (DPSK) and Frequency Shift Keying (FSK) on Additive White Gaussian Noise (AWGN) and Multipath Rayleigh fading channels is investigated. The proposed approach is simulated in MATLAB 7.6 for BER evaluation and optimization of signal-to-noise ratio (SNR). Results indicate that the bandwidth efficiency of FSK signal decreases with increasing modulation order in both AWGN and Rayleigh fading channels and that PSK is more robust in terms of receiver's performance than FSK and DPSK due to its less susceptibility to noise. Results further indicate the need for a careful choice of BER threshold for minimized network defects and delivery of optimal rating to digital signal

.

Keywords: BER, SNR, Modulation techniques, Fading channels, Performance evaluation, B3G networks

1. INTRODUCTION

Mobile radio channels are characterized for signal strength and its variations. This characterization affords system designers adequate information for analysis and design of transmission systems over such channels. The undesirable impact of the environment causes multipath signal propagation which makes the radio link unreliable. Obviously, degradation in the received signal quality (SQ) is experienced, which can be evaluated using bit error rate (BER) or signal-to-noise ratio (SNR) [1]. The relatively poor signal reception due to high BER can make communication difficult if not impossible. Since, the physical layer is responsible for converting electrical signals to bit streams and transmitting them through a medium accurately, its performance can be measured in terms of the BER, which defines data integrity at the destination node [2-3]. While digitized voice and video traffic can tolerate a relatively high BER up to 10^{-3}, information from computer requires perfect integrity of data with BER of about 10^{-9}. The task of maximizing data throughput in a limited transmission bandwidth with minimum BER in beyond third generation (B3G) networks is very challenging. In practice, very low error rates are difficult to achieve in high-speed digital communication systems due to noise, high processing delay and implementation complexity. Therefore, BER minimization is aimed at achieving low BER as an important indicator of a good communication system design with myriad implications for spectrum and spectral efficiency, implementation complexity, power efficiency, robustness and flexibility.

BER simply refers to the number of bits received over a communication channel that have been misrepresented due to certain predictable factors such as interference, noise, jitter, etc. The BER can be mathematically expressed as the number

Corresponding Author**:** Asuquo D., Email: danielasuquo@uniuyo.edu.ng, Tel: +2348035680549

of bit errors, N_e divided by the total number of bits transferred, N_b during a transmission, as shown in (1). It may also be expressed as the percentage of bits that have errors relative to the total number of bits received during a transmission.

$$BER = \frac{N_e}{N_b} \quad (1)$$

If the medium between the transmitter and the receiver is good and the SNR is high, then the BER will be very small and insignificant with no noticeable effect on the overall system. However, if noise can be detected, then BER probability has to be considered as there is nothing as a zero BER [4]. Unlike other forms of assessment, BER analyses the complete end-to-end performance of a system including the transmitter, the receiver and the medium between them. In this way, it enables the assessment of the actual performance of a system in operation, rather than testing the component parts and hoping that they will operate satisfactorily when in use.

BER may be improved through robust modulation and channel coding schemes like forward error correction (FEC) codes [5], which is a system of adding redundant or parity data to a message such that it can be recovered by a receiver either during transmission, or on storage. In that case, the number of errors introduced must be up to the capability of the code being used. A back channel is not required in FEC as the receiver is not expected to request for retransmission as widely applicable in simplex communication (e.g. broadcasting). Modulation is simply the process of transmitting a message signal (e.g. a digital bit stream), inside another signal. Thus, a sine waveform can be modulated by being transformed from a baseband message signal to a passband signal (e.g. a radio frequency (RF) signal). In full duplex communication systems, electrical signals can only be transferred over a limited passband frequency spectrum, with specific (non-zero) lower and upper cut-off frequencies [6]. The good digital modulation format prefers a waveform that can optimally preserve the information in transmission and reception in order to maximize the spectral efficiency of the modulation format. The fundamentals of all modulation techniques depend on varying three major properties of carrier sinusoidal signal represented as:

$$c(t) = A\cos(2\pi . f_c .\ t + \Phi) \quad (2)$$

where, A is the amplitude of carrier signal, f_c is the frequency of carrier signal, and Φ is the phase of carrier signal. Digital modulation are mainly classified into linear (change amplitude or phase) and non-linear (change frequency) schemes. The works in [7-9] indicate that most widely used modulation techniques in satellite communication, wireless cellular and sensor networks include amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), binary phase shift keying (BPSK), quadrature-phase shift keying (QPSK), minimum shift keying (MSK), continuous phase modulation, (CPM), continuous-phase frequency shift keying (CP-FSK), and quadrature amplitude modulation (QAM) where QAM is a combination of ASK and PSK. QPSK can be interpreted as two independent BPSK systems (one on the I-channel and the other on the Q-channel), offering the same performance but a twofold bandwidth (spectrum) efficiency. According to [10], the bit error probability (P_{be}) of FSK modulation is given in (3) as:

$$P_{be,FSK} = Q(\sqrt{\gamma}) \quad (3)$$

where, $\gamma = E_b/N_o$ is the signal-to-noise ratio; E_b is the transmitted signal energy per bit; N_o is the noise power spectral density. This indicates that P_{be} is a function of E_b/N_o, where $Q(z)$ is the tail probability of a Gaussian random variable, given by $Q(z) = \frac{1}{2} erfc\left(\frac{z}{\sqrt{2}}\right)$ and verifiable in MATLAB as useful functions where $erfc$ denotes complementary error function. The P_{be} of M-ary PSK modulation is given as:

$$P_{be,M-PSK} = \frac{2}{k} Q\left(\sqrt{2k\gamma}\right)\sin\frac{\pi}{4} \quad (4)$$

where, $k = \log_2 M$ is the number of bits transmitted; M is the modulation index. Also, the P_{be} of differential phase shift keying (DPSK) is given as:

$$P_{be,DPSK} = \frac{1}{2} e^{\left(-\frac{E_b}{N_o}\right)} \quad (5)$$

Within the wireless networks protocol, bits of information are packaged into frames. Any error detected within a frame would affect data throughput and slow down network performance thereby requiring a retransmission of the affected frame [11]. Modulation techniques that can deliver more bits per symbol are less vulnerable to errors caused by noise and interference in the channel. Rate adaptation and other frame recovery schemes have also been proposed to improve packet loss resilience and increase throughput of wireless networks [12]. More recent proposals have begun to look at using data bits at sub-frame level [13], where frame combining allows multiple erroneous receptions of a given frame to be merged for recovering the original frame and avoid retransmission. BER estimation techniques have attracted much attention and useful application in Automatic Repeat Request (ARQ) and Hybrid ARQ systems [5, 14-15], in which packets may be retransmitted if the BER estimates are too high. Accurate BER estimates can therefore be used as feedback criteria to evaluate SQ and power control mechanisms [16]. Although, the popular Monte-Carlo (MC) simulation technique is convenient for estimating BER by dividing the number of incorrect received bits by the total number of transmitted bits during a given time, it requires very high computational cost for achieving low BER. This paper develops a framework for optimized BER performance to sustain desired network SQ and compares through simulation, the performance of PSK, DPSK, and FSK techniques at different modulation orders on Additive White Gaussian Noise (AWGN) and Multipath Rayleigh fading channels for robustness and spectral efficiency.

