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LoRaWAN: The dilemma of optimal transmission parameter

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Abstract

Low-Power Wide-Area Network (LPWAN) technologies, particularly LoRaWAN, have gained significant attention for their ability to facilitate long-range communication with low power consumption, making them ideal for Internet of Things (IoT) applications. However, achieving optimal performance in LoRaWAN systems requires careful selection of transmission parameters such as spreading factor, bandwidth, and coding rate. This paper addresses the dilemma faced by network designers and operators in determining the optimal transmission parameters for LoRaWAN deployments. We provide an overview of the key parameters and their impact on network performance, considering factors such as latency, packet delivery rate, and energy efficiency. Furthermore, we discuss the trade-offs involved in parameter selection. Through simulations, we evaluate the performance of different parameter configurations under various network conditions and provide insights into achieving the best balance between coverage, capacity, and energy consumption in LoRaWAN deployments. Findings from the study established that using high coding rate and bandwidth only provides minimal improvement in packet delivery rate particularly at large distances but at the cost energy consumption while spreading factor remains the most important transmission parameter in LoRa networks.

Keywords: LoRaWAN; Spreading Factor; IoT; Optimal Parameter; LPWAN; ADR

1. Introduction

The emergence of LoRaWAN technology has ushered in a new era of connectivity for the Internet of Things (IoT) applications by providing a robust framework for long-range, low-power wireless communication [1]. The Long-Range Wide Area Network (LoRaWAN) is a wireless communication protocol designed for long-range communication between IoT devices and gateways. It is the most popular technology of a group of wireless communication protocol referred to as Low Power Wide Area Network. Their advantage comes from their ability to provide extensive wireless connectivity often in the range of several kilometres at low cost with very minimal energy usage [2]. These properties make LoRaWAN in particular, an ideal candidate for applications like smart cities [3], agriculture [4], [5], [6], and industrial monitoring [7] [8]. LoRaWAN achieves its exception long range communication by utilizing chirp spread spectrum (CSS) modulation [9]. The CSS modulation scheme enables efficient communication by spreading the signal across multiple channels. This spreading technique enhances robustness against interference and enables below-noise-floor communication, thus ensuring reliable and scalable IoT deployments in diverse challenging environments. Another important characteristic of LoRaWAN is the use of an unlicensed spectrum. Consequently, LoRaWAN operators do not require a license to operate the network as long as their operation is within the allowable duty cycle specifications by regulators.

Central to the efficacy of LoRaWAN deployments are its transmission parameters, which dictate the performance and efficiency of communication between IoT devices and gateways [10]. However, configuring these parameters optimally poses a significant challenge, as it involves compromises and trade-offs to achieve desired network characteristics. In this paper, we proposed an appropriate insight for obtaining a balance between the major transmission parameters

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employed in LoRaWAN for IoT deployments. Specifically, we studied how parameters such as spreading factor (SF), bandwidth (BW), coding rate (CR), and output power (TP) influence LoRaWAN performance and how informed trade-offs can be made to achieve the specific requirement of each LoRaWAN deployment.

In implementing a LoRaWAN network, there are several key parameters that must be carefully selected to ensure optimal performance of the network. The first and arguably the most important transmission parameter is the spreading factor (SF). The SF determines the duration of each transmitted symbol and directly impacts the communication range and data rate. LoRaWAN supports SF values ranging from 7 to 12, with higher SF values providing longer range but lower data rates [11]. This trade-off between range and data rate allows LoRaWAN to adapt to diverse deployment scenarios, from urban environments with dense infrastructure to rural areas with sparse coverage.

Another critical parameter is bandwidth, which defines the width of the radio channel used for communication. LoRaWAN supports bandwidth options of 125 kHz, 250 kHz, and 500 kHz, each offering different trade-offs in terms of communication range and spectral efficiency. Narrower bandwidths result in longer communication range but lower data rates, while wider bandwidths enable higher data rates at the expense of range [12].

