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Original Article

Enhanced Resource Allocation Mechanism for LoRaWAN in IoT Applications

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Abstract *- Long Range Wide Area Networks have recently gained major relevance in Internet of Things applications because of their broad coverage and minimal power consumption. It employs an energy-effective Adaptive Data Rate to organize assists of resources like Transmit Power and Spreading Factor to numerous End Devices. We present a Network server-controlled adaptive data rate system, specifically the Savitzky-Golay filter, to mitigate rapid variations in signal-noise ratio. According to the simulation outcomes, the suggested approach improves the average packet delivery ratio by 129.8 % and 85.2 % for single and two gateways in an urban scenario and 46.1% and 14.6% for the sub-urban scenario. The total network energy expenditure was reduced by 3% for a single gateway, 15.89 % for two gateways in the urban scenario and 4.73% and 11.32 for single and two gateways in the sub-urban scenario.*

Keywords *- Adaptive data rate, LoRaWAN, Resource allocation, Spreading Factor, Transmission power.*

1. Introduction

The expansion of the Internet of Things (IoT) contributed to the proliferation of many connected devices, including mobile devices, intelligent home appliances, and industry sensors. The swift expansion of IoT has significantly complicated network management and resource allocation. The exponential increase of connected end nodes presents a substantial issue for network operators, who must guarantee uninterrupted access while preserving optimal network performance. Consequently, network operators are implementing sophisticated technology to adjust to evolving conditions and satisfy the varied requirements of distinct applications while enhancing resource efficiency [1]. Low Power Wide Area Network (LPWAN) is a wireless network regarded as an up-and-coming developing technology for (IoT) applications. The long-range Wide Area Network (LoRaWAN) establishes a desirable communication infrastructure for IoT devices within this network category. The major benefits are long-range wireless capability with low power consumption and cost-effective deployment, facilitating reliable and efficient communication via various IoT applications [2, 3]. Many IoT devices and applications may live in harmony with one another because of LoRaWAN's layout. Nonetheless, interference and performance deterioration arise as numerous end nodes transmit packets via the same channel through the Gateway. The main reason for this problem is that the LoRaWAN gateway cannot correctly process concurrently received pockets from a group of IoT end nodes, maintaining the same carrier frequency and using the same spreading factor.

LoRaWAN resolves this issue by establishing a series of radio factors that are dynamically modified through a resource allocation system, including Bandwidth (BW), Carrier Frequency (CF), Coding Rate (CR), Spreading Factor (SF), and Transmission Power (TP). The network server could provide the downlink's specified radio factors through resource allocation. Techniques for allocating resources modify radio configurations in real time in response to changes in signal-to-noise ratio, data rate, number of GWs and signal strength. This configuration adjusts channel usage, consumption of energy, radio disruption transmission rate, and coverage by radio as required [4, 5]. LoRaWAN utilizes the Adaptive Data Rate (ADR) to facilitate the assignment of SFs and TP. The ADR protocol regulates transmission characteristics, including DR, range of communication, reliability, and energy expenditure, by dynamically modifying the SF and TP, considering the link budget for each connected node in the LoRaWAN network [6, 7]. The Chirp Spread Spectrum (CSS) modulation method possesses pseudo-orthogonal characteristics, enabling various spreading factor signals to accommodate many end devices inside a single channel. ADR increases end-device transmission efficiency in LoRaWAN. However, as the network grows, packet collisions occur, increasing interference, decreasing range, and lowering data rates. This results in heightened interference, reduced range, and impaired data rates [8]. It is important to design an allocation mechanism of radio-related parameters to mitigate packet loss and interference and deliver an efficient IoT network based on LoRa wireless communication technology. The two primary considerations in the design of LoRaWAN networks are energy expenditure and delivery ratio. Consequently, it is advantageous to identify supplementary strategies that address this problem. Current research mainly focuses on energy consumption and link-level throughput, frequently neglecting packet success probability in LoRaWAN networks. This paper presents Savitzky-Golay filter-dependent ADR (SG-ADR). This adaptive approach dynamically allocates TP and SF by minimizing packet collisions to improve the average Packet Delivery Ratio (PDR) and optimize the overall energy expenditure of the LoRaWAN network. The following are the primary highlights of this work's contributions:

- The SG-ADR mechanism was presented to improve the signal-to-noise ratio (SNR) arrived at the network server by convolving the SNR with the convolution coefficients of the Savitzky-Golay filter. SG-ADR can efficiently identify SF and TP parameters to distribute appropriate resources for the LoRaWAN network.
- Reduce the total Network Energy Consumption (NEC) and improve the average Packet Delivery Ratio (PDR) for single and two getaway deployment scenarios compared to the typical ADR and two ADR algorithms.
- Improving the distribution of different SFs across end device nodes in a balanced way to get a trade-off between enlarging the range of communication in the LoRaWAN network and minimizing the time on air of a communication network compared with the typical and two ADR algorithms.

The article's remaining part is structured as follows: The technological context is the subject of section two, while the associated research is laid out in section three. The proposed scheme is demonstrated in Section four, while the system model is stated in Section five. The findings of this work are depicted and discussed in section six. Finally, section seven discusses the conclusion of this work.

2. Technological Context

Figure 1 illustrates the star-of-star layout of the LoRaWAN's three primary components: End Devices (ED), Gateways (GW), and the centralized Network Server (NS). EDs are end nodes, like sensors or actuators, that utilize the LoRa PHY layer technology for data transmission and reception to engage with the network. The Media Access Control (MAC) layer is where LoRaWAN falls. Through the GW, the NS sends packets to the EDs (downlink packets) and receives packets from EDs (uplink packets). Direct connectivity between end devices is non-existent. The GW mediates communication between the NS and the EDs via an IP-based backhaul link. The network server controls access permissions and makes network administration easier. The NS regulates the distribution of network transmission parameters, controls transmission scheduling, and supervises ED authentication. For user access, the NS then communicates with several application servers. To accommodate a variety of application protocols inside the IoT, there are three categories of LoRaWAN device classes: A, B, and C. Because the downlink latency differs between device classes, LoRaWAN forces a compromise between latency and power consumption. In LoRaWAN, a transmitted packet may be incorrectly received for two reasons: when the SNR drops below a certain threshold and when a collision occurs, but the SNR is insufficient. As seen in Table 1, various SFs have varied sensitivity levels and SNR thresholds [5].

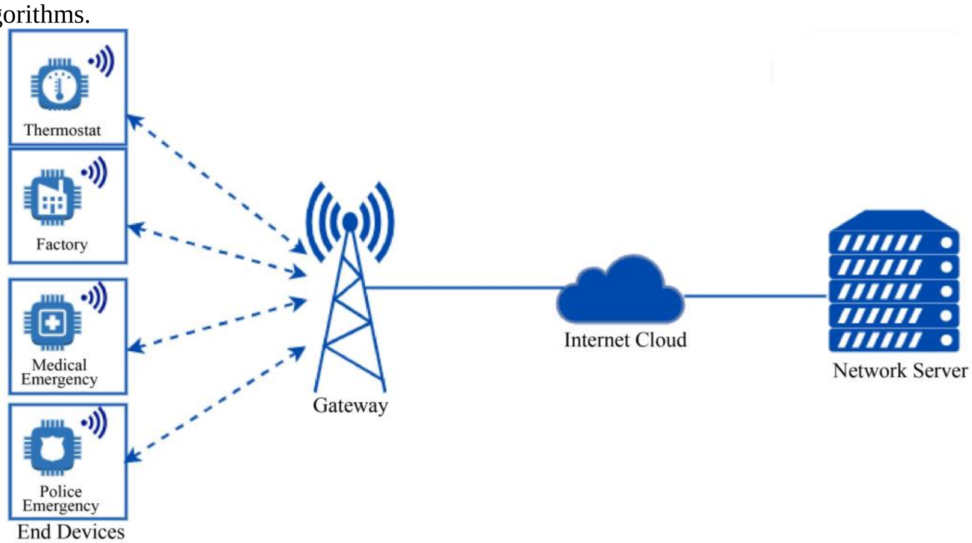


Fig. 1 LoRaWAN architecture

2.1. Modulation in LoRaWAN

The essential transmission parameters used in LoRaWAN are TP, BW, CR, and SF. BW denotes the frequency range, CR facilitates error correction, and SF signifies data that spreads throughout time. These variables affect the radio range, airtime, noise resiliency, data rate, and reception decoding [6]. LoRa modulation utilizes SFs from 7 to 12 to balance communication range and data throughput. LoRa symbols comprise 2^{SF} chirps, distributed over the whole frequency band. LoRaWAN operates with bandwidths of 125 kHz, 250 kHz, or 500 kHz, depending on regional specifications [6]. LoRa utilizes a CSS technology that generates $M = 2^{SF}$ possible signal waveforms within a set of bandwidths with the symbol duration defined as $Ts = M/BW$ [6].