The rest of the paper is organized as follows: section 2 reviews related works on BER evaluation in digital transmission channels while section 3 presents the proposed system design for optimizing BER performance in communication systems. In section 4, the experimental results obtained from simulating and comparing the three modulation schemes for AWGN and multipath fading channels are discussed. Finally, section 5 concludes the paper with direction for future research.

2. RELATED WORKS

In this section, an overview of BER evaluation on digital channels for improved packet resilience and efficient signal transmission is highlighted. A tabular summary of references to network application of some modulation schemes is also presented.

A. BER on Digital Channels

The emergence of 4G Long Terminal Evolution mobile communication system is to complement existing 3G Wideband Code Division Multiple Access (WCDMA) networks for a large variety of communication services such as high-speed data transfer, audio and video calls as well as internet services without incessant signal deterioration. Due to frequent occurrence of bit errors on digital channels, wireless networks require increasing bandwidth to improve packet loss resilience. To this effect, there is redundancy on the network. The use of digital modulation techniques to control BER performance parameters for efficient signal transmission on a communication channel has been widely researched. However, AWGN model is observed not suitable for terrestrial links because of multipath, terrain blocking, and interference that modern radio systems encounter in terrestrial operation. Figure 1 shows the characteristics of a multipath wireless channel with signal deterioration due to attenuation, distortion, reflection, fading, and interference. This signal scattering and shadowing greatly reduces the received signal power in proportion to the distance between the transmitter and the receiver [17]. Although this power loss can be compensated for by increasing the transmitted power by the same amount, the error probability decreases much more slowly with increasing power when such variations are experienced in fading channels [18].

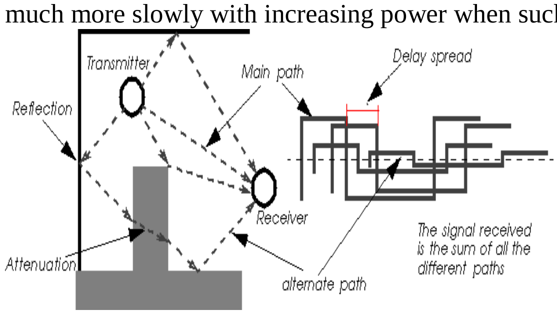

Figure 1: Characteristics of a multipath wireless channel

Optical Time Domain Reflectometer (OTDR) device and OptiSystem 9.0 was used to analyze BER on optical fibre systems operating with a non-return-to-zero (NRZ) format and tested at transmission rates of up to 10Gbps [5]. Simulation results indicate a noticeable improvement of the system BER and the optimum solution reduced BER by using Return-to-Zero (RZ) signal generator through Electro-Absorption modulation techniques. By using a software-defined radio, the error patterns of individual 802.15.4 chip sequences was characterized [19], in order to determine the channel conditions. The work in [20] studied corruption in an IEEE 802.15.4-based outdoor network and observed that bit errors are not equally probable over all positions in the payload in 802.15.4 packets. A probabilistic approach was proposed in [21] to recover information about the original content of a corrupt packet for an outdoor sensor network deployed on low-cost IEEE 802.15.4 transceivers and independent transmission errors. The approach greatly reduced the uncertainty about the original content, as measured by a multiple reduction in entropy which was implemented with the use of MSK demodulators. A genetic algorithm was used in [22] to determine which modulation technique best optimize BER and power in a wireless ad-hoc network. The performance of BPSK, M-PSK, and QAM was evaluated and results indicate that 8-PSK performs best compared to others at permissible values of BER (less than 10^{-3}) required for IEEE 802.11 WLAN. Different patterns in the bit error probabilities of the payload in IEEE 802.11 WLAN were observed in [13] to be neither due to the channel conditions nor hardware-specific implementations. Experiments performed on the sub-frame bit error characteristics of the WLAN transmissions identified three distinct patterns for sub-frame bit errors and their location distribution as slope-line, saw-line, and fingers patterns. However, it is believed that identifying repeatable and predictable bit error patterns is imperative for providing valuable insights for modelling sub-frame bit errors especially when designing more efficient dynamic intra-packet encoding schemes and packet retransmission mechanisms.

The possibility of having errors as the number of users increase with increased user mobility [23] is driving research into the application of higher order modulations. Enhanced Data Rate for GSM Evolution (EDGE) was proposed as a Time

Division Multiple Access (TDMA)-based radio access using the 800, 900, 1800 and 1900 MHz frequency bands. Their work indicated that EDGE enables significantly higher peak rates and triples the spectral efficiency by employing 8-PSK modulation. They also reported that a modulation technique with good bandwidth efficiency in Wideband Code Division Multiple Access (WCDMA) cellular network requires perfect modulators, demodulators, filter and transmission path, which are however, difficult to achieve in practical radio environment. Their developed model was simulated under AWGN noise and Multipath fading channel in MATLAB with 16-Quadratic Amplitude Modulation (16-QAM) and QPSK modulation schemes. Both modulation techniques could deliver higher data rate for High Speed Downlink Packet Access (HSDPA), an extension of 3G networks.

A comparison of Symbol Error Probability (SEP) for different M-ary modulation techniques over slow, flat, identically and independently distributed Rician fading channel was made in [24]. They performed exact analysis of SEP for M-ary differentially encoded PSK and coherent M-ary PSK, transmitted over Rician fading channel with N branch receive diversity using maximal ratio combining (MRC) where channel side information is known at the receiver. Simulation results based on Model Sim (wave) and Xilinx-ISE using VERILOG hardware descriptive language for binary ASK (BASK), BFSK, BPSK and QPSK modulation schemes on a 32-bit serial data transmission was presented in [9]. The proposed method of implementation proved to be resilient and efficient with results indicating that QPSK technique was the most efficient in terms of data transmission rate and bandwidth utilization compared to BASK, BPSK and BFSK.

The BER performance of a WCDMA system using BPSK modulation technique in AWGN and Multipath Rayleigh fading channel was studied in [25] while [26] obtained BER performance for BPSK-based scheme under the AWGN and Rayleigh fading channel using MC-based algorithm. Results indicate that the performance of a direct sequence BPSK is better than simple BPSK for higher gain of more than 14dB. Also, the convergence rate of AWGN channel is faster than the Rayleigh channel indicating that it needs more power than the AWGN channel. Although, the simulated results present better BER performance, there is need to improve their power requirements. An analytical framework and simulation testbed for performance analysis of a system in various diversity mechanism environments for improving BER was proposed in [3]. Diversity technique was capable of generating several copies of the signal, which experience independent or estimated independent fading, to decrease the probability of instantaneous deep fades. Of the three compared diversity schemes, maximum ratio combining (MRC) achieves the best performance, followed by equal gain combining (EGC) and then selective combining (SC).