In addition to SF and bandwidth, LoRaWAN defines other transmission parameters such as coding rate and output power. Coding rate determines the level of error correction applied to transmitted data, balancing robustness against noise and spectral efficiency. LoRaWAN supports coding rate options ranging from 4/5 to 4/8, with higher coding rates providing better immunity to noise but reducing effective data throughput. Output power, on the other hand, regulates the signal strength of transmitted packets, influencing communication range and energy consumption. LoRaWAN devices typically operate at output power levels ranging from 5 dBm to 20 dBm, with higher power settings extending the reach of transmissions but consuming more battery power. Optimizing output power is crucial for achieving desired coverage while maximizing device battery life, especially in battery powered IoT deployments.

The use case of each LoRaWAN deployment is critical in parameter selection to ensure optimal performance within the network. These deployment cases can be classified as delay tolerant, moderate delay tolerant and delay intolerant applications. The selection of the appropriate transmission parameters these applications is contingent on gaining sufficient insight into their potential response in network environment. This knowledge and insight is what we seek to provide in this study.

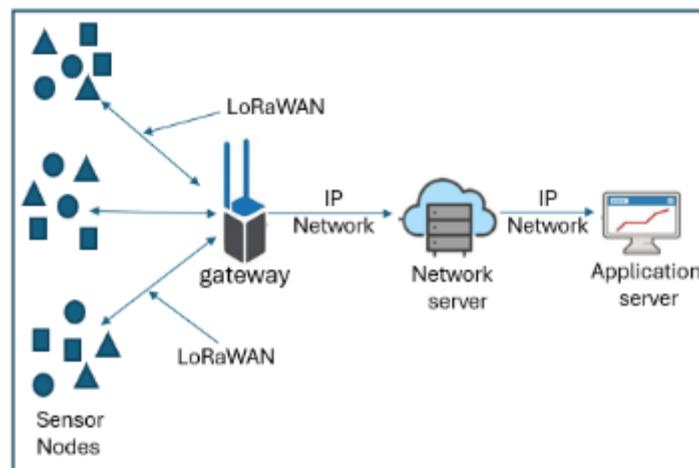


Figure 1 LoRaWAN setup

1.1. Related work

LoRaWAN is a well-researched subject in literature due to its long-range and low power consumption capability particularly for low data rate non-critical applications. Due to several key parameters like SF, TP, ADR among several others, different studies have attempted several approaches in optimization a number of these parameters with a view to improve the overall performance of the network in terms of packet delivery rate, error rate, range, or energy utilization. For example, authors in [13] explored the impact of different transmission parameters on the performance of LoRaWAN networks. The study investigated the impact of the tunable LoRaWAN parameters on the uplink packet delivery rate and the Confirmed Packet Success Rate (CPSR) of the network. The study revealed that confirmed traffic can present a hinderance to the efficiency of LoRaWAN since in this situation, the gateway is expected to send

Acknowledgement (ACK) signals which can increase interference in the network. Consequently, the study noted that by adjusting ACK procedures and prioritizing reception at gateways system performance can be enhanced, especially with mixed traffic. However, the interaction between parameters was considered intricate and thus recommended the use of sophisticated system design tools.

The study carried out in [14] evaluated the performance of LoRaWAN when employed in scenarios such as urban, suburban, and rural environment. The study identified a trade-off between the link robustness and the LoRa node data-rate particularly in the urban scenario. The study recommended high data rate in applications where minimal time on air (ToA) is required. Another study conducted by [15] noted that there are over 6720 different parameter configurations that can be obtained in LoRa. To obtain a suitable combination for specific applications, the authors proposed the probing algorithm. The algorithm aims to optimise energy consumption while optimising the number of probes employed. The study demonstrated that with only 285 probes, a configuration can be obtained that consumes only 44% more energy than the optimal setup. Also, [16] also carried out an evaluation of LoRaWAN performance with optimised configuration. The study noted that the efficiency and reliability of LoRaWAN is largely dependent on the configuration of the spreading factor, coding rate and uplink frequency selection.

