A Comprehensive Strategy for Implementing Adaptive Data Rate (ADR) in LoRaWAN Technology: Optimizing IoT Networks

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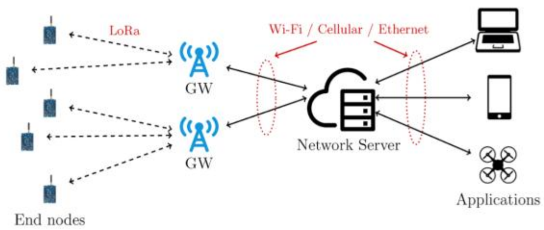
Abstract*: The Internet of Things (IoT) is increasingly essential for creating innovative environments by establishing long-range connectivity among devices. LoRaWAN is a prominent technology choice for these applications due to its energy efficiency and extensive coverage. Central to LoRaWAN's functionality is the Adaptive Data Rate (ADR) mechanism, which optimises network performance by dynamically adjusting each device's data rate and transmission power. This study examines the operational principles, benefits, and implementation challenges of ADR in LoRaWAN networks. The proposed simulation model, featuring configurable parameters such as the spreading distribution factor (SF), the adjustable number of devices, and the SNR threshold, demonstrates enhanced network performance after implementing the ADR algorithm. With an SNR threshold of -15 dB, ADR reduced the average transmission power of 200 devices from 7 dBm to -3 dBm after twenty iterations, underscoring ADR's role in minimizing energy consumption while improving network efficiency.

***Keywords*: LoRaWAN, Adaptive Data Rate, IoT, Network Optimization, Efficiency, Performance**

I. INTRODUCTION

The Internet of Things (IoT) is revolutionizing industries by enabling vast networks of devices to communicate and share data. Among the many technologies powering the IoT, Long Range Wide Area Network (LoRaWAN) stands out for its ability to connect devices over long distances with minimal power consumption [1]. A key feature that makes LoRaWAN particularly effective is its Adaptive Data Rate (ADR) mechanism [2]. ADR is designed to dynamically adjust devices' data rate and transmission power based on network conditions. This capability is essential for optimising performance and energy efficiency in IoT devices, particularly in networks with numerous nodes distributed at varying distances from the gateway. Consequently, ADR is a key feature of the LoRaWAN protocol, enabling dynamic adjustments that improve network performance, extend battery life, and ensure broad coverage. ADR enables LoRaWAN networks to adaptively adjust the data rate and transmission power of end devices, allowing them to function efficiently and reliably across diverse environmental conditions. This adaptability helps optimise network resources, enhancing both the energy efficiency and operational effectiveness of LoRaWAN deployments across various scenarios. While implementing ADR comes with challenges, its benefits make it an essential feature for any LoRaWAN deployment.

LoRaWAN networks typically consist of three main components: End Devices, Gateways, and Network Servers. The end device's primary function is to acquire sensor data, format the messages, and send the LoRaWAN message via radio to the gateway. The Gateways receive data from end devices and forward it to the network server, which corresponds to centralized systems that manage the network, process data, and handle communications with application servers, as represented in Fig. 1 [3].



[Fig.1: LoRa ED Uplink Packet Structure][1]

Since ADR is a built-in protocol, it is not a subject that has been extensively explored in scientific studies. Several works exploit this theme as a survey or a summary of the specificity of ADR [4]. In the paper [5], the authors introduce autonomous time-slotted LoRa, a protocol enabling LoRaWAN nodes to autonomously determine their optimal transmission parameters with minimal downlink transmissions from the Gateway.

This paper presents a simulation model with a configurable number of end devices positioned within a set radius from a Gateway. It enables the analysis of end-device power variation across different configurations, including the threshold Signal-to-Noise Ratio (*SNR*) for each Spreading Factor (*SF*), device transmission power (P_{TX}), and transmission time for each LoRaWAN packet (*ToA*).

This paper is structured as follows: Section II discusses the principles of LoRaWAN ADR. Section III introduces the proposed simulation model for ADR analysis. Section IV presents simulation results, focusing on binary rate, device transmission power, and Time-on-Air (*ToA*). Finally, Section V concludes the work and outlines future research directions.