The performance of Orthogonal Frequency Division Multiple Access (OFDMA) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) systems over international telecommunication union (ITU) vehicular-A channel using minimum mean square error equalization was simulated in [27]. Results indicate that the performance with interleaved mapping outperform that with localized mapping. Furthermore, the performance with QPSK is better than that with 16-QAM. Generally, SC-FDMA yields a better performance than OFDMA with QPSK scheme and vice versa with 16-QAM. Jagadeesh in [28] discovered from simulations that BPSK allows BER to be improved in a noisy channel at the cost of maximum data transmission capacity. The use of QPSK allows higher transmission capacity, but not without some increase in the probability of error. It was revealed that orthogonal frequency division multiplexing (OFDM) with QPSK is advantageous for short distance transmission links while OFDM with BPSK is useful for long distance transmission links. A wireless communication structure based on two coupled chaotic systems in order to enhance the error rate performance of multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) system was proposed in [29]. A comparative evaluation of the performance of the MIMO-OFDM system in AWGN, Rician and Rayleigh fading channels was performed for two cases – with and without adaptive beamforming. Results indicate that chaotic communication system has the potential to improve the system's security due to its bifurcation behavior when varying the initial condition. On the other hand, adaptive beamforming can effectively mitigate interference and greatly enhance system performance with BPSK compared to QPSK and the best performing channel - less SNR requirement, to maintain the required BER was AWGN while the worst was Rayleigh. Khalaf and Mohammed in [30] proposed an AC-MAP scheme based on Alamouti combining (AC) and maximum a posteriori (MAP) decoder to estimate the data at the destination and minimize the end-to-end BER. They derived a closed form expression for the upper bound (UB) on the end-to-end error probability with results showing that the closed form UB almost coincides with the exact BER results obtained from simulations. The derived UB expression can be used to study the effects of the relay position on the BER performance in multiple input single output relay networks.

Moreover, multiple access interference (MAI) has significant impact on the capacity of wireless communication systems. The overall performance of wireless communication systems requires accurate calculation of BER in the presence of MAI and can only be implemented with considerable computational effort. The exact calculation of BER in the presence of MAI is difficult and emphasis has been given to bounds and approximations [31]. A simple approximation is to treat MAI as standard Gaussian and the bit errors as independent. The following subsection presents a Gaussian approximation modeling of received signal's BER for digital communication systems.

B. Modeling Radio Frequency for Bit Error Ratio

A radio is a technology that allows transmission of signals by modulation of electromagnetic waves. It captures the amount of signal sent over a radio wave, renders the modulated signal as sound, and continues broadcasting the sound recordings via the internet. In an RF system, shown in Fig. 2, a carrier is modulated based on the (Q) components input data and some defined modulation format. In general, this signal may be represented as a complex envelope about the carrier, which offers simulation efficiency not possible if the signal is represented as a baseband signal. However, when adding noise, the complex envelope representation must be considered. Furthermore, it is desirable that the In-phase (I) and Quadrature of the envelope be uncorrelated. The I and Q are also known as the amplitude modulated sinusoids [32].

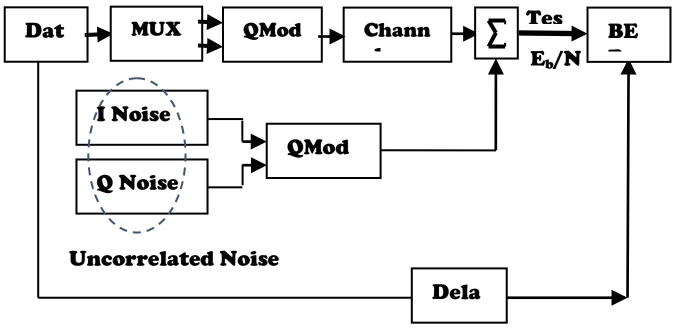

Figure 2: A typical RF system

In the RF system, data are created in the same manner as for the baseband system where they become modulated for higher throughput. The uncorrelated Gaussian noise sources are equally modulated and added. Unlike the baseband system, the noise is injected at RF as a complex modulation envelope, and is uncorrelated with the transmitted signal. If an automatic synchronization function is provided, only an upper bound needs to be specified. If the system is modeled using only digital signal processing functions, including digital filtering, the delay can usually be found by inspection and analysis. However, if the system includes analog or RF models, the delay is often not easily obtained without additional simulation. A possible approach is to excite the system with an impulse (a signal of very narrow, ideally infinitely small width) and observe the output time domain response. Another is to graphically compare the reference and test bit streams. Typically for RF systems, the impulse source is normally amplitude-modulated onto an RF carrier. However, a separate I and Q impulse source is not required. This allows the simulator to sample just the impulse signal's envelope, not the carrier itself, which is much more efficient.

Many techniques and algorithms have been developed to monitor BER key performance parameters in order to attain a considered optimization level and to reduce error redundancy. One of the existing system is the pseudo-error counting scheme. A pseudo-error counting scheme was analyzed in [33] with a proposed algorithm to achieve both BER monitoring and adaptive decision threshold optimization. Figure 3 shows the pseudo-error counting scheme.

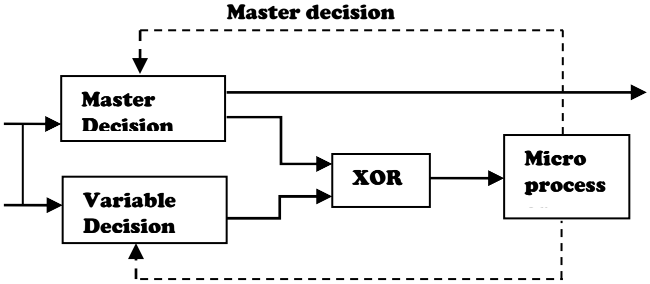

Figure 3: Pseudo-error counting scheme

In this scheme, the master decision gate is for communication and the variable decision gate is for BER monitoring and adaptive decision threshold optimization. Thus, the master decision threshold (MDT) is the main decision threshold required to be optimized. The variable decision threshold (VDT) is the secondary decision threshold used to obtain the pseudo-error. The pseudo-error is generated by the decision difference between the two decision thresholds. The exclusive OR (XOR) logic gate generates '1' when the outputs of the two decision gates are different and '0' when the outputs of the two decision gates are same. The microprocessor counts the total number of pseudo errors and controls the master and variable decision thresholds. This way, the desired optimization of the end-to-end key performance parameters of the wireless communication system can be achieved. Although, the exact values of the true BER and the pseudo BER are different, the dominant parts of the two BERs become similar especially when the VDT is far enough apart from the MDT. The pseudo-error counting scheme assumes a Gaussian approximation for evaluating the true BER of the received signal and the pseudo BER counted in microprocessor, given in (6) and (7), respectively as:

$$BER_{true} = 0.25 \cdot \left| erfc\left(\frac{D-V_0}{\sigma_{0\sqrt{2}}}\right) + erfc\left(\frac{V_1-D}{\sigma_1\sqrt{2}}\right) \right| \quad (6)$$

$$BER_{pseudo} = 0.25 \cdot \left| erfc\left(\frac{D_v-V_0}{\sigma_{0\sqrt{2}}}\right) - erfc\left(\frac{D_m-V_0}{\sigma_{0\sqrt{2}}}\right) \right| + 0.25. \left| erfc\left(\frac{V_1-D_v}{\sigma_1\sqrt{2}}\right) - efrc\left(\frac{V_1-D_m}{\sigma_{1\sqrt{2}}}\right) \right| \quad (7)$$

where, erfc is the complementary error function, V_0 and $V_1$are the voltage of level 0 and 1, σ_0 and σ_1 are the standard deviation of the noise imposed on level 0 and 1, D is the decision threshold, and D_m and D_v are the master and variable decision thresholds, respectively.