Table 1. Required SNR and threshold sensitivity associated with each spreading factor

SF	SNR [dB]	Sensitivity [dBm]
7	-7.5	-123
8	-10	-126
9	-12.5	-129
10	-15	-132
11	-17.5	-134.5
12	-20	-137

The LoRa utilizes a coding rate that enhances resilience to interference and protects against decoding errors. The CR values are limited to 4/5, 4/6, 4/7, or 4/8, according to the LoRa specification. A high CR value signifies increased error-correcting bits, enhancing the protection of the sent data. The TP is a variable that can be modified to improve the efficacy of communication. LoRa modulation bit rate, Rb, is delineated as presented in (1) [6].

$$R_b = BW * \frac{SF}{2^{SF}} * CR \tag{1}$$

2.2. Path Loss Model in LoRaWAN

The transmission attributes of the LoRa, including SF, CF, BW, CR, and TP, determine the transmission distance range and the probability of collisions. The LoRa transmission is considered excellent when the power of the received signal is higher than the sensitivity threshold. Losses attributable to signal shadowing, attenuation, and transmission strength determine the received power. This is based on the long-distance path loss model with shadowing [9], and the formula for path loss with end device and gateway distance is as follows [9]:

$$PL(d) = \overline{PL}(d_0) + 10n\,log\left(\frac{d}{d_0}\right) + X_\sigma \tag{2}$$

Where,

- $\overline{PL}(d_0)$; $mean\ path\ loss\ for\ distance\ d_0.$
- n; $path\ loss\ exponent.$
- $\boldsymbol{X_\sigma}$; $zero - mean\ Gaussian\ distributed\ random\ variable\ with\ standard\ deviation\ \sigma.$

2.3. Adaptive Data Rate in LoRaWAN

The Adaptive Data Rate is an essential part of the LoRaWAN standard that serves many fundamental objectives. The ADR seeks to enhance the battery longevity of EDs, optimize service quality standards, and improve data throughput while increasing the network's overall capacity. Adjusting the TP and SF on the fly is crucial to achieving these objectives. The research in [10] offers a detailed investigation of the LoRaWAN ADR applied on the NS and ED sides. The NS's responsibilities include keeping the transmission parameters and sending the ED the appropriate ADR commands. The ED regularly checks the network server's SNR connection margin input to ensure it has successfully received packets. The main goal of the ED is to increase the SF, which decreases the DR when uplink signals do not reach the Gateway. In addition, the ED will proactively raise the SF for the next uplink packet if the number of unconfirmed downlink packets exceeds a certain level. This improves communication with the GW and increases the range of transmissions.

3. Related Work

Slabicki et al. [11] analysed the conventional LoRaWAN ADR. The network's parameter distribution and collision probability were considered during the ADR extension. This enhances network performance in congested IoT environments. The simulation outcomes indicate a wireless channel with significant fluctuations profoundly impacts the ADR. The suggested method improves communication reliability and energy consumption in noisy channels.

Lim and Han [12] established an optimization problem to maximize the Packet Delivery Ratio (PDR) via the RA strategy. This is accomplished by improving the interconnected IoT devices by appropriately assigning the SF to each network traffic according to the distance of the IoT from the Gateway. Researchers developed a paradigm for optimization to improve the average probability of successful delivery of packets. They suggested a suboptimal SF allocation technique for every type of traffic. The results of the simulation demonstrate that the proposed strategy attained the highest average PDR and assured excellent connection.

Cuomo et al. [13] presented resource allocation methods (Explora-SF and Explora-AT) to enhance LoRaWAN performance. The models utilize a Received Signal Strength Indicator (RSSI) to determine the SF values for EDs, as an increased RSSI results in a decreased SF for a specific IoT device.