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II. LORAWAN ADAPTATIVE DATA RATE

LoRa is a modulation technique based on linear frequency variation within a specific bandwidth (*BW*) during symbol duration (T_{symb}), given by (1)

$$T_{symb} = \frac{2^{SF}}{BW}, \quad (1)$$

where *SF* corresponds to the spreading factor whose values can change between 7 and 12 [1][6]. *BW* may assume three typical values: 125 kHz, 250 kHz, and 500 kHz [6].

LoRaWAN data rate can be expressed by equation (2)

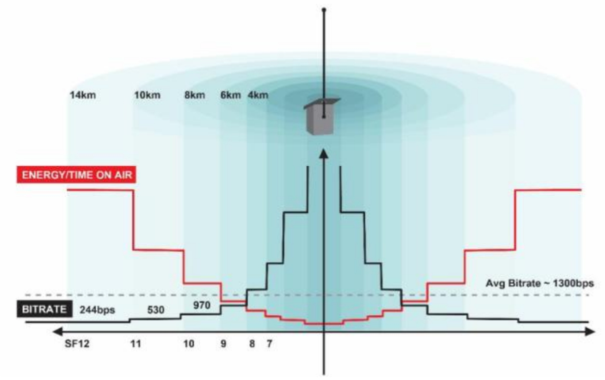
$$R_b = SF \frac{BW}{2^{SF}} CR \quad (2)$$

where *CR* is the code rate corresponding to configurable forward error correction of 4/5 to 4/8 [6].

ADR dynamically adjusts the data rate and transmission power of each end device based on the quality of the radio link, as explained in the next section. By optimizing these parameters, ADR helps achieve the best possible balance between network capacity, battery life, and coverage [2].

A. Mechanisms Underlying ADR Functionality

ADR allows the network server to monitor the radio conditions for each end device. The server uses metrics such as the *SNR*, Received Signal Strength Indicator (*RSSI*), and the number of successfully received packets to determine the optimal data rate and transmission power for each device. Thus, the ADR mechanism can adjust two main parameters: data rate and transmission power, as depicted in Fig. 2 [7].



[Fig.2: LoRaWAN ADR Bit Rate and ToA]

The data rate of LoRaWAN end devices, given by equation (2), can be adjusted by changing the *SF*. As denoted in Fig. 2, a higher spreading factor increases the range and robustness of the signal but reduces the data rate. However, a lower *SF* increases the data rate but reduces the range. ADR adjusts the spreading factor to optimize the balance between these factors.

ADR can also adjust the transmission power of the end device. Reducing the transmission power can extend battery lifetime, while increasing it can improve signal strength and reliability, especially in challenging radio environments.

B. LoraWan Link Budget

The link budget in LoRaWAN is essential for determining the effective range and reliability of communication between devices and gateways. It considers the total signal loss that can occur during transmission while still allowing the signal to be received accurately. This value is calculated by combining the transmitter power, antenna gains, and receiver sensitivity, often reaching values above 150 dB, which supports long-range communication. A higher link budget generally improves coverage and is a significant reason LoRaWAN is suitable for low-power wide-area networks (LPWANs) in IoT applications across varying landscapes.

Equation (3) describes the free space path loss, which is determined by the distance (in kilometres) and frequency (in GHz) [8].

$$FSPL = 20\log_{10}(d_{[km]}) + 20\log_{10}(f_{[GHz]}) + 20\log_{10}\left(\frac{4\pi}{3\times10^8}\right) \quad (3)$$

The end device RSSI is given by (4), where G_{Ant} corresponds to the LoRa antenna gain [7]. For the sake of simplicity, it is assumed that both antennas are isotropic with a gain of 0dBi. For this work, the *NF* is considered 6dB [8].

$$RSSI_{dBm} = P_{TX_{dBm}} + G_{Ant} - FSPL_{dB} + NF_{dB} \quad (4)$$

If a device has a high link budget (e.g., high *RSSI* value), ADR will reduce the power to conserve battery life. Lowering power for closer devices also reduces network interference, allowing other devices to communicate more effectively.