The SQ provided by any wireless communication system can be significantly improved with proper selection of digital modulation scheme, giving room for increased radio coverage and reduced power consumption. Although, some of the techniques involve little complexities in the modulation and demodulation system design and prove cost-effective (e.g. BASK, BFSK, BPSK and DPSK) with tolerable BER performances for certain applications [34-35], there is need for continuous search for a better modulation scheme in wireless communication as the criterion for higher data rate communication is taking the lead role in almost every field of communication. Therefore, the evaluation of SNR and BER performance become very crucial and important aspect for any modern digital modulation scheme. Table 1 presents a summary of application areas of some digital modulation techniques.

Table 1: Summary of Applications Using Various Digital Modulation Schemes

S/N	**Modulation Scheme**	**Reference**	**Application Area**
1	OOK (ASK), BASK	[9], [34], [35]	IR remote control devices; Fibre optic transmissions
2	FSK, BFSK, GFSK, M-FSK	[9], [34], [35]	cdmaOne cellular network, Paging systems, Bluetooth, IEEE 802.11 Wireless networks, Cordless telephones, DSL MODEM (OFDM)
3	BPSK, QPSK, M-PSK	[9], [22], [23], [24], [25], [26], [27], [28]	WLAN, Satellite telemetry, Dialup computer MODEMS, cdmaOne cellular network, Satellite television digital video broadcast (DVB), GPRS/GSM cellular network, 3G Evolution (M = 8)
4	M-QAM	[22], [23], [27]	Digital cable television (M = 16/64/128/256)
5	GMSK	[21]	Wireless cellular and sensor networks, DECT, Cordless telephone

In this paper, we investigate degradation in transmitted signal quality on mobile radio channel and develop an innovative framework based on signal processing techniques that minimize propensity to channel impairments. The signal sources are capable of generating a variety of signals like voice, data, compressed video and image signals. The signals are either in analog or digital format. A few times a new modulation choice is warranted, and it is important to compare the performance of the various modulation choices available and suggest alternatives. Often times, the performance measures of interest include spectrum utilization, data transmission quality, throughput and cost of implementation. This paper is concern with the first measure that has to do with BER performance as a function of SNR or received power, which will have direct impact on the link budget.

From literature, it can be observed that FSK, PSK and their variations are digital modulation techniques typically useful for BER testing and evaluation in wireless cellular networks. DPSK has not received much attention compared to other modulation formats in B3G wireless cellular networks, hence, this paper. Consequently, this paper evaluates the performance of FSK, PSK and DPSK at different modulation orders in both AWGN and Rayleigh fading channels, different from [36] that estimate BER performance in AWGN and Rician channels for MSK-based modulated signals alone, [37] that compared BER performance of PSK-based techniques under multipath fading and [34] that worked on wireless infrared communication.

3. SYSTEM DESIGN

A. Design of Proposed BER Testing Framework

This paper designs a framework for optimized BER testing (BERT), monitoring and evaluation to achieve an efficient and accurate BER performance in a communication system. The design of a system for BERT requires a transmitter, a receiver and a channel. Here, the emphasis is on WCDMA mobile networks where noise in a receiver is modeled to avoid high BER. The proposed scheme uses a processing gain serial pseudo-noise modulation as a multi-rate strategy. Assuming we generate a long sequence of random bits as inputs to the transmitter, the transmitter modulates these bits onto some form of digital signals which is scaled through a modulated channel. Then, some frequencies of BER key performance parameters are introduced into this channel as receiver's inputs. Hence, signal deterioration due to attenuation, fluctuation, fading, jitter, and redundancy with some level of errors, inconsistencies, and delay will occur, resulting to inefficient, inaccurate and non-optimized digital signals in the receiving side of the communication system.

The architectural design of the proposed BERT scheme, shown in Fig. 4, is an optimized modification of the principle of pseudo-error counting scheme developed by [33]. The various components of the proposed BERT scheme are *data bit streams (DBS)*, *a transmitter* transmitting the DBS to modulated digital pulse, *wireless network channel* (air interface), *the complexity of noise*, *pseudo-error counting principle* (the master decision gate, the variable decision gate, the XOR counter, and the micro processor) and finally *the receiver*. The communication system is developed with a transmitter, which converts an incoming data (bits) stream from a sender into a symbol stream. Each symbol represents a group of one or more bits of a theoretical and experimental digital signal. The arrow symbol represents the communication flow from the sender to the receiver. The Air Interface is a pathway for wireless network communication. Therefore, the existence of bit errors is inevitable, because it is exposed to the atmosphere where it encounters noise, fading, attenuation, interference, crosstalk, resistance, impendence, signal diversity, and multiple line-of-sights (LOS). Consequently, the channel is inducted with certain BER key performances parameters such as the Receiver's Input. This may be as a result of AWGN, multipath fading or Rayleigh fading, etc. The effects of these parameters on the channel may result to jitter, interference, fading or attenuation, causing a complexity of noise in the stream of digital signal.

As the flow of the modulated digital signal tends towards the receiver's side, it splits into the pseudo-error mechanism consisting of the Master Decision Gate (MDG) and the Variable Decision Gate (VDG). The MDG is for communication while the VDG is for BER monitoring and adaptive decision threshold optimization. Thus, the MDT is the main decision threshold required to be optimized. The VDT is the secondary decision threshold used to obtain the pseudo-errors. The pseudo-error is generated by decision differences between the two decision thresholds. A logic gate mechanism known as the Exclusive OR (XOR) generates these bits. It generates "1" when the outputs of the two decision gates are different (indicating a bit error) and generates "0" when the outputs of the two decisions are the same. The Microprocessor counts the total number of pseudo-errors and controls the Master and Variable Threshold. The Bit Error Counter is essentially a digital comparator, for a simple binary signal. For multi-level QAM-type signals, where there is more than one threshold, the circuit becomes more complex. In the XOR gate mechanism, an integrator sums the error signals so that its output is proportional to the number of errors found. The ratio of this output to the total number of samples is the BER. In a simulation environment, this circuit may be provided or can be built from simple library components. After a proper management of these key performance parameters in the communication system, the bit errors are optimized before it is being sent to the receiver which is displayed in simulations plots.

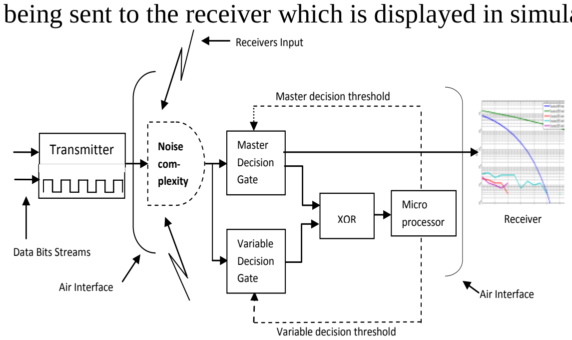

Figure 4: Proposed scheme for optimized BER testing and evaluation

B. Model Formulation and Description

The increasing demand for more network capacity requires higher performance communication systems. A key technique to operate and maintain high-capacity networks is cost-effective performance monitoring. BER monitoring is more effective than other monitoring techniques for the optimal compensation in the real non-linear transmission lines. A model for this technique is described in many ways for easy understanding. This section highlights the theoretical and graphical approaches to BER modeling and computation.