Nonetheless, both proposed systems impose varying restrictions on the number of EDs within each SF. Explora-SF regulates the number of EDs within each SF and mitigates the risk of packet collisions by limiting the number of devices in a specific SF. Conversely, Explora-AT allocates devices in each SF according to the airtime.

Babaki et al. [14] developed a unique ADR algorithm for LoRa networks' core platform. The suggested approach used an ordered weighted average OWA operator to achieve reliable operation across various channel conditions by dynamically customizing transmission parameters. The results demonstrate that the suggested method outperforms the original ADR and other algorithms regarding packet delivery ratio while consuming the least energy.

Kerkouche et al. [15] developed an RA mechanism to balance EC and Packet Loss Rate (PLR), wherein the IoT end devices employed a lightweight learning scheme to identify the transmission parameters. Parameter selection aims to enhance reliability and EC by decreasing power after achieving the maximum data rate. The findings indicate that the suggested algorithm facilitates a superior compromise between EC and PLR compared to ADR. As outlined in [16], an alternative to improve PDR employs two strategies: initially, the authors categorize EDs according to their Received Signal Strength Indicator (RSSI) and allocate a distinct channel to each category. Second, using the RSSI, the writers distribute SFs to EDs in each category. The suggested methods have decreased collisions by assigning each group the most suitable SF and channel. Resource Allocation with the Collision Avoidance method is detailed in [17], wherein the suggested approach improves network bandwidth and minimizes collision occurrences. CARA assigns the wireless channel's available bandwidth into resource components as a function of the channel and the Spreading Factor (SF). Although this method improves throughput, it increases energy consumption and transmission time.

Arshad Farhad et al. [18] suggest two ADRs that NS can manage: one that uses a Gaussian filter (G-ADR) and another that uses an exponential moving average (EMA-ADR). Both techniques attempt to provide the appropriated SF and TP to static and mobile EDs by reducing the convergence duration in the confirmed mode of LoRaWAN. Compared to typical ADR, the suggested techniques improve EDs' packet success ratio while decreasing convergence time and energy expenditure.

Dakdouk H et al. [19] utilize multi-player, multi-armed bandits to deal with the distribution of resources in LoRa networks, emphasising transmission parameter optimization to lessen interference, decrease packet loss, and reduce energy consumption.

4. System Model

One or more LoRa end devices and gateways connected to a single network server compose the intended network for configuration. The ED and GW distances are assigned while all nodes stay stable. Each node can utilize an SF from a range of 7 to 12 and a TP from a range of 2 to 14 dBm. Nodes may be associated with one or many gateways; all nodes may access at least one Gateway with the highest throughput. The path loss (in dB) between the ED and GW is depicted using the logarithmic distance expressed in Equation (2). The size of the deployment region varies between the two scenarios because the path loss values employed are different in each. Each scenario consists of two cases of getaways: a single gateway and two gateways, respectively. The configuration comprises a central gateway linked to a singular network server within the deployment area. Alternatively, a scenario involves two gateways: GW1 positioned at coordinates ($x = x_{max}/4$, $y = y_{max}/2$) and GW2 at ($x = 3x_{max}/4$, $y = y_{max}/2$), enabling uniform distribution throughout the deployment area. The path loss parameters employed differ among the designed scenarios, leading to variations in the dimensions of the deployment area. Table 2 outlines the standard path loss parameters employed in each scenario.

Table 2. Propagation model parameters

Scenario	d_0 [m]	$\overline{PL}(d_0)$ [dB]	n	σ [dB]
Urban	40	127.41	2.08	3.57
Sub-Urban	1000	128.95	2.32	7.08

The parameters provided were derived from the measurements performed in references [20] and [21]. The parameters in [20] are for an urban region partially indoor environment, while the measurements in [21] pertain to a suburban environment with a restricted presence of tall buildings. Table 3 presents the simulation environments.