C. ADR Benefits and Challenges

The primary benefits of the ADR mechanism in LoRaWAN include extending battery lifetime, enhancing network capacity, optimising network coverage, and improving spectrum allocation efficiency.

Increasing battery lifetime is obtained from the data rate adjustment [8]. This is achieved by adjustment of the SF values in the function of transmission power of the device based on its distance from the gateway and SNR threshold [9].

The network capacity is also obtained by dynamically adjusting the data rate for each end device. Therefore, end devices closer to a gateway can transmit at higher data rates, releasing network resources and allowing more devices to connect and transmit data. This is particularly important in dense IoT deployments, where network congestion can be a significant challenge, such as in urban scenarios. Finally, spectrum allocation efficiency is achieved by ADR since it manages spectrum usage efficiently by adjusting the data rate and transmission power to match the network conditions. This minimizes interference and ensures that the spectrum is used effectively, allowing more devices to coexist in the same frequency band [6].

The primary challenges of using ADR in LoRaWAN are related to network complexity, variable radio environment, and end-device constraints.

ADR adds complexity to the network since the network server must

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continuously monitor the radio conditions and adjust The data rate and transmission power for each device. This requires sophisticated algorithms and real-time processing capabilities. Since the radio conditions can vary significantly due to environmental factors such as weather, physical obstructions, and interference from other devices, ADR must account for these variations and adjust the parameters accordingly. However, rapidly changing conditions can make it challenging to maintain optimal settings, resulting in potential trade-offs among data rate, coverage, and reliability. Another challenge in using ADR in the LoRaWAN network is centred on end devices, as not all LoRaWAN devices support the full range of ADR capabilities. Some low-cost devices may have limited processing power or battery capacity, making it challenging to implement ADR effectively. Finally, the latency and response time must be considered, since ADR adjustments are not instantaneous and may introduce some latency in response to changing network conditions. In applications where low latency is critical, such as real-time monitoring or control systems, this delay could be a concern.

III. SIMULATION-BASED EVALUATION OF ADAPTIVE DATA RATE IN LORAWAN

In this section, the simulation model for LoRAWAN ADR evaluation is presented. The focus is on the description of the ADR algorithm itself, the initial variables, as well as a brief analysis of the results obtained.

A. ADR Simulation Parameters

The proposed simulation model, developed in MATLAB, enables the simulation of LoRaWAN ADR, enabling a robust framework for simulating and analyzing radio parameters, allowing the detailed modelling of network conditions, including varying the amount of end devices ' transmission power, and spreading factor [9]. These simulation parameters are presented in Table I. The end device position, SF, and initial power are randomly distributed according to a uniform distribution.

Table 1: MATLAB Simulation Parameters

Simulation Parameters	Initial Value
numDevices	200
maxSF	12
minSF	7
maxPower	15 dBm
minPower	-4 dBm
initialPower	15 dBm
thresholdSNR	-20 dB

B. LoRA Radio Parameters

The values for the LoRa radio parameters used in this study, including the maximum and minimum Spreading Factor (*SF*), are provided in Table II. The binary rate is obtained using equation (2) for a bandwidth of 125 kHz.

The *ToA* corresponds to the time that a LoRaWAN packet is transmitted and is obtained by an expression presented in [6]. Thus, for a payload of 32 bytes, a CR of 4/5, and a CRC for error control, the ToA for SFs 7 and 12 are presented in Table II.