It is not an easy task to control system noise in a communication system. Thus, a good noise modeling approach for an accurate BER is very essential. The visualization of BER in a communication system without the application of mathematical model is practically unavoidable. In mobile communication systems, the sent bit streams are normally modulated or encoded (0 = +1 and 1 = -1). The modulated source code bits are mapped to real electric voltage labeled as '+p' and '-p' ('+1 = +p mV and -1 = -p mV') in real transmission. With this mapping, if no noise occurs, only two clear dots would appear even though a lot of data are transmitted. From the constellation diagram in Fig. 5, the entire +1s and -1s are superimposed onto the single Red and Blue dots, respectively.

BER means the probability that a noise power becomes larger than a certain desired level. The mathematical analysis of BER can be done simply by taking the area after a certain value under the normal distribution graph as shown in Fig. 6, while the performance model of noise in a wireless communication system is illustrated in Fig. 7, where x is the transmitted symbol, n is noise of the receiver and y is the received symbol. In Figure 6, the square of standard deviation (variance) is known as the noise power, as the spread of the variance increases, the spread of the Gaussian noises increases.

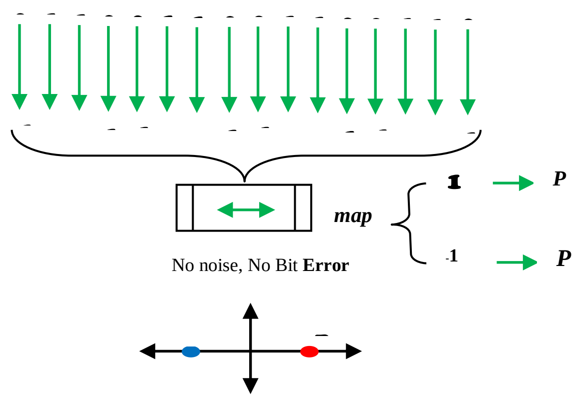

Fig. 5. Modeling BER for BPSK

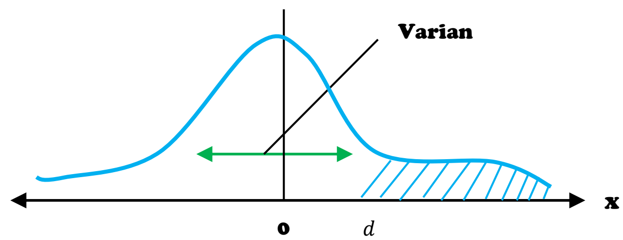

Figure 6: Distribution of noise

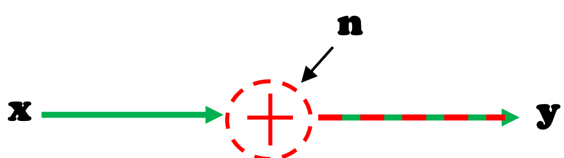

Figure 7: Noise model

In a communication channel where the noise is a White Gaussian noise process, the system is known as an AWGN system. The noise relation is given as:

$$y = x + n \tag{8}$$

where, $x = \begin{cases} 1 & if -\sqrt{P} \\ 0 & if \sqrt{P} \end{cases}$ (9)

BER is bound to occur if $\boldsymbol{y} \leq 0$; this is because the amount of noise n, is greater than or equivalent to the amount of transmitted signal ($n \geq x$) or the amount of transmitted signal plus the additive noise is greater than the maximal signal voltage which is zero (0). The probability of bit error rate (p_{be}) is frequently expressed as $0 \leq p_{be} \leq 0.5$. If the noise process is wide, then Gaussian noise will have a Gaussian probability density function, and the system is modeled as an AWGN channel. The distribution of noise power is given as:

$$F_n(n) = \frac{1}{\sqrt{2\pi\sigma^2}} . e^{\frac{-x^2}{2\sigma^2}} \tag{10}$$

Assuming a situation where the probability of noise power is greater than "d", then the probability of deviated data bits is greater than "d". To this effect, a resultant higher bit error ratio will occur causing the integrity of the communication system to be truncated. The relation for achieving the Gaussian probability of noise power that is greater than "d" is given as:

$$P(x \geq d) = \int_d^\infty \left(\frac{1}{\sqrt{2\pi\sigma^2}} . e^{\frac{-x^2}{2\sigma^2}} \right) dx \tag{11}$$

To obtain required physical meaning of SNR, (11) is modified to become (12) as:

$$P(x \geq d) = \int_d^\infty (\frac{1}{\sqrt{2\pi\sigma^2}} . e^{-\frac{1}{2}(\frac{x}{\sigma})^2}) dx \tag{12}$$

where, $\frac{x}{\sigma} = t;\ dx = \sigma . dt$, then (12) becomes (13) as:

$$P(x \geq d) = \int_{\frac{d}{\sigma}}^{\infty} (\frac{1}{\sqrt{2\pi\sigma^2}} . e^{-\frac{1}{2}t^2})\sigma . dt = \int_{\frac{d}{\sigma}}^{\infty} (\frac{1}{\sqrt{2\pi\sigma^2}} . e^{-\frac{1}{2}t^2}\sigma) dt \quad (13)$$

The physical meaning of $\frac{d}{\sigma}$ is SNR, where the probability of errors is determined by SNR and the relation becomes:

$$P(x \geq d) = \int_{\frac{d}{\sigma}}^{\infty} (\frac{1}{\sqrt{2\pi}} . e^{-\frac{1}{2}t^2}) dt \quad (14)$$

An AWGN channel adopts a model where the only impairment to communication is a linear addition of wideband or white noise with a constant spectral density and a Gaussian distribution of amplitude. The model assumes there is no amplitude or phase distortion by the channel and does not account for fading, interference, frequency selectivity, or nonlinearity. The wideband Gaussian noise causing performance degradation is assumed to occur through natural sources such as thermal noise generated in the receiver.

A Rayleigh fading channel, on the other hand, adopts a statistical model to study the effect of a propagation environment such as heavily built-up urban areas on a radio signal [38-40]. Due to the existence of multipath propagation, it assumes that the magnitude of a signal that passes through the channel fades or vary randomly according to a Rayleigh distribution, which is the radial component of the sum of two uncorrelated Gaussian random variables. The model is most applicable when there is no dominant propagation along a LOS between the transmitter and receiver while a Rician fading is applicable when there is a dominant LOS. According to the central limit theorem, if there is sufficiently much scatter of the signal before it gets to the receiver, the channel impulse response is modeled as a Gaussian process irrespective of the distribution of the individual components. The envelope of the channel response is therefore Rayleigh distributed. Let this random variable be $\mathfrak{R}$, then its probability density function is given in [39] as:

$$P\mathfrak{R}(r) = \frac{2r}{\Omega} e^{-r^2/\Omega},\ r \geq 0 \quad (15)$$

where, $\Omega = \mathrm{E}(\mathfrak{R}^2)$. Often, the gain and phase elements of a channel's distortion are conveniently represented as a complex number. In this case, Rayleigh fading is exhibited by the assumption that the real and imaginary parts of the response are modeled by independent and identically distributed zero-mean Gaussian processes so that the amplitude of the response is the sum of two such processes.

Mathematically, the multipath Rayleigh fading wireless channels modeled by the channel impulse response is given in [29] as:

$$h(t) = \sum_{l=0}^{L_p-1} \alpha_l \delta(t - \tau_l) \quad (16)$$

where, $L_p$is the number of channel paths, $\alpha_l$and τ_l are the complex value and delay of path l, respectively. The paths are assumed to be statistically independent, with normalized average power while the channel is time variant due to the motion of the mobile terminal.