Table 3. Simulation parameters

Parameter	Description
Simulation Program	OMNeT++ 6.0.2 IDE
Simulation Time	4 Days
Simulation Runs	30
Modulation	LoRa Modulation based on CSS.
No. of ED	100 to 700 with step 100
No. of GW	1 and 2
No. of NS	1
CF	868MHz
BW	125 kHz
CR	4/5
SF	7 to 12 (initial 12)
TP	2 dBm to 14 dBm (initial 14 dBm)
Deployment Area	Urban (480m * 480m)
	Sub-Urban(9.8km * 9.8km)

5. Proposed Savitzky-Golay Filter Based ADR (SG-ADR)

An adaptive data rate approach called Savitzky–Golay filter-based ADR (SG-ADR) was presented in this section. The goal of the suggested algorithm is to reduce energy consumption without sacrificing the average packet delivery ratio through the reduction of interference. This algorithm accomplishes this through the dynamic control of SFs and TP allocation.

5.1. Chosen of Savitzky-Golay Filter to Smooth SNR

The selection of the Savitzky–Golay filter to smooth the SNR at the NS side is based on Figure 2. Figure 2 shows that the Savitzky–Golay filter is a good choice to smooth the SNR at the receiver side by removing the noise to allocate SF and TP better. The SNR value in Figure 2 was obtained from a time experiment using the deployment of two EDS, as shown in Figure 3.

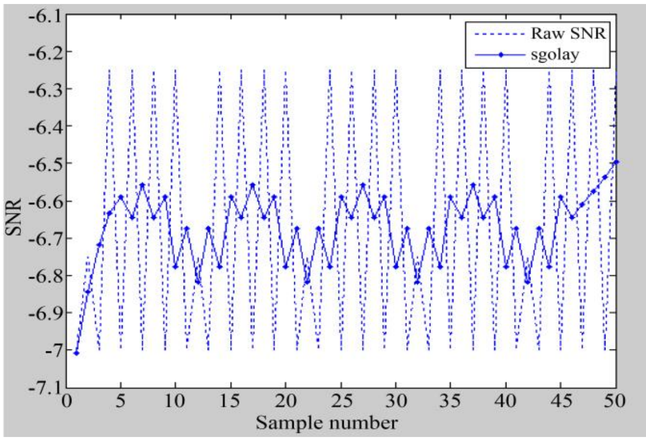


Fig. 2 Smoothed SNR using Savitzky–Golay filter

5.2. The Proposed SG-ADR

This part delineates the suggested SG-ADR algorithm operating on the NS side, as emphasized in algorithm 1. The remainder of this section discusses these algorithms in further detail. It is important to remember that the ADR mechanism at ED has not changed. The following is a list of the procedures that are involved in the SG-ADR scheme that has been proposed:

- The suggested approach is executed when NS receives M packets to enhance SNR from a relevant ED. The proposed ADR starts monitoring the SNR of the incoming packets.
- The SG-ADR mechanism is initialized by selecting the convolution coefficients using the savisky-golay filter as in [22]. The choice of the degree of polynomial and window size depends on the savisky-golay filter criteria to improve SNR. A trade-off between distortion and noise reduction will determine the best polynomial order and number of convolution coefficients, and the SNR will be enhanced when the polynomial degree decreases and the window size of the filter [23]. So, the best choice of the convolution coefficients is a quadratic degree of polynomial and window size 7 for a better smoothing process of SNR to obtain the kernel of the convolution process as:

$$h(n) = \frac{1}{21}(-2,3,6,7,6,3,-2) \tag{3}$$

- Compute the convolution between the set of incoming SNR packets (20 packets) with the kernel obtained from (3):

$$New\ row\ of\ SNR(y) = SNR(m) * h(n) \tag{4}$$

- To find smoothed SNR, the SG-ADR algorithm chose the minimum SNR value to enhance the TP and SF according to the worst signal strength from the new row of SNR values as below:

$$SNR_s = Min\left(SNR_y\right) \tag{5}$$

Where n is the nth value among new row of SNR

- The SG-ADR computes the SNR required (SNRreq, demodulation floor according to present DR, as shown in Table 1 and calculates the SNRmargin and Nstep using (6) and (7), respectively.