Authors in [17] explored the impact of different transmission parameters on the performance of LoRaWAN networks in urban environments. Their findings highlighted the importance of balancing spreading factor, bandwidth, and coding rate to achieve optimal communication range and data rate. Similarly, [18] conducted extensive experiments to evaluate the effects of transmission parameters on network performance and energy consumption. Their study emphasized the role of adaptive data rate (ADR) mechanisms in dynamically adjusting parameters based on network conditions, thereby enhancing scalability and efficiency. A similar study in [19] proposed an algorithm to optimize energy consumption in a LoRaWAN network by optimising the spreading factor and transmission power in LoRaWAN. The author noted the developed algorithm provides improved performance over the native ADR algorithm implemented in native LoRaWAN.

Despite the progress made in optimizing transmission parameters in LoRaWAN, several challenges and limitations persist. One of the primary challenges is the trade-off between communication range and data rate. As spreading factor increases to extend range, data rate decreases, impacting the responsiveness of real-time applications [20]. Furthermore, the selection of transmission parameters is influenced by environmental factors such as terrain, interference, and signal attenuation, adding complexity to parameter optimization [21]. Additionally, regulatory constraints and regional variations in frequency bands and transmission power limits pose challenges for global deployments [16].

A variety of approaches and methodologies have been proposed for optimizing transmission parameters in LoRaWAN deployments. Machine learning techniques have gained traction for predicting optimal parameter configurations based on historical data and network characteristics [8]. Reinforcement learning algorithms have also shown promise in autonomously adapting transmission parameters to changing environmental conditions [22], [23], [24], [25]. [26] employed reinforcement learning to reduce latency for LoRaWAN application in automated metering infrastructure. However, despite all efforts expended in improving the performance of LoRaWAN particularly in ensuring optimality in transmission parameter selection, the lack of sufficient insight into the behaviour individual parameter combination remains a challenge. In this

2. Research Methodology

The objective of this research is to solve the dilemma of optimal transmission parameter selection which is expected to assist network owners with adequate information in network configuring. For this study, the Packet Delivery Rate (PDR), latency and Energy consumption which are the three major indices for LoRaWAN network assessment were considered. These are. The packet delivery rate as shown in Equation (1) is the ratio of packets delivered to the packets transmitted.

$$PDR = \frac{\sum_{n=1}^N \varrho_n}{\sum_n^N T_n} \quad (1)$$

Where ϱ_n is the number of packets successfully delivered and T_n the total number of transmitted packets.

The latency was estimated using Equation (2) to (6). To achieve this, first, the symbol duration was calculated using Equation (2) where:

$$T_{sym} = \frac{2^{SF}}{BW} \quad (2)$$

Where T_{sym} is the symbol duration and BW the bandwidth.

Next the duration of the LoRa preamble and the number of payload symbol was calculated using Equations (3), (4) and (5) respectively.

$$T_{preamble} = (n_{preamble} + 4.25)T_{sym} \quad (3)$$

$$n_{payloadSym} = 8 + \max\left\{\text{ceil}\left(\frac{8PL-4SF+28+16-20H}{4(SF-2DE)}\right)(CR + 4), 0\right\} \quad (4)$$

$$T_{payload} = n_{payloadSym} \times T_{sym} \quad (5)$$

Where $T_{preamble}$ is the duration of the preamble, $n_{preamble}$ the number of preamble symbols, $n_{payloadSym}$ is the number of payload symbol, PL the payload size in bytes, DE is the data rate optimization factor, SF the spreading factor and H which indicates whether preamble header is enabled or not. Finally, the packet duration is estimated using Equation (6).

$$T_{packet} = T_{preamble} + T_{payload} \quad (6)$$

The total energy consumption in the Network was calculated using Equation (7).

$$E = \sum_{i=0}^n (T_{packet(i)} \times Tx_i \times V \times N_s) \quad (7)$$

Where E is the energy consumption, $T_{packet(i)}$ the time of arrival of the packet i , Tx_i is the power consumption of a transmitting node i , V is the operating voltage and N_s is the total packet sent.

