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REDUCING THE ERROR RATE USING ADDITIVE WHITE GAUSSIAN NOISE AND RAYLEIGH CHANNELS IN THE COMMUNICATION SYSTEM

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Abstract. *Long Range (LoRa) with chirp spread spectrum (CSS) modulation technique has been widely developed on the Internet of Things. In this study, we tested the LoRa performance of other LoRa users with additive white Gaussian noise (AWGN) and Rayleigh fading characteristics where the distracting user was not aligned with the chip or phase with the desired signal. In addition, this study also proves that two symmetries in the interfering signal and low requirements can significantly reduce symbol computation and error rate compared to complete expressions. This paper focuses on LoRa performance by considering the error rate in the CSS modulation system. This study is based on coherent and noncoherent detection using binary frequency shift keying (BFSK). The method used in this study is comparative analytic with simulation results showing that the expression of bit error rate (BER), symbol error rate (SER), and packet error rate (PER), using coherent and noncoherent detection, estimates generate precise numbers for SF = 7, BER = 0.03 against E_bN_0 = 1 dB, SER = 0.8 against E_sN_0 = 1 dB, and PER = 0 against signal-to-noise ratio (SNR) 1 dB. In this study, coherence detection, AWGN channel, and numerical approach can reduce the required error rate in the communication system.*
Keywords: LoRa, Error rate, AWGN, Rayleigh, BFSK

1. **Introduction.** The LoRa (Long Range) communication system has become excellent in the research community and commercial users because of its advantages in transmitting data over long distances with relatively low energy costs. This study presents new results for the bit error rate, symbol error rate, and packet error rate performance of a Long Range (LoRa) system operating in the presence of AWGN and Rayleigh channels. In detail, this study proposes how to reduce the error rate to increase the reliability of the communication system. This study presents analytical and numerical equation validation using orthogonal signaling [1]. LoRa is an independent, spectrum-license-free wireless system with low costs, low power requirements, and low bit rates for long-distance communication. Users can create their network, gateway, and nodes using LoRa [2]. LoRa uses the chirp spread spectrum (CSS) modulation, created by Semtech, at the physical layer (PHY) of the protocol stack as a form of communication [3-7]. The noise power added by the AWGN block is connected to the signal power subsystem along with the display block to the input of the AWGN block, the output signal power of the channel, which will be the difference between the sum of the input signal power and the noise power [8,9]. The contribution

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of this research is to produce an appropriate coherent and noncoherent detection model used in the LoRa communication system to get the value of the BER to E_bN_0, SER to E_sN_0, and PER to ideal SNR using the AWGN and Rayleigh methods using MATLAB by considering the parameters, the best input parameter to get a low error value using BFSK modulation technique. Section 2 gives a literature review, and in Section 3, this study discusses the method using comparative analytical-numerical, where the authors compare the analytical and numerical error rate calculations using AWGN and Rayleigh channels. Section 4 discusses the results and discussion of the values of SF with BER against E_bN_0, SER against E_sN_0, and PER against SNR at 125 kHz bandwidth using coherent and noncoherent detection. Section 5 concludes by determining the correct detection and channel for the LoRa communication system using the SX1276 transceiver analytically and numerically.