Table 2: Binary Rate and ToA for SF=7 and 12

SF	Rb [kbps]	ToA [s]
7	5.468	0.072
12	0.292	1.657

C. ADR Algorithm

This section presents the ADR algorithm implemented in MATLAB. In the Global Variables phase, all simulation variables are initialized and defined, as shown in Table I. These include environmental parameters such as noise floor, gateway position, and the distribution of end devices. In the Device Initialisation phase, each deployed end device is assigned initial values, such as its geographic position relative to the gateway, spreading factor, and initial transmission power (P_{TX}). The ADR Loop then iteratively adjusts the LoRa radio parameters (SNR, RSSI, and SF) for each device. After a specified number of iterations, the loop finalizes with the optimized P_{TX} and SF values for each end device. Finally, the Evaluation after the ADR phase enables performance comparison of the LoRa network before and after the ADR algorithm is applied, focusing on metrics such as bit rate, power consumption, and network capacity.

```
Global Variables
   Set the simulation parameters (Table I)
   Define the environmental parameters:
   Noise floor and gateway Position
Device Initialization
   Random initialization of:
   Distance to Gateway < 20km
   SF for each device -> [7 to 12]
   Transmission power for each device -> [-4 to 14]
Adaptive Data Rate (ADR) Process
 |for each iteration:
 | for each device:
 | | Obtain the distance between the ED and GW
 | |   Compute path loss
 | |   Calculate RSSI and SNR
 | |   Adjust the spreading factor (SF):
 | |     if SNR<thresholdSNR && deviceSF<maxSF
 | | Increase the SF
 | |     else if SNR>thresholdSNR && deviceSF > minSF
 | | Decrease the SF
 | |       end
 | |   Adjust the transmission power:
 | |     if SNR < thresholdSNR && devicePower < maxPower
 | | Increase the transmission power
 | |     else if SNR > thresholdSNR && devicePower>minPower
 | | Decrease the transmission power
 | |       end
   end
 end
LoRaWAN Parameters - Evaluation after ADR
   Bit rate evaluation
   Time Over the Air
   Transmitted End Device Power
```

D. Simulation Results

Based on the simulation parameters outlined in Table I and the ADR algorithm described in Section III C, the simulation results are presented, showing the impact on SNR, transmission power [7], and spreading factor for 200 devices after 20 iterations [9].

Fig. 3 illustrates the distribution of end devices around the LoRaWAN gateway within a 20 km

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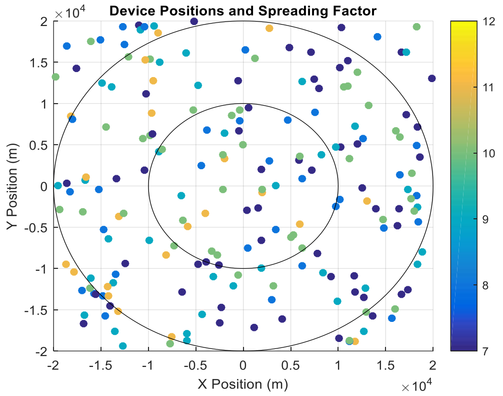
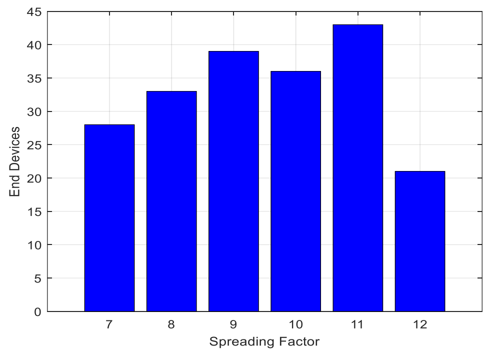
radius. Each point represents an end device, with the colour indicating its initial spreading factor value before the application of the ADR algorithm. As observed, SF values range from 7 to 12, independent of each device's location, following a uniform distribution, as depicted in Figure 5.

The figures shown represent the starting conditions for all LoRaWAN end devices, which correspond to the Global Variables and Device Initialisation stages of the algorithm described in Section III-B.