The LoRaWAN radio operates according to four critical parameters that dictate its performance regarding latency, range, and resilience to interference, among other factors. Within the LoRaWAN standard, three of these parameters—coding rate, bandwidth, and spreading factor—are contained in the LoRaWAN data rate equation, denoted as Equation (8) with the fourth being the transmission power.

$$R_b = \left(\frac{4}{4+CR}\right) \left(\frac{BW}{2^{SF}}\right) SF \quad (8)$$

Where R_b is the data rate, CR the coding rate, BW the bandwidth and SF the spreading factor.

Given the challenge of deploying numerous nodes, this study utilized the LORAWANSim simulator [27]. This simulator is a modified version of the well-known LoRaSim simulator, enhanced with additional features such as the capability to simulate imperfect Spreading Factor orthogonality, downlink traffic, and various duty cycles.

3. Results and Discussion

In this study, the focus was to investigate how critical LoRaWAN parameters like the coding rate, bandwidth, spreading factor and the transmission power affect the performance of LoRaWAN. The impact of coding rate on the packet delivery rate of LoRaWAN is shown in Figure 2. The result in Figure 2 shows that at short distances typically distances less than 4 km, the use of high coding rate (CR4) is not necessary and can even be counterproductive. Slight coding gain were only noticeable at distances exceeding 8 km. The impact of coding rate on energy consumption is as shown in Figure 3. The result in Figure 3 shows that for the slight coding gain obtained at high data rate particularly for long distances, there is an approximately 19 percent increase in energy consumption. This increase in energy consumption for a slight coding gain provides for a weak argument in favour of high coding rate in LoRaWAN. Figure 4 also shows that employing high coding rate increases latency in LoRaWAN. The result also shows that this is true irrespective of the spreading factor employed. The results presented in Figure 2 to 4 shows that cost of using high coding rate is excessive compared to the benefits it confers on the LoRa network.