2. **Literature Review.** BER simulations are presented by a researcher and evaluated using parameters of the LoRa modulation patterns, such as spreading factor, code rate, symbol frequency, and SNR. The accuracy of the BER was described, and the LoRa performance was investigated using numerical results – the relationship between the energy per bit and the noise power spectral density (E_bN_0). According to the numerical results, these estimations yield accurate values for $SF = 7$, BER values of $10^{-0.8}$ equal to 0.15, and $SNR = -10$ dB with a coding rate of 4/5 [10]. A researcher tested the error probability performance of a LoRa communication system by proposing an accurate estimate for the bit error probability of CSS modulation in an AWGN channel. BER performance of LoRa systems uses uncoded and coded transmissions with coherent and noncoherent detection for Hamming-coded LoRa signals with decoded and coherent (or noncoherent) detection, both in the AWGN channel. System performance has been simulated on multipath channels, utilizing a simplified equalizer on the receiving end. The SNR value in this study is up to 1 dB [11]. Other researchers have proposed that multicarrier modulation schemes such as orthogonal frequency division multiplexing (OFDM) provide an efficient solution to this problem. This researcher performs grayscale image processing using the least mean square (LMS) algorithm with a wavelet-based OFDM system using a quadrature phase shift keying (QPSK) modulation scheme on AWGN and Rayleigh channels in the single input single output (SISO) environment. The results are compared with a conventional adaptive OFDM system based on Fast Fourier Transform (FFT) [12,13]. Another researcher tested LoRa performance in the presence of AWGN and interference from other LoRa users by extending the existing interference model, which assumes perfect alignment of the desired signal and existing harmonized interference overestimating the effect of interference at an error rate of 1 dB [14]. This study also features numerical simulations to strengthen the theoretical analysis to verify the accuracy of the proposed estimates [15]. Other researchers measured the SER of AWGN and Rayleigh fading channels. The accuracy of the forecast was confirmed by comparing the estimates obtained with the numerical data and discussing the sensitivity of the receiver and the associated coverage range in an AWGN-type environment using the SX1272 transceiver with a sensitivity of $PRx = -137$ dBm [16], whereas, in this paper, the authors use the SX1276 transceiver with a sensitivity of $PRx = -148$ dBm. The comparison to the numerical results confirms a relatively accurate estimate of the presented analysis. The results for the Rayleigh fading environment show that LoRa cannot sustain long-distance communication in an urban environment with Rayleigh fading characteristics [17-19].

Researchers [10] suggest adopting a low CR to reduce the BER value, we have done the same thing, but it does not significantly reduce the BER value, so it is optimized in the BFSK modulation process to reduce noise. Researchers [11-16] focus on the value of $SNR = 1$ dB. Table 2 shows the same weight but in more detail, calculating other parameters such as BER, SER, and PER values. Researchers' statements [17-19] have been proven in this study and contribute to the right communication system used in urban environments by comparing Rayleigh and AWGN channels using coherent and noncoherent detection for SNR values of 1 dB and reducing BER, SER and PER values.

3. **Proposed Method.** The authors analyze the error rate calculation in the LoRa communication system using AWGN and Rayleigh channels analytically and numerically in a comparative method. AWGN is one type of noise in communication systems, commonly called thermal noise. The AWGN channel is a universal channel model for analyzing modulation schemes. In this model, the AWGN channel is added to the signal passing through it using coherent and noncoherent detection. This indicates that the channel amplitude frequency response is flat, and the phase response is linear for all frequencies. The modulation passes through it without amplitude, phase loss, or distortion of the frequency components. In this study, the code designed on the AWGN channel serves to optimize its inherent diversity. The performance of the communication system on Rayleigh fading can also be seen from the characteristics of BER, which theoretically has one path.

A message sent in binary data from the SM (smart metering) is modulated on the LoRa transmitter and then encoded using additional input parameters. In this experiment, the LoRa transmitter encodes the message before being sent as packets. The LoRa sends the packet-modulated signal to the frequency shifter, which creates a modulated signal. Figure 1 shows a flowchart of the Lora communication system on the transceiver (transmitter and receiver).