$$SNR_{margin} = SNR_s - SNR_{req} - adr\ device_{margin} \tag{6}$$

$$N_{step} = int\left(SNR_{margin}/3\right) \tag{7}$$

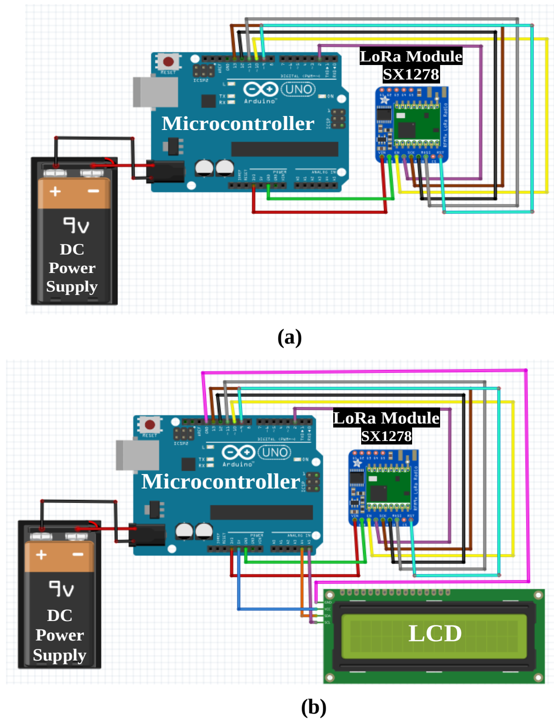


Fig. 3 Deployment of two EDs with SF10, (a)Transmitter side, and (b) Receiver side.

In order to decrease the probability of packet loss and interference at the Gateway under the given sensitivity, the SG-ADR finds an acceptable SF based on the gateway sensitivity values (Sg). The suggested approach gets the appropriate TP for the applicable ED following a predetermined procedure. The SG-ADR already uses the optimal TP value if the steps are zero. Increased energy expenditure and poor airtime, which negatively impact the PDR, are consequences of current TP and SF not being optimized when the number of steps surpasses zero. In order to maximize efficiency, power consumption reduction, and throughput, the suggested ADR lowers the TP by three and the SF by one until it reaches the minimal limit. However, when steps are negative, the suggested ADR raises the TP by a factor of three until it reaches its maximum. The appropriate ED receives the SF and TP parameters after they have been identified through a MAC command called LinkADRReq.

Algorithm 1: Proposed (SG-ADR) Scheme.

Input: $TP = 2 \sim 14, SF = 7 \sim 12, SNR\ of\ 20\ Packet$ $, kernel\ SG - filter, SNR_{req}, adr\ device_{margin}$
Output: SF_{new} $and\ TP_{new}\ for\ each\ ED$
// computes
(x,h)←(Input signal, kernel)
x→SNR of 20 Packet
h→convolution coefficient using SG filter
m→ dimension of input signal
n → dimension of kernel
$for\ i \leftarrow 0\ to\ m\ do$
  $for\ j \leftarrow 0\ to\ n\ do$
  $SNR_{new}(i,j) = \text{convolve}\,(x_i, h_j)$
  end
end
  $Min(\ SNR_{new}(i,j))$
// computes
1. $SNR_{req} = demodulation\ floor\ (current\ DR)$
2. $adr\ devicemargin = 10\ LoRaWAN\ default$
3. $SNRmargin = (SNR_s - SNR_{req} - adr\ device_{margin})$
4. $N_{steps} = int\ (SNR_{margin}/3)$
$while\ (N_{steps} > 0\ and\ SF > SF_{min})\ do$
  $SF = SF - 1$
  $N_{steps} = N_{steps} - 1$
end
$while\ (N_{steps} > 0\ and\ TP > TP_{min})\ do$
  $TP = TP - 3$
  $N_{steps} = N_{steps} - 1$
end
$while\ (N_{steps} < 0\ and\ TP < TP_{max})\ do$
  $TP = TP + 3$
  $N_{steps} = N_{steps} + 1$
end
$SF_{new} \leftarrow SF$
$TP_{new} \leftarrow TP$
$NS\ transmits\ LinkADRReq$