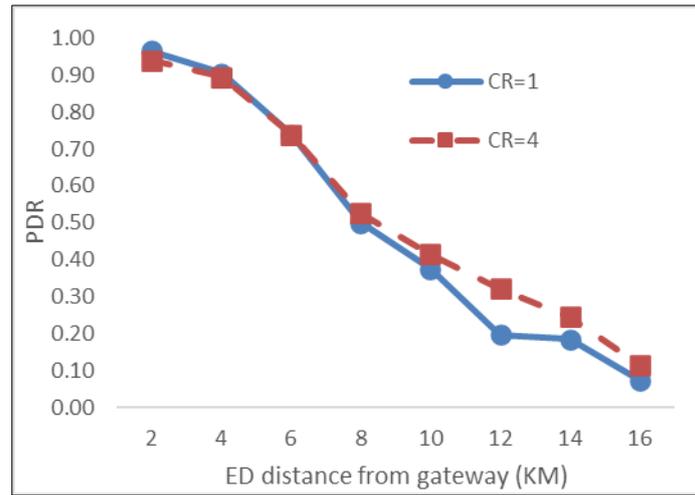


Figure 2 PDR against distance at different coding rate

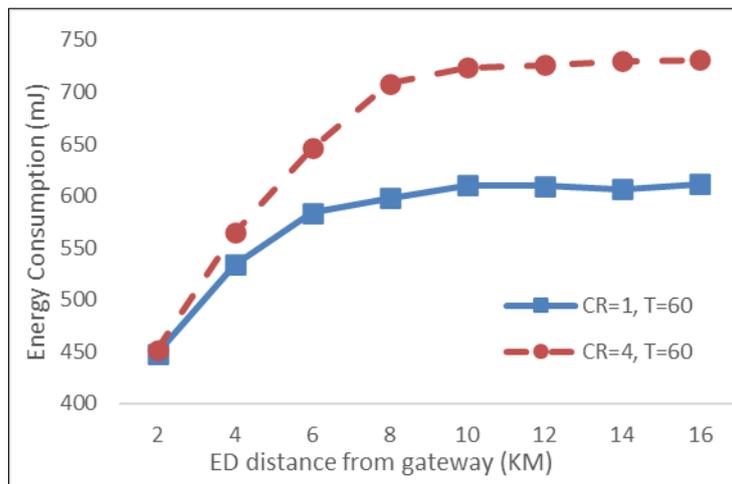


Figure 3 Energy consumption against distance at different coding rate

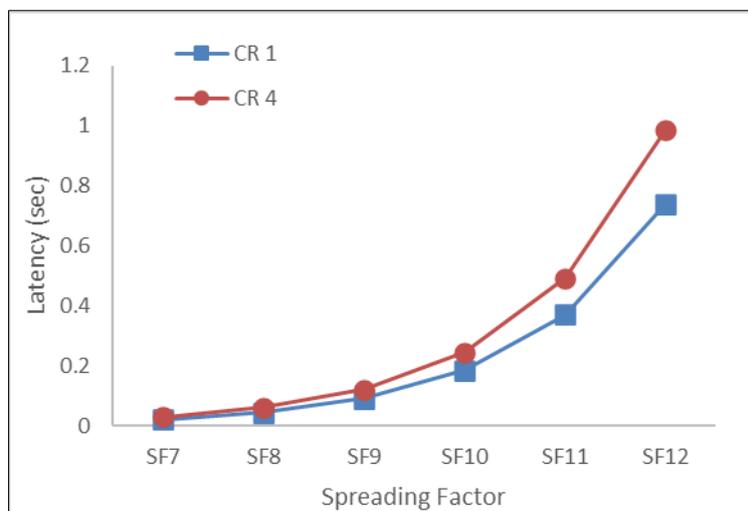


Figure 4 Effect of Coding Rate Effect on Latency

The impact of bandwidth on LoRaWAN is presented in Figure 5 to 7. The result presented in Figure 5 shows the packet delivery rate at distances ranging from 1 km to 16 km using bandwidth of 125 kHz and 250 kHz. At shorter distances, Figure 5 reveals that employing a bandwidth of 250 kHz results in a slightly higher packet delivery rate. Conversely, beyond 8 km, the narrower bandwidth of 125 kHz exhibits a marginal advantage. This outcome aligns with common findings in communication systems, where narrowband transmission typically extends transmission range. Utilizing a narrow bandwidth constitutes a common strategy for achieving long-range communication in LoRaWAN and other Low Power Wide Area Networks. The primary impact of bandwidth in LoRaWAN is more pronounced in energy consumption, as depicted in Figure 6. Utilizing a narrower bandwidth of 125 kHz results in an average energy consumption increase of 10.3% compared to a wider bandwidth of 250 kHz. This discrepancy stems from the findings illustrated in Figure 7, where a 125 kHz bandwidth exhibits double the latency of its 250 kHz counterpart, indicating prolonged transmission durations and subsequently higher energy usage. Additionally, Figure 7 underscores that applications reliant on minimal latency can derive advantages from the reduced latency and transmission times afforded by higher bandwidths.

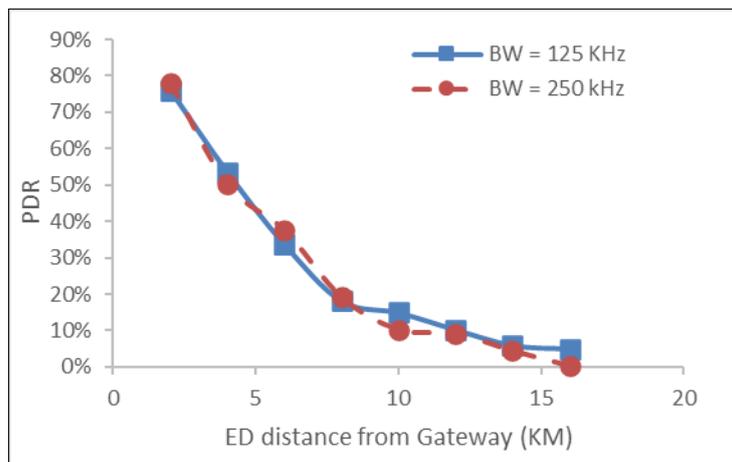


Figure 5 PDR Variation with Distance at different Bandwidth (BW)