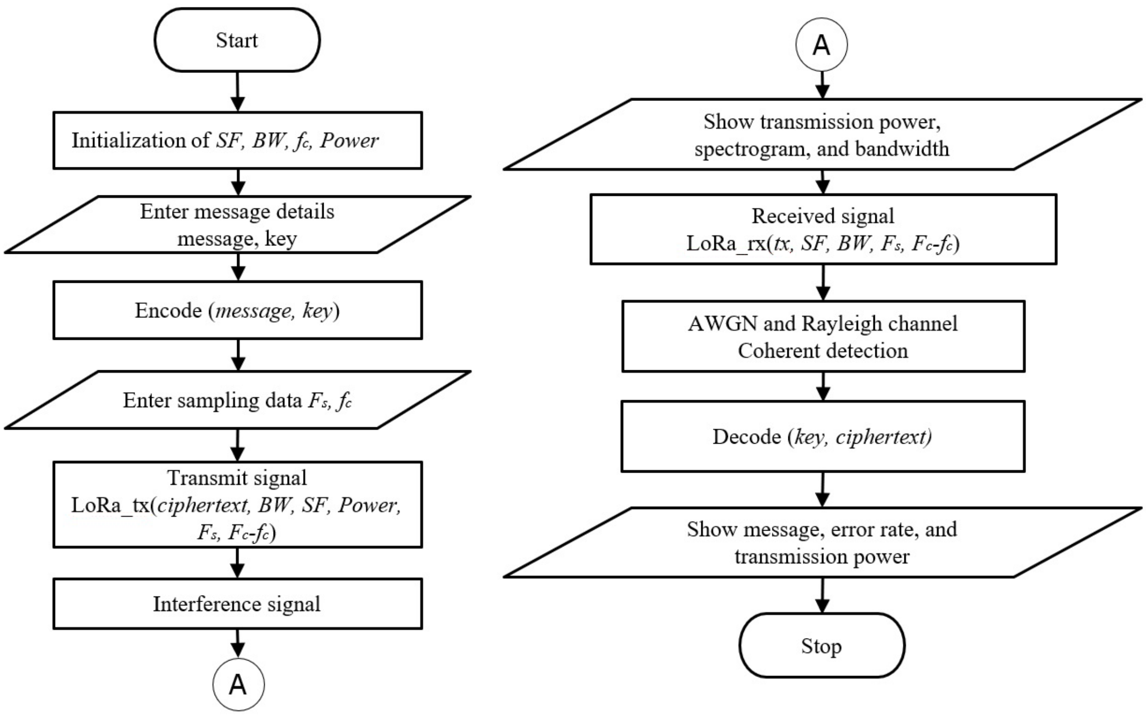


Figure 1. Flowchart of the LoRa communication system on the transceiver

In Figure 1, the LoRa communication system begins with initializing the input value $SF = 7$, $BW = 125$ kHz, $f_c = 915$ MHz, and transmit power of 14 dBm. The message is sent from the transmitter to the receiver as a message with 79 characters. The message is coded, and the input data sampling is F_s and f_c. LoRa transmitter sends information to the receiver; this process is the same as the transmitter process in general, but what is different is on the receiver side. This study uses an unlicensed spectrum so that the interference on the channel will be substantial and requires special handling [20,21]. At the receiving end, LoRa receives the tx, SF, BW, F_s, and F_c-f_c signals the same as those emitted. On the receiving side, research was developed to produce coherent and noncoherent detection models appropriate for LoRa communication systems using the AWGN and Rayleigh methods to obtain low error values by modulating BFSK using MATLAB.

The signal modulation procedure has been examined and verified using MATLAB utilizing messages corresponding to the data sent [22]. The node will receive data from the transmitter on the receiver, which will then recapitulate the SNR. AWGN or Rayleigh channels will be used if the value of $F_s = BW$; otherwise, it will be transmitted to the frequency modulation process using BFSK and filtered using LPF. In contrast to traditional frequency modulation, BFSK is a constant-envelope version of angle modulation where the modulating signal alternates between two discrete voltage levels (1 and 0) instead of a continually changing value like a sine wave. Rayleigh or AWGN processes the following procedure due to signal interference or interference in overlapping bands. This study sends messages repeatedly to test the system's reliability [18]. A BER system can be used to evaluate the effectiveness of communication systems [23-25]. It is possible to see the power spectral density of the random signal by looking at the time domain signal in the baseband, produced by the information bit sent from the transmitter to the receiver in the communication system. Bit 1 denotes the transmission condition of the information from the transmitter to the receiver. To generate an independent noise sample and a flat noise spectrum labeled $N_0/2$, which is two-sided such that the convenience factor of two in labeling is two, the AWGN channel also represents a Fourier transformation. The probability of bit error using BFSK can be seen in the following Equation (1) for the binary case where $M = 2^b$, $b = 1$ coherent (synchronous) detection:

$$Q\left(\sqrt{\frac{E_s/2}{N_0/2}}\right) = Q\left(\sqrt{\frac{SNR_r}{2}}\right) \tag{1}$$