4. SIMULATION RESULTS AND DISCUSSION

A. Implementation Procedure

The task of obtaining optimal reception signal quality that achieves minimal BER requires an extensive research of modulation techniques and their performance at different modulation orders on communication channels. Finding analytical expressions for the bit error probability for more complex channels and coded modulation systems is sometimes not possible. On this note, [41-42] recommend simulation as a useful tool to obtain needed performance estimates. The system implementation is done by generating a long sequence of random bits provided as inputs to the transmitter. The transmitter converts these sequences of bits to some form of digital signal which is scaled through a modulated path. There is an induction of certain key performance parameters of BER at different frequencies of the modulated path which serves as the receiver's input. To this effect, delay, jitter, and slow flow of digital signal in a modulated pathway are bound to occur.

MATLAB source code was used for computing the BER with the modulation techniques and simulation outputs are displayed for performance evaluation in both AWGN and Rayleigh fading channels. The basic operations performed include:

(i) Generate random modulated symbols +1's and -1's of length 32 bit for each vector
(ii) Pass them through AWGN (or Rayleigh fading) channel using MATLAB function
(iii) Demodulate the received symbol based on the location in the constellation mapping of modulation format used in the transmitter side
(iv) Count the number of errors in reference to the transmitted symbols
(v) Repeat previous steps for multiple E_b/N_o values
(vi) Plot the results using appropriate MATLAB tools

Table 2 shows the different implemented modulation types, orders and communication channels adopted for this study. The three modulation formats at each modulation order are implemented on each channel type.

Table 2: Modulation Format and Order in AWGN and Rayleigh Channel

Channel Type	**Modulation Format**	**Modulation Order**
AWGN RAYLEIGH	PSK + DPSK + FSK	2
		4
		8
		16
		32

B. BER Performance Comparison in AWGN Channel

The BER performance comparison of the modulation types implemented on modulation orders 2, 4, 8, 16, and 32 in AWGN channel for a WCDMA system is presented in this section. Figures. 8 - 12 show the graphical plots for visualization and results indicate that at lower modulation orders of 2 and 4, PSK has best BER performance closely followed DPSK at order 2 and FSK at order 4, respectively. However, FSK is observed to outperform others with a wide margin at higher orders of 8, 16, and 32 leaving PSK to narrowly perform better than DPSK at order 8. Furthermore, PSK and DPSK have nearly similar BER performance up to 14dB E_b/N_o at modulation order 16 and up to 18dB E_b/N_o at order 32. The bandwidth efficiency of the modulation signals decreases with increasing modulation order. For instance, FSK has 14dB E_b/N_o at order 2 and 11dB E_b/N_o at order 4 for 10^{-5} BER.

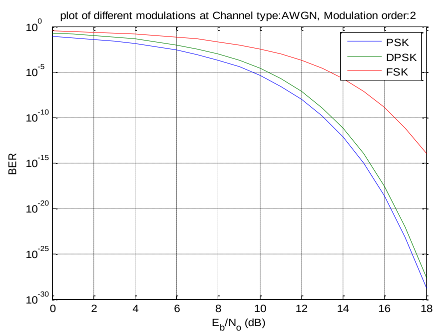

Figure 8: BER Performance at modulation order of 2 in AWGN channel

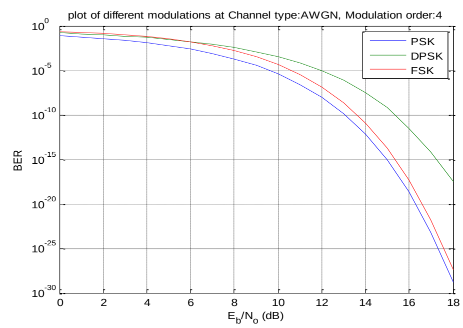

Figure 9: BER Performance at modulation order 4 in AWGN channel

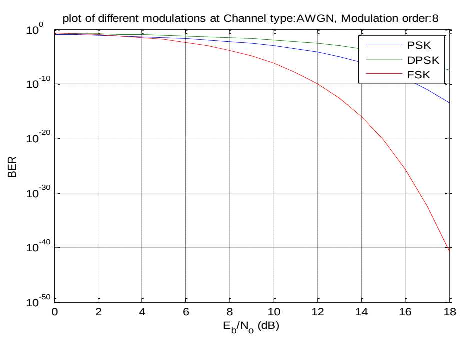

Figure 10: BER Performance at modulation order 8 in AWGN channel

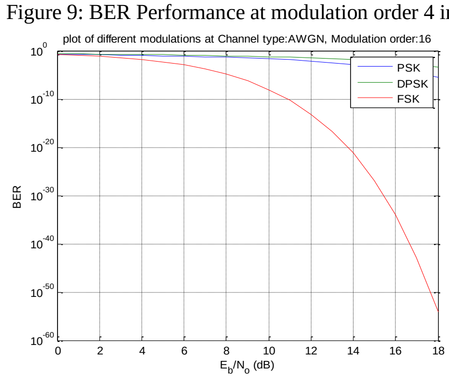

Figure 11: BER Performance at modulation order of 16 in AWGN channel

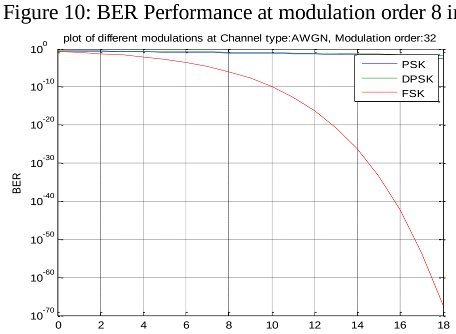

Figure 12: BER Performance at modulation order 32 in AWGN channel

C. BER Performance Comparison in Rayleigh Channel

The BER performance comparison of the modulation formats implemented on modulation orders 2, 4, 8, 16, and 32 in Rayleigh channel for a WCDMA system is presented in this section. Results from Figures 13 - 17 indicate that PSK has best BER performance at orders 2, 4 and 8 while FSK outperforms others at higher orders of 16 and 32, leaving DPSK with the worst BER performance for both AWGN and Rayleigh fading channels.

At lower modulation orders of 2 and 4, formats such as PSK and DPSK show advantage in that the receiver requires less power to achieve a given SNR. This required power to achieve a desired BER probability is known as receiver sensitivity. For example, for a P_{be} of 10^{-2} at order 4, PSK requires E_b/N_o of about 14 dB, while DPSK and FSK require 17dB and 18dB, respectively. These values when translated to power at a given data rate become useful to designers. Consequently, the PSK schemes ensure more bandwidth efficiency compared to the FSK scheme.