6. Results and Evaluating Performance

The efficiency of the LoRaWAN network under the effect of the SG-ADR algorithm with different deployment areas is tested using the simulation tool. Given the study's criteria, the OMNeT++ 6.0.2 IDE open-source simulation program was chosen. Figure 4 illustrates the application of the tool in modeling the PHY layer of LoRa, MAC protocol for LoRaWAN, and the associated network components, including network servers, end devices, and gateways. Informed by the presented relevant study, the assessment measures to evaluate the efficacy of LoRaWAN networks are as follows:

6.1. Average Packet Delivery Ratio (PDR)

The Packet Delivery Ratio (PDR) for each LoRa node in the network has been computed to characterize their coverage. The PDR is the ratio of data packets successfully received to the total number of data packets sent. For every node, PDR is computed using Equation (8):

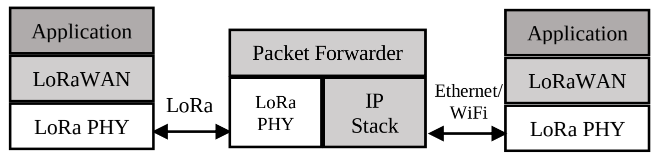


Fig. 4 Modules in FLoRa and relevant protocol stack [11]

$$PDR = \frac{Total\ amount\ of\ packets\ received}{Total\ amount\ of\ packets\ transmitted} . 100\% \qquad (8)$$

6.1.1. PDR in Urban Scenario

The evaluation analysis of the suggested approach with the standard ADR [6], OWA-ADR [14] and G-ADR [18] in an urban context with one and two gateways is presented. Figure 5 illustrates the effect of SG-ADR on the delivery ratio for both single and two gateways. The delivery ratio for SG-ADR surpasses standard ADR by 129.8 % and 85.2 % for single and two gateways, respectively. With an increasing number of nodes in the network, the delivery ratio decreases slightly.

6.1.2. PDR in Sub-Urban Scenario

The efficacy of SG-ADR in sub-urban scenarios with single and two Gateway is presented in this section. Figure 6 depicts how SG-ADR affects the delivery ratios for single and two gateway scenarios. The findings show that the delivery ratio for sg-ADR is better than standard ADR by 46.1% and 14.6% for single and two gateways, respectively. There is a slight reduction in the average PDR as the number of EDs in the network increases.

6.2. Network Energy Consumption (NEC)

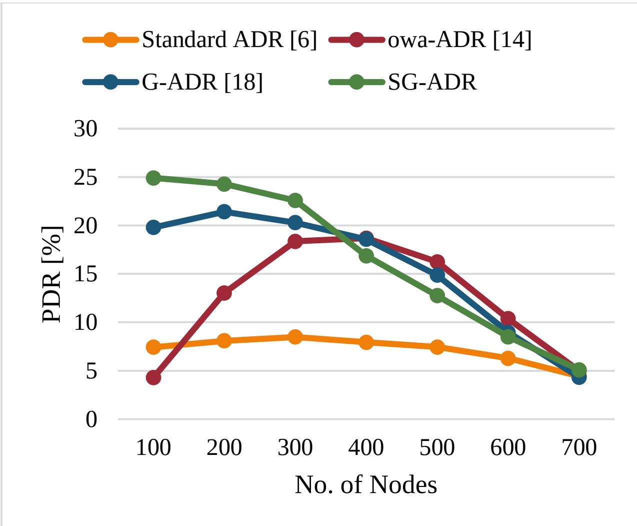
Monitoring energy usage as the simulation progressed calculated total network energy consumption. The model calculates the battery life of each ED and provides the overall energy usage for each ED as follows:

$$E_{ED} = E_{tx} + E_{rx} + E_s \qquad (9)$$

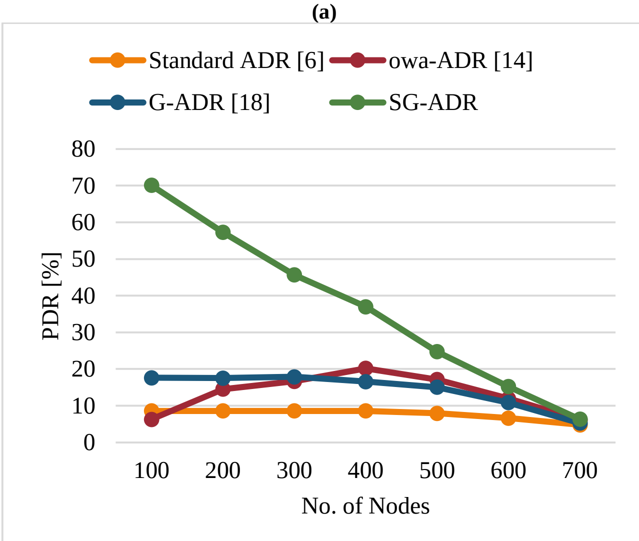
$$NEC = \frac{\sum_{i=1}^{No.\ of\ ED} E_{ED}(i)}{Total\ amount\ of\ successfully\ received\ messages} \qquad (10)$$