E_s is an energy per symbol, N_0 is a noise energy, and SNR_r is an SNR in the RC (reference channel). For noncoherent detection Equation (2) is as follows:

$$\frac{1}{2}e^{-SNR_r/4} \tag{2}$$

The binary case where $M = 2^b$, $b > 1$ using coherent (synchronous) detection in Equation (3):

$$\frac{\frac{M}{2}}{M-1}\left\{1 - \frac{1}{\sqrt{\Pi}}\int_{-\infty}^{\infty} q(y)e^{-y^2}dy\right\} \tag{3}$$

M is a digit that indicates the number of conditions, levels, or combinations that can be made for a specific number of binary variables. $M = 2^{SF} = Ts * BW = 128$, Equation (4) presents the quality of SNR.

$$q(y) = Q^{M-1}\left(-\sqrt{2y} - \sqrt{bSNR_{r,b}}\right) \tag{4}$$

And for noncoherent detection it is presented in Equation (5):

$$\frac{\frac{M}{2}}{M-1}\sum_{m=0}^{M-1}(-1)^{m+1}\left(\begin{array}{c} M-1 \\ m \end{array}\right)\frac{1}{m+1}e^{-\frac{mbSNR_r}{2(m+1)}} \tag{5}$$

Therefore, the FSK coherent signal's bandwidth and bandwidth efficiency can be expressed as the following Equations (6) and (7):

$$B_{COH,FSK} = 2R_s + (M-1)\frac{R_s}{2} = \frac{(M+3)R_b/\log_2 M}{2} \tag{6}$$

$$\frac{R_b}{B_{COH,FSK}} = \frac{2\log_2 M}{M+3} \tag{7}$$

The receiver's sensitivity (S) is described in the following Equation (8):

$$S = -148 + 10\log_{10}(B) + NF + SNR \tag{8}$$

where (-148) is the result of thermal noise at the receiver in a 1 Hz bandwidth, NF is the noise figure at the receiver (specified for hardware configuration data), and SNR is the signal-to-noise ratio necessary for modulation. The SER is evaluated while varying the SNR, defined as the device's received power to the noise power [26]. The SER can be used to determine the symbol error rate at the receiver and decoder performance evaluation. The symbol rate (R_s) is calculated using the following Equation (9):

$$R_s(\text{symbol/sec}) = \frac{BW}{2^{SF}} = \frac{R_c}{2^{SF}} \tag{9}$$

$R_s = 125{,}000/2^7 = 976$ symbol/sec. To offer functionality for ACK packets, PER measurement typically requires temporal dynamic of register configuration, interrupt handling (to verify valid/invalid packets), and switching between T_X and R_X modes. Bit error probability can be calculated as the following Equation (10):

$$P_b \approx 0.5 \times Q\left(\frac{\sqrt{E_s} - \mu_{\hat{p}}}{\sigma_{\hat{p}}^2 + N_0/2}\right) \tag{10}$$

P_b is a bit probability, $Q(x)$ is the Gaussian Q-function in a standard normal distribution or the same as a tail distribution, and N_0 is a noise density (watts/Hz) [11,27,28].

As a necessary form indicates the precise likelihood of error for simplex signals in AWGN, which can be laborious to compute, shorter arrangements are of interest. Calculate simplex signals' error probabilities in AWGN. Coherent quaternary frequency-shift keying (FSK) and pulse-position modulation are two orthogonal sets that can easily be included in the new boundaries [29]. A simple radio signal merely indicates that the transmitter is still turned on. Signals need to be modified in some way before they can transfer data. There are numerous ways to accomplish this. The most common techniques involve changing the frequency and amplitude [30]. In this study, the frequency is modified using BFSK. Table 1 shows the input parameters used in this study.