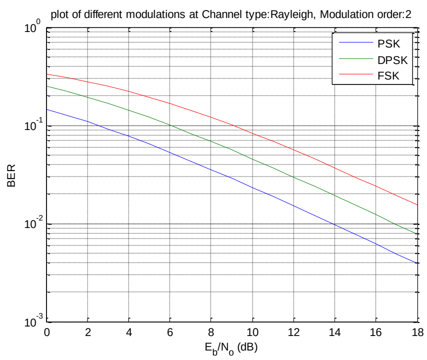

Figure 13: BER performances at modulation order of 2 in a Rayleigh channel

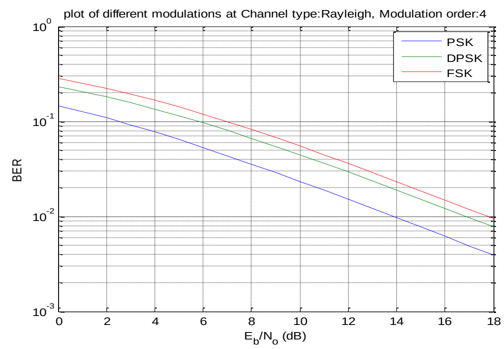

Figure 14: BER performances at modulation order of 4 in a Rayleigh channel

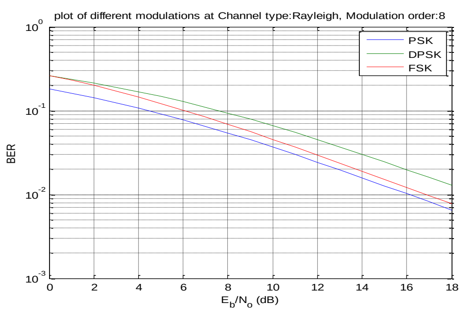

Figure 15: BER performance at modulation order of 8 in Rayleigh channel

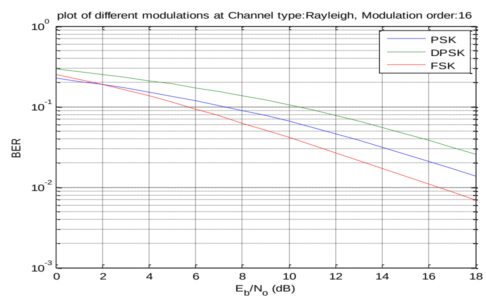

Figure16: BER performance at modulation order of 16 in Rayleigh channel.

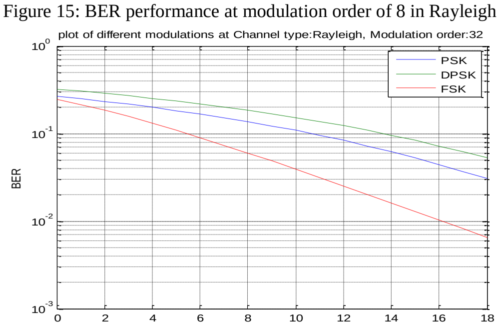

Figure 17: Performance of modulation at order of 32 in Rayleigh channel

D. Summary of Results on AWGN and Multipath Rayleigh Fading Channels

Results from a summary of the signal bit-energy-to-noise spectral density values for both AWGN and Rayleigh channels at desired BER probability (P_{be}) confirm that AWGN channel converges much faster than Multipath Rayleigh fading channel. This means that BER decreases with increasing E_b/N_o in AWGN channel but slightly decreases with increasing E_b/N_o in Rayleigh channel. Consequently, Rayleigh fading channel needs more power for data transmission than AWGN counterpart.

Furthermore, for both AWGN and Multipath Rayleigh fading channels, PSK outperforms others at lower modulation orders while at higher orders of 16 and 32, FSK performs best followed by PSK and then, DPSK. This indicates that higher rate PSK schemes are limited by the ability of equipment to distinguish small differences in phase and its performance degrades when the speed of mobile terminal is increased. The reason behind the poor performance of DPSK in WCDMA system on a Multipath Rayleigh fading channel is basically due to the interference between adjacent carriers phase in the constellation of the modulation technique. It is observed that DPSK as a non-coherent form of PSK though being easy to build and cheap to implement, has the worst BER performance in wireless communication. Minimal interference between adjacent carrier phase in the constellation of this techniques is required.

It is suggested that error correction coding such as convolution coding or turbo coding can be used for better performance of DPSK technique in WCDMA system. Another option is the use of a RAKE receiver or a smart MIMO antenna to exploit the delayed signals generated in multipath fading channel. Finally, with the technique of coding, it is very possible to vastly improve on the error rate without sacrificing the data rate, increasing the bandwidth or increasing the power, but at the expense of complexity.

5. CONCLUSION AND FUTURE WORK

In this paper, experimental results from a practical study for understanding the key performance parameters of bit errors and how to manage them to obtain optimal and efficient digital signal for a wireless communication system is presented. The BER probability results obtained from simulation both in AWGN and Rayleigh fading channels show that the error probability falls sharply with increasing E_b/N_o. PSK modulation technique has the best performance at lower modulation orders for both AWGN and Multipath Rayleigh fading channels. Thus, PSK-based schemes are more bandwidth efficient than FSK while the later is more power efficient than the former as its improves signal quality at higher modulation orders. PSK is much more robust in terms of receiver's performance than FSK as it is not that vulnerable to noise, which changes amplitude of the signal.

BER testing is a powerful tool for end-to-end evaluation of digital transmission systems as it provides a measurable and useful indication of the operational performance of the system. Numerical simulation shows a noticeable improvement of the system's BER after optimization of the suggested processing operation on the detected signals. Significant implications include improving existing communication system performance and thereby reducing call dropping and users' dissatisfaction on SQ delivery. Future works shall consider identifying the bit error behaviour in IEEE 802.15.4 wireless sensor networks and simulation of some advanced modulation techniques such as offset quadrature phase shift keying (OQPSK), QAM, MSK, and CP-FSK.

REFERENCES

[1] Clerckx, B. (2016). Waveform and transceiver design for simultaneous wireless information and power transfer, *CoRR*, vol. abs/1607.05602, 2016. Available online at: http://arxiv.org/abs/1607.05602.

[2] Sheikh, A. U. H. (2004). Signal Transmission over Mobile Radio Channels. In: Wireless communications, Springer, Boston, MA, Kluwer Academic Publications, 149-223. https://doi.org/10.1007/978-1-4419-9152-2_4.

[3] Ghosh J, Dey A. and Bachhar, S. (2014). Performance Analysis by Improving Bit Error Rate (BER) through various Diversity Techniques in Wireless Communication, *International Journal of Computer Applications,* 95(9), 1-5.

[4] Baldman, A. (2003). Bit Error Ratio Testing: How Many Bits Are Enough? UNH Inter Operability Lab.

[5] Alam, S. M. J., Alam, M. R. Hu, G. and Mehrab, Z. (2011). Bit Error Rate Optimization in Fiber Optic Communications, *International Journal of Machine Learning and Computing*, 1(5), 435-440.

[6] Barry, J. R., Lee, E. A. and Messerschmidt, D. G. (2004). Digital Communication, Kluwer Academic Publishers, 203-205.

[7] Alamouti, S. M. (1998). A simple transmit diversity technique for wireless communications, *IEEE Journal on selected areas in communications*, 16(8), 1451-1458.

[8] Carlson, A. B. and Crilly, P. B (2010). Communication systems, 5e.

[9] Sharma, A., Majumdar, S. and Naugarhiya, A. (2017) VERILOG-based Simulation of ASK, FSK, PSK, QPSK Digital Modulation Techniques. International conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud), 403-408.

[10] Webb, W. T. (1992). Modulation methods for PCNs, *IEEE Communications magazine*, 30, 90-95.

[11] Dong, J (2013). Estimation of Bit Error Rate of any digital Communication System. Signal and Image Processing. Télécom Bretagne, Université de Bretagne Occidentale.