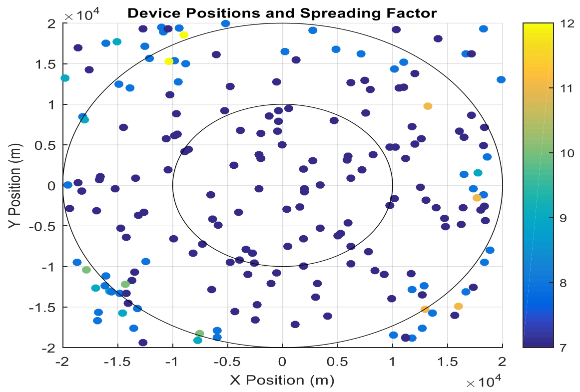


[Fig.3: Initial Distribution of 200 Devices with Initial SF]

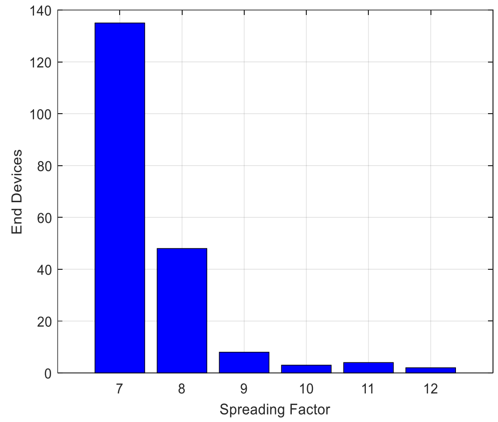


[Fig.4: Histogram of end Devices SF in the Initial Phase]

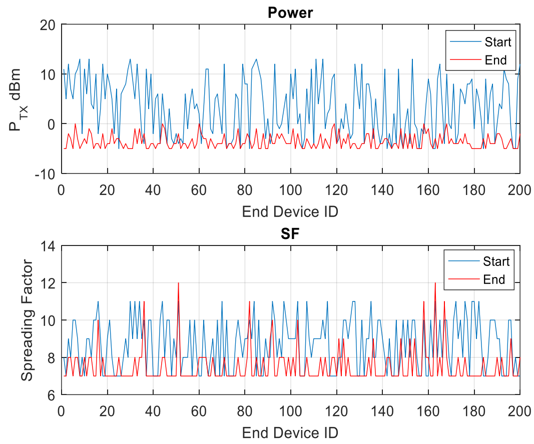
Fig. 5 represents the distribution of all end devices and their assigned spreading factors after applying the ADR algorithm proposed in this work. As shown, compared to Fig. 4, end devices deployed within a 10 km radius of the LoRaWAN gateway are primarily assigned an SF of 7, with SF values increasing as the distance from the gateway increases. However, the majority of the 200 end devices maintain an SF of 7, as illustrated in Fig. 6.



[Fig.5: LoRaWAN ADR Bit Rate and ToA]



[Fig.6: LoRaWAN ADR Bit Rate and ToA]



[Fig.7: Evolution of ADR Parameters for 200 end Devices]

The spreading factor and transmitting power for all end devices used in ADR simulation are presented in Fig. 7. As denoted, the initial transmitting power for each end device, represented by the blue line, is approximately 15 dBm. After applying the proposed ADR algorithm, all end devices decrease their transmission to almost -4 dBm after 20 iterations. The initial spreading factor is uniformly distributed among all end devices, as illustrated in Fig. 4. However, after the ADR algorithm, most end devices reduce their SF to 7, as indicated by the red line in Fig. 7, whose respective histogram is depicted in Fig. 6.

IV. DISCUSSION RESULTS

In this section, the results of the proposed ADR simulation model are discussed. For this purpose, several simulations are performed where the threshold *SNR* used in the ADR algorithm is modified. With this method, it is possible to infer several LoRaWAN parameters during the adaptive mode. For all performed simulations, 200 end devices were used, and the adaptive process had 20 iterations, as summarised in Table I. The LoRa radio parameters used for these simulations are described in Section III B.