Table 1. LoRa parameters [11,31]

Parameter	**Value**
Bandwidth (BW)	125 kHz
Spreading factor (SF)	7
Frequency sampling (F_s)	10 MHz
Frequency carrier (F_c)	921.5 MHz
Transmit power in decibels (P_t)	14 dBm
Frequency center (f_c)	915 MHz
Number of conditions (M)	128
Modulation technique	CSS
Digital modulation	BFSK
Noise channels	AWGN, Rayleigh
SNR	$-30:30$
Time duration (T_d)	0.999

This study uses $SF = 7$, the lowest spreading factor that increases the data rate, leading to faster transmission time and boosting energy to the signal more resilient to remote deployments.

The simulation loop method creates a Gaussian distributed random number design array. Parameters are utilized in communication to control the communication system's error. Here, the digital modulation technique uses the BER and SNR parameters.

$$SNR = \Gamma$$
$$\Gamma = \frac{E_s/T_s}{N_0 \cdot BW} = \frac{E_s}{N_0 2^{SF}} \tag{11}$$

E_s is the power spectral density of signal energy, N_0 is the noise energy, and T_s is the time of signal energy.

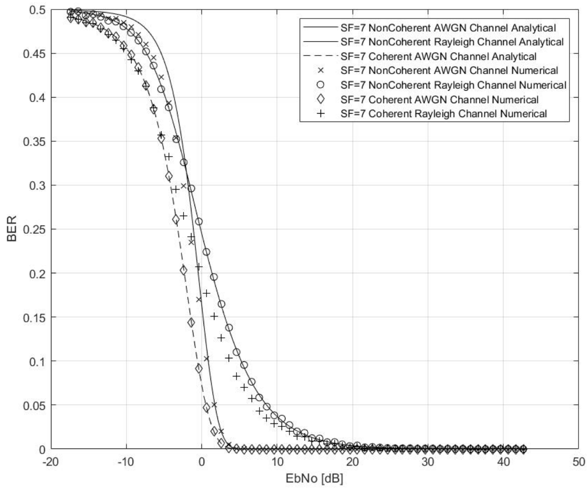
4. **Simulation Result and Discussion.** Performance of BFSK detection coherent and noncoherent features, such as known frequency and phase, known frequency and unknown phase, and unknown frequency and phase, are present. When the frequency or phase of the received signal is unknown, noncoherent detection should be used according to this knowledge-based characteristic of the received signal. With the known frequency and unknown phase, the theoretical loss of incoherent BFSK detection performance is reduced by around 0.9 dB at $P_{be} = 10^{-5}$ relative to coherent BFSK detection. The theoretical loss of coherently detected BFSK close to antipodal signaling is 3 dB for all bit error situations. However, when the frequency and phase are unknown, the loss depends on the frequency uncertainty range, with a loss of 17 dB at $P_{be} = 10^{-5}$ compared to coherent detection for the bit rate uncertainty range at a frequency of 104 times.

The results of a computer simulation program utilizing MATLAB using an analytical and numerical approach to wireless communication systems are covered in this chapter's portion, which also considers AWGN and Rayleigh fading. Figure 2 shows the test results as the bit energy ratio to noise power spectral density (E_b/N_0) and BER.

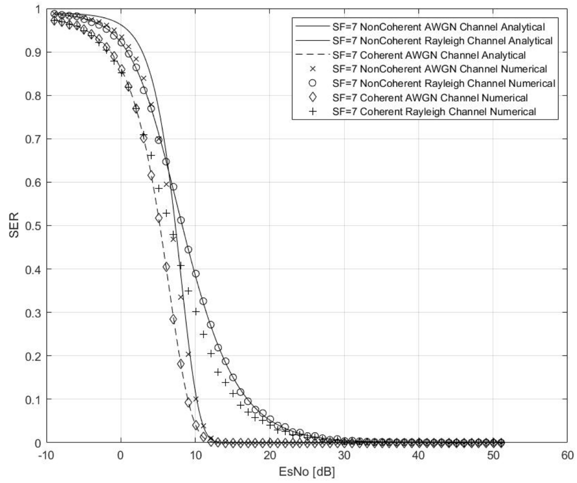
BER and E_bN_0, SER and E_sN_0, PER, and SNR simulation results are shown in Table 2.