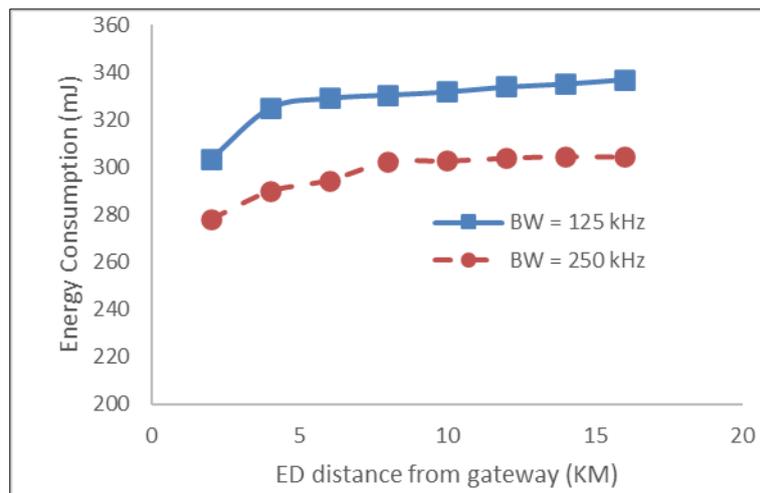


Figure 6 Energy consumption variation with distance at different bandwidth

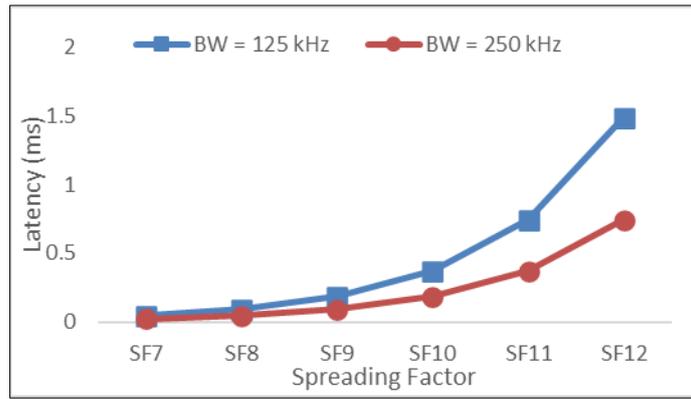


Figure 7 Latency at different SF for 125 kHz and 250 kHz Bandwidth

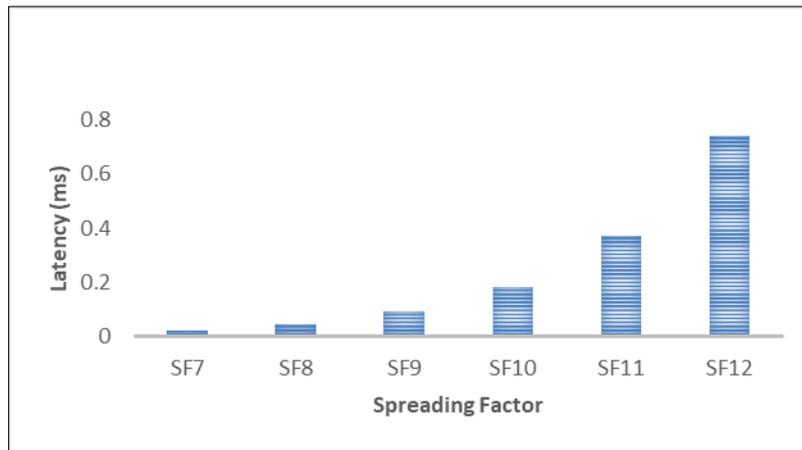


Figure 8 Latency at different spreading factor

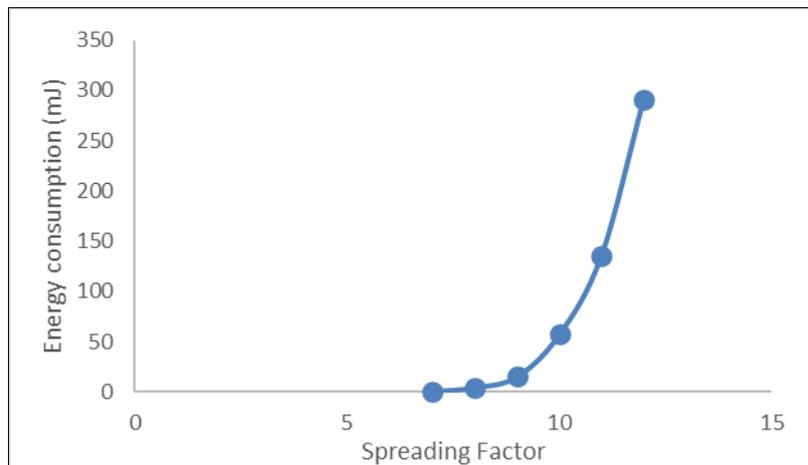


Figure 9 Energy Consumption at different Spreading Factor

The two other critical parameters that affects the performance of LoRaWAN are the Transmission Power (TP) and Spreading Factor (SF). Figure 8 and 9 shows the impact of the spreading factor on Latency and Energy consumption respectively. The higher the spreading factor, the higher the range but at the cost of higher latency as shown in Figure 8 and energy consumption as shown in Figure 9. Consequently, there is always a tradeoff between energy consumption and spreading factor in LoRaWAN. When a high spreading factor is selected (for example spreading factor 12), the transmission range increases but the latency also increases thereby increasing the airtime and invariably energy consumption. In every LoRaWAN application, this balance between range, energy consumption and latency are critical

and must be designed to be application specific. Finally, the energy consumption at different transmission power is as shown in Figure 10. The Figure shows that energy consumption increases slightly as the transmission power is increased from 2 dBm up to the maximum allowable power level of 14 dBm. By comparing Figure 8 