The average binary rate evolution for all 200 end devices along the ADR process is presented in Fig. 8. As denoted, the difference between the initial and final average binary rate increases when the Delta

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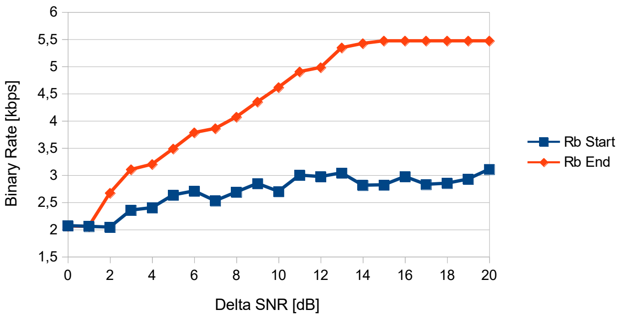
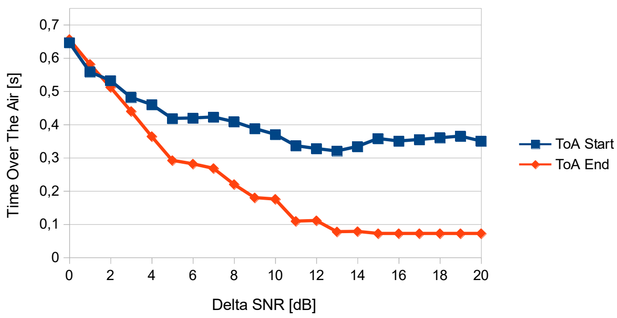
SNR increases, because of the ADR algorithm. For Delta *SNR* greater than 15dB, the average binary rate converges to 5.4 kbps, due to LoRa radio parameters described in section III B.



[Fig.8: Binary Rate Evolution with ADR]

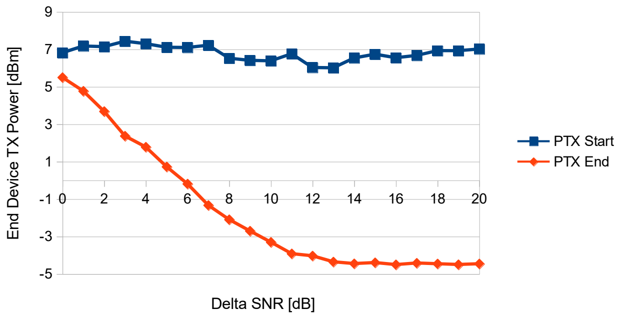
The evolution of *ToA* before and after the ADR is presented in Fig. 9. As depicted, for Delta *SNR* greater than 15 dB, the transmission packet time after ADR converges to 71ms, corresponding to a maximum data rate of 5.4 kbps, as indicated in the values listed in Table II.



[Fig.9: Time over The Air Evolution with ADR]

In Fig. 10, the average transmission power of the 200 devices is presented before and after applying the ADR algorithm. As can be seen, the initial value remains constant, although below the maximum value of 15 dBm. This occurs due to the initial uniform distribution of power across all devices at the start of the simulation.

For Delta *SNR* values above 15 dB, the final average power value converges to -4 dBm, which corresponds to the minimum value indicated in the simulation. It was concluded that, under these conditions, all devices are set to SF=7 when Delta *SNR* values exceed 15 dB.



[Fig.10: End Device Transmitted Power with ADR]

V. CONCLUSIONS AND FUTURE WORK

This work provides an analysis of LoRaWAN's Adaptive Data Rate to optimize network performance. It examines how binary rate, spreading factor, Time-on-Air, and transmission power of end devices vary. The findings show significant variation in these parameters relative to the SNR threshold within the ADR algorithm, highlighting how adjustments impact network efficiency and device operation.

The results of this study demonstrate that the ADR algorithm in LoRaWAN networks effectively reduces device energy consumption by lowering the spreading factor (SF) after 20 iterations. This reduction in *SF* decreases the Time-on-Air (*ToA*), which improves both consumption and network management. With a 1% duty cycle, a lower *ToA* can reduce the likelihood of frame collisions. This work used the full transmission power range (15 dBm to -4 dBm), and after 20 iterations at an *SNR* threshold of -15 dB, most devices converged to the lowest *SF*. Future work includes adapting the algorithm to incorporate more gateways, thereby enhancing network capacity and energy efficiency. A suggested direction for future work is to utilise propagation models more suitable for urban environments. This would enable a more detailed study of the ADR algorithm in areas with higher sensor density and, consequently, a greater number of LoRaWAN devices transmitting data.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed solely.

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