Figure 2 and Table 2 show that the numerical technique using the AWGN channel and coherent detection of the bit error rate value, namely a BER of 0.03 and an E_bN_0 of 1 dB, is optimal for the LoRa communication system. The greater the SF value, the more sensitive the receiver is. However, it also accounts for the faster bit rate, lengthening the transmission time, which is especially problematic if the subscriber is far from the base station. LoRa operates on a 125 kHz fixed bandwidth channel, offering a trade-off between sensitivity and data rate [32]. LoRa also uses an orthogonal dispersion factor. This higher dispersion factor provides increased processing gain and greater reception sensitivity. After being simulated on AWGN and Rayleigh channels, BER analysis shows that the LoRa modem performs well, with a BER value of 0.5 and an E_bN_0 value of up to 20 dB. Figure 2 shows the test results as the bit energy ratio to noise power spectral density (E_b/N_0). BER displays the energy per symbol to noise power spectral density (E_sN_0) and SER ratios. The optimal value for the noncoherent AWGN channel is discussed in this simulation, which uses MATLAB software to analyze and numerically model wireless communication systems while considering AWGN and Rayleigh fading.

The numerical method employing the AWGN channel and coherent detection of the symbol error rate value, namely an SER of 0.8 and an E_sN_0 of 1 dB, is shown to be the best for LoRa communication systems. Assuming one LoRa device has 30000 symbols, Figure 2 depicts the symbol error rate versus the E_sN_0 for $SF = 7$ in the LoRa network's performance. With fewer iterations and numerical calculations, the symbol error rate employing coherence detection on the AWGN channel can significantly lower the E_sN_0 number. Figure 2 and Table 2 demonstrate that the numerical method using the AWGN channel and coherent detection for packet error rate is the best for LoRa communication systems with PER 0 and an SNR equal to 1 dB. The packet error rate curve is used for LoRa, specifically on AWGN or Rayleigh channels, to forecast the performance of the communication system [33]. The LoRa Semtech transceiver supplied SNR to calculate the whole curve using measurements, empirical representations, and closed-form estimation



(a)



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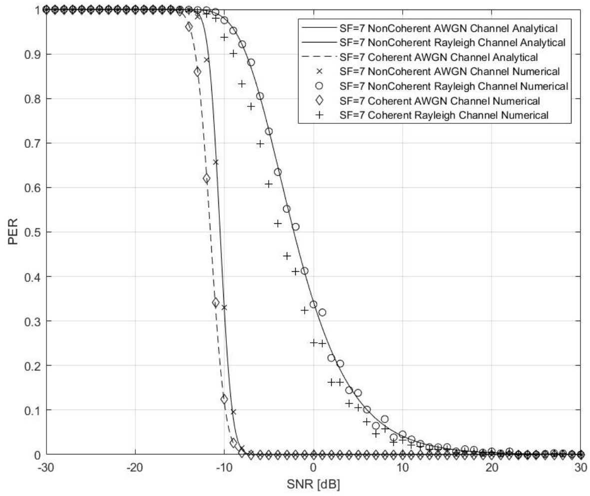

(c)

FIGURE 2. (a) Bit error probability, (b) symbol error probability, and (c) packet error probability with coherent and noncoherent demodulation using AWGN and Rayleigh

TABLE 2. Simulation result of BER against E_bN_0, SER against E_sN_0, and PER against SNR

Method	Channel	Detection	BER	E_bN_0 (dB)	SER	E_sN_0 (dB)	PER	SNR (dB)
Numerical	AWGN	Coherent	0.03	1	0.8	1	0	1
	AWGN	Noncoherent	0.08	1	0.9	1	0	1
	Rayleigh	Coherent	0.1	1	0.8	1	0.2	1
	Rayleigh	Noncoherent	0.2	1	0.9	1	0.3	1

assuming AWGN or Rayleigh fading channels, which serve as benchmarks. In addition to considering interference effects and thinking of network-generated interference, this model forecasts LoRa performance. The received signal is less distorted when the value is closer to +10 dB. LoRa can demodulate signals between −7.5 dB and −20 dB below the noise level [33].