[12] Miu, A., Balakrishnan, H. and Koksal, C. E. (2005). Improving Loss Resilience with Multi-Radio Diversity in Wireless Networks, *In Proceedings of the* 11th Annual International Conference on Mobile Computing and Networking, MOBICOM 2005, Cologne, Germany, August 28 - September 2, 16-30, http://doi.org/10.1145/1080829.1080832.

[13] Han, B., Ji, L., Lee, S., Bhattacharjee, B. and Miller, R. (2012). All Bits Are Not Equal – Experimental Study of IEEE 802.11 Communication Bit Errors, IEEE/ACM Trans. Netw. 20(6), 1-9.

[14] Minn, H., Zeng, M and Bhargava, V. K. (2001). On ARQ scheme with adaptive error control. Vehicular Technology, IEEE Transactions on, 50(6):1426–1436.

[15] Soljanin, E., Liu, R. and Spasojevic, P. (2003). Hybrid ARQ in wireless networks. In DIMACS Workshop on Network Information Theory.

[16] Land, I. and P. A.Hoeher (2001). Using the mean reliability as a design and stopping criterion for turbo codes. In Proceedings of IEEE Information Theory Workshop, 27-29.

[17] Burdah, S., Alamtaha R., Samijayani, O. N., Rahmatia, S. and Syahriar, A. (2019). Performance Analysis of Q Factor Optical Communication in Free Space Optics and Single Mode Fiber, Universal Journal of Electrical and Electronic Engineering 6(3), 167-175, http://doi.org/10.13189/ujeee.2019.060311. [18] Simon, M. K. and Alouini, M-S. (2005). *Digital Communication over Fading Channels*, John Wiley & Sons, Inc.

[19] Wu, K., Tan, H., Ngan, H.L., Liu, Y., Ni, L. (2012). Chip Error Pattern Analysis in IEEE802.15.4. IEEE Trans. Mob. Comp. 11(4), 543-552.

[20] Schmidt, F., Ceriotti, M., Wehrle, K. (2013). Bit Error Distribution and Mutation Patterns of Corrupted Packets in Low-Power Wireless Networks. WiNTECH '13.

[21] Hermans, F., Wennerstrom, H., McNamara, L.,Rohner, C. and Gunningberg, P. (2014). All Is Not Lost: Understanding and Exploiting Packet Corruption in Outdoor Sensor Networks, Conference paper, http://doi.org/10.1007/978-3-319-04651-8_8

[22] Choudhary, A. (2015). Optimization of Bit Error Rate and Power of Ad-hoc Networks Using Genetic Algorithm International Journal of Electronics and Communication Engineering, 9(1), 28-34.

[23] Masud, M. A, Samsuzzaman, M. and Rahman, M. A. (2010). Bit Error Rate Performance Analysis on Modulation Techniques of Wideband Code Division Multiple Access, Journal of Telecommunications, 1(2), 22-29.

[24] Ahmed, R., Ahmed, R. and Robin, R. A. (2010). Performance analysis of different M-AryModulation Techniques in Fading Channels using different Diversity, *Journal of Theoretical and Applied Information Technology*, 3(2), 23-28.

[25] Soni, M., Singh, K. D. and Srivastava, V. (2011). Performance of BPSK Modulation Scheme Using AWGN and Multipath Rayleigh Fading Channel for WCDMA System, *VSRD International Journal of Electrical, Electronics, and Communication Engineering*, 1(2), 99-107.

[26] Tripathi, M. P., Changlani, S.and Ali, S. T. (2013). Performance Comparison of Bit Error Rate for BPSK and DS-BPSK for AWGN and Rayleigh Channels, *International Journal Of Advance Research In Science and Engineering*, 2(11),131-137.

[27] Al-Rawi, M. (2017). Performance Analysis of OFMA and SC-FDMA, Int. Rev. Appl. Sci. Eng. 8(2), 113-116, http://doir.org/10.1556/1848.2017.8.2.2

[28] Jagadeesh, D. (2007). Simulation of Wireless Communication System using OFDM Principle, An M. Tech. Thesis, Department of Electronics and Communication Engineering, National Institute of Technology, Rourkela.

[29] Varade, S. and Kulat, K. (2012). BER Comparison of Rayleigh Fading, Rician Fading and AWGN Channel using Chaotic Communication based MIMO-OFDM System, International Journal of Soft Computing and Engineering, 1(6), 107-115.

[30] Khalaf, T.A. and Mohammed, H. (2020). Bit error rate performance analysis of AC-MAP in multiple input single output wireless relay network. Journal of Wireless Communication Network**,** 12. https://doi.org/10.1186/s13638-019-1633-8.

[31] Pursley, MB (1977). Performance evaluation for phase-coded spread spectrum multiple-access communication, Part 1: System analysis. IEEE Trans. Commun., 25: 795-799.

[32] *Matthew G(2005). 802.11 Wireless Networks: The Definitive Guide.* ***1*** *(2ed.). Sebastopol, CA: O'Reilly Media. pp. 284.*

[33] Kim, S. (2010). An Algorithm for Bit Error Rate Monitoring and Adaptive Decision Threshold Optimization Based on Pseudo-error Counting Scheme. Journal of The Optical Society of Korea, 14, 22-27, http://doi.org/10.3807/JOSK.2010.14.1.022.

[34] Ghassemlooy, Z., Popoola, W. O., Rajbhandari, S., Amiri, M. and Hashemi, S. (2007). A Synopsis of Modulation Techniques for Wireless Infrared Communication, ICTON-MW'07, http://doi.org/10.1109/ICTONMW.2007.4446952.

[35] Barnela, M. (2014).Digital Modulation Schemes Employed in Wireless Communication: A Literature review. *International Journal of Wired and Wireless Communications*, 2(2), 15-21.

[36] Bepery, C., Hasan, Md. M., Farhana, T. Basir, G. Md. M. and Paramanik, Md. I. (2013). Estimate Better Channel from Additive White Gaussian Noise and Rician Channel for Minimum Shift Keying Signal. International Journal of Electronics and Informatics, 2(1), 19-25.

[37] Chauhan, V., Arora, M. and Chauhan, R. S. (2011). Comparative BER Performance of PSK-based modulation Techniques under Multipath Fading, *Advances in Applied Science Research*, 2(4), 521-527.

[38] Proakis, G. J. (1995). Digital Communications *(3rd ed.). Singapore: McGraw–Hill Book Co. pp.* 767–768.

[39] *Sklar, B. (1997). Rayleigh Fading Channels in Mobile Digital Communication Systems Part I: Characterization. IEEE Communications Magazine. 35(7), 90-100, http://*doi.*org/*10.1109/35.601747.

[40] Sklar, B. (2005). Digital Communications (2nd ed.): Fundamentals and Applications. Prentice-Hall, New York.

[41] Gilley, J. E. (2003). Bit-Error-Rate Simulation Using Matlab, Transcrypt International, Inc.

[42] Anderson, J. B. and Svensson, A. (2002) Introduction to Fading Channels. In: Wolf J.K., McEliece R.J., Proakis J., Tranter W.H. (eds) Coded Modulation Systems. Information Technology: Transmission, Processing and Storage. Springer, Boston, MA. https://doi.org/10.1007/0-306-47792-0_7.