and 9 with Figure 10, it is obvious that the spreading factor has a much greater effect on LoRaWAN. Every step increase in the spreading factor leads on the average to a 211.13 percent increase in energy consumption whereas for the transmission power, a step increase in the transmission power only leads to a corresponding 11.32 percent increase in transmission power.

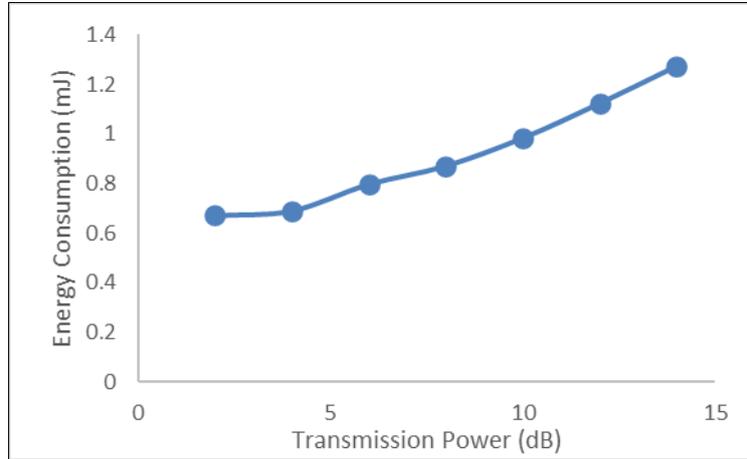


Figure 10 Energy Consumption at Different Transmission Power

4. Conclusion

In this study we showed the dilemma that LoRaWAN operators face in their quest to optimal transmission parameter allocation. The study identified coding rate, bandwidth, spreading factor and transmission power as the critical factors affecting the performance of LoRaWAN in terms of packet delivery rate, energy consumption and latency. Findings from this study showed that using high coding rate and bandwidth can only present marginal improvement in LoRaWAN performance especially at large distances. However, the marginal improvement comes at the cost of increased energy consumption. The study also identified the spreading factor as the most important LoRaWAN parameter since it has a more significant impact on the latency and energy consumption of nodes in LoRaWAN network. Consequently, LoRaWAN operators must employ robust algorithm to optimise the selection of appropriate spreading factor in an application specific manner to ensure maximum performance of LoRa nodes in a LoRaWAN network.

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