5. **Conclusions.** The performance of the LoRa network demonstrates that coherent detection on the AWGN channel effectively reduces noise values at $SNR = 1$ dB. This research's contribution has been verified to accurately compare analytical and numerical calculations with coherent and noncoherent detection using AWGN and Rayleigh channels successfully simulated in MATLAB. The coherent detection with the AWGN channel is the appropriate model in this study when considering the best input parameters. In the future, the authors will implement this research on a smart grid communication system with a security system to produce high reliability.

REFERENCES

[1] R. Hamdi, M. Qaraqe and S. Althunibat, Dynamic spreading factor assignment in LoRa wireless networks, *IEEE International Conference on Communications*, vol.6, pp.5-9, 2020.

[2] N. F. A. Rashid et al., Development of smart campus applications based on wireless technologies using open-source platforms, *J. Teknol.*, vol.84, no.3, pp.173-184, 2022.

[3] C. Milarokostas, D. Tsolkas, N. Passas and L. Merakos, A comprehensive study on LPWANs with a focus on the potential of LoRa/LoRaWAN systems, *IEEE Communications Surveys & Tutorials*, vol.25, no.1, pp.825-867, DOI: 10.1109/COMST.2022.3229846, 2023.

[4] A. A. Tesfay, E. P. Simon, G. Ferre and L. Clavier, Serial interference cancellation for improving uplink in LoRa-like networks, *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. (PIMRC)*, vol.8, 2020.

[5] B. Reynders, W. Meert and S. Pollin, Range and coexistence analysis of long range unlicensed communication, *2016 23rd International Conference on Telecommunications (ICT 2016)*, 2016.

[6] S. Robson and A. Haddad, A chirp spread spectrum modulation scheme for robust power line communication, *IEEE Transactions on Power Delivery*, vol.37, no.6, pp.5299-5309, DOI: 10.1109/TPWRD.2022.3175830, 2022.

[7] C. Lehong, B. Isong, F. Lugayizi and A. Abu-Mahfouz, A spreading factor congestion status-aware adaptive data rate algorithm, *J. Sens. Actuator Networks*, vol.10, no.4, DOI: 10.3390/jsan10040070, 2021.

[8] W. Y. Yang, Y. S. Cho, W. G. Jeon, J. W. Lee, J. H. Paik, J. K. Kim, M.-H. Lee, K. I. Lee, K. W. Park and K. S. Woo, *MATLAB®/simulink® for Digital Communication*, A-Jin Publishing Co., 2009.

[9] L. C. Hwang, C. S. Chen, T. T. Ku and W. C. Shyu, A bridge between the smart grid and the Internet of Things: Theoretical and practical roles of LoRa, *Int. J. Electr. Power Energy Syst.*, vol.113, no.5, pp.971-981, 2019.

[10] H. Mroue, A. Nasser, B. Parrein, S. Hamrioui, E. Mona-Cruz and G. Rouyer, Analytical and simulation study for LoRa modulation, *2018 25th International Conference on Telecommunications (ICT 2018)*, pp.655-659, 2018.

[11] G. Baruffa, L. Rugini, L. Germani and F. Frescura, Error probability performance of chirp modulation in uncoded and coded LoRa systems, *Digital Signal Processing: A Review Journal*, vol.106, 102828, 2020.

[12] A. Mannan and A. Habib, Adaptive processing of image using DWT and FFT OFDM in AWGN and Rayleigh channel, *Proc. of 2017 Int. Conf. Commun. Comput. Digit. Syst. (C-CODE 2017)*, pp.346-350, 2017.

[13] S. A. Arnomo, Yulia and N. Ibrahim, Comparison of wireless adapters interference based on differences of floor position, *J. Teknol.*, vol.83, no.4, pp.151-157, 2021.

[14] G. S. Kishore and H. Rallapalli, Performance assessment of M-ary ASK, FSK, PSK, QAM and FQAM in AWGN channel, *Proc. of the 2019 IEEE International Conference on Communication and Signal Processing (ICCSP 2019)*, pp.273-277, 2019.

[15] O. Afisiadis, M. Cotting, A. Burg and A. Balatsoukas-Stimming, On the error rate of the LoRa modulation with interference, *IEEE Trans. Wirel. Commun.*, vol.19, no.2, pp.1292-1304, 2020.

[16] Semtech, *LoRa SX1276*, Semtech Corporation, no.SX1276/77/78/79, 2016.

[17] T. Elshabrawy and J. Robert, Closed-form approximation of LoRa modulation BER performance, *IEEE Commun. Lett.*, vol.22, no.9, pp.1778-1781, 2018.

[18] ITU-R M.1225-1997, *Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000*, 2015.

[19] N. T. Awon, M. A. Islam, M. M. Rahman and A. Z. M. T. Islam, Effect of AWGN & Fading (Raleigh & Rician) channels on BER performance of a WiMAX communication system, *International Journal of Computer Science and Information Security (IJCSIS)*, vol.10, no.8, pp.11-17, 2012.

[20] Isminarti, A. A. Ilham, A. Arief and Syafaruddin, Improved data security using advanced encryption standard algorithm on long-range communication system at smart grid, *ICIC Express Letters, Part B: Applications*, vol.14, no.5, pp.499-508, DOI: 10.24507/icicelb.14.05.499, 2023.

[21] K. M. G. B. Al Homssi, A. Al-Hourani, K. Magowe, J. Delaney, N. Tom, J. Ying, H. Wolf, S. Maselli, S. Kandeepan and K. Wang, A framework for the design and deployment of large-scale LPWAN networks for smart cities applications, *IEEE Internet of Things Magazine*, vol.3, pp.53-59, 2021.

[22] A. A. I. Isminarti, S. Syafaruddin and I. A. Ahmad, Modeling and simulation of long range (LoRa) communication system on smart grid, *2022 7th International Conference on Informatics and Computing (ICIC)*, pp.14-19, 2022.

[23] L. Vangelista, Frequency shift chirp modulation: The LoRa modulation, *IEEE Signal Process. Lett.*, vol.24, no.12, pp.1818-1821, 2017.

[24] S. Bharati, M. A. Rahman and P. Podder, Implementation of ASK, FSK and PSK with BER vs. SNR comparison over AWGN channel, *arXiv Preprint*, arXiv: abs/2002.03601, 2020.

[25] D. Borovina, M. Zajc, A. Mujcic, A. Tonello and N. Suljanovic, Error performance analysis and modeling of narrow-band PLC technology enabling smart metering systems, *Int. J. Electr. Power Energy Syst.*, vol.116, 2020.

[26] R. Hamdi, M. Qaraqe and S. Althunibat, Dynamic spreading factor assignment in LoRa wireless networks, *IEEE Int. Conf. Commun.*, vol.6, pp.5-9, 2020.

[27] T. Elshabrawy and J. Robert, Analysis of BER and coverage performance of LoRa modulation under same spreading factor interference, *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. (PIMRC)*, vol.9, 2018.

[28] J. Courjault et al., Accurate LoRa performance evaluation using Marcum function, *IEEE International Conference on Global Communications (Globecom)*, 2019.

[29] L. Rugini, Tight upper bounds on the probability of error of quaternary simplex signals, *IEEE Commun. Lett.*, vol.19, no.6, pp.1001-1004, 2015.

[30] P. Seneviratne, *Begining LoRa Radio Networks with Arduino*, Apress, 2019.

[31] L. Alliance and S. Ramon, *LoRaWAN® 1.1 Regional Parameters*, Technical Report, 2017.

[32] P. Maurya, A. Singh and A. A. Kherani, Design LoRaWAN network for unbiased communication between nodes and gateway, *2022 14th International Conference on COMmunication Systems & NETworkS (COMSNETS)*, Bangalore, India, pp.581-589, DOI: 10.1109/COMSNETS53615.2022.9668447, 2022.

[33] B. Al Homssi, K. Dakic, S. Maselli, H. Wolf, S. Kandeepan and A. Al-Hourani, IoT network design using open-source LoRa coverage emulator, *IEEE Access*, vol.9, pp.53636-53646, 2021.

[34] M. Allegretti and L. Matekovits, LoRa©: Applications and validations in complex urban environment, *Corso di laurea magistrale in Ingegneria Elettronica (Electronic Engineering)*, 2021.