Where

- E_{tx} energy consumption of ED in transmitting mode.
- E_{rx} energy consumption of ED in receiving mode.
- E_s energy consumption of ED in sleep mode.



(a)



(b)

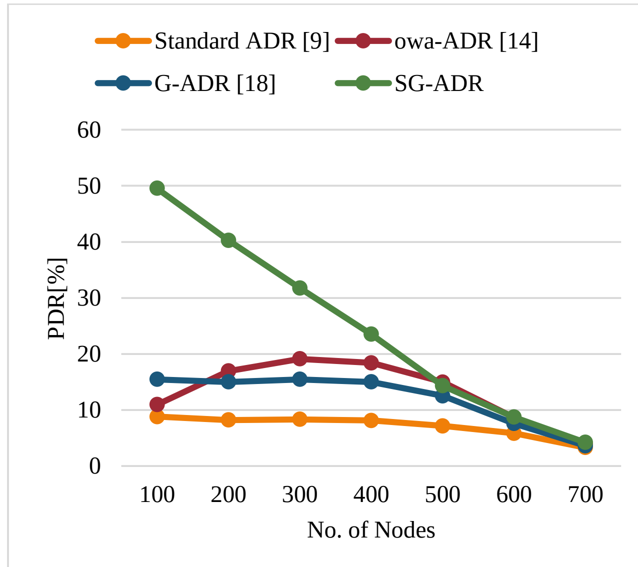
Fig. 5 PDR in urban scenario (a) Single gateway, and (b) Two gateways.

A lower NEC value indicates a more efficient network. The energy consumer module from [11] was utilized alongside the Semtech SX1273 datasheet, which specifies a supply voltage of 3.3V.

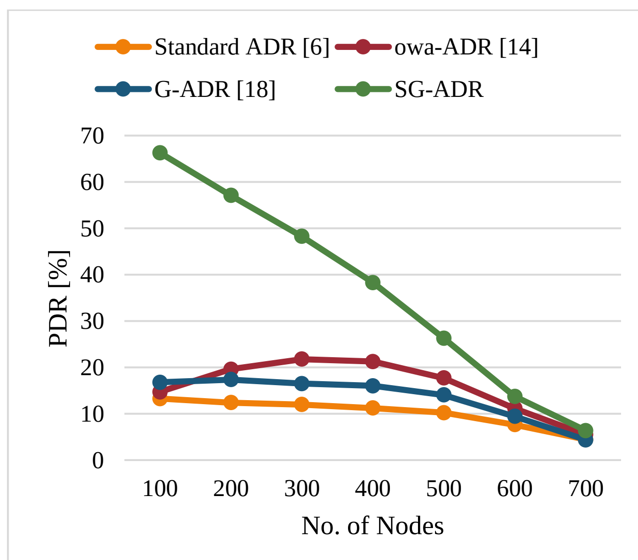
6.2.1. NEC in Urban Scenario

In an urban environment, the assessment of LoRaWAN network effectiveness within a deployment area of 480m by 480m was illustrated. The total number of EDs escalated from 100 to 700 with the inclusion of one and two gateways. Figure 7 demonstrates that energy consumption increases with the expansion of EDs. This occurs as the ADR algorithms utilize SF = 12 during the first network deployment, leading to significant interference caused by increased ToA. In the proposed ADR, energy consumption is reduced by designing an appropriate SF and TP and implementing a savisky Golay filter to improve SNR. The suggested ADR (SG-ADR) utilizes an average NEC of 2.26j and 1.27j for single and two gateways, respectively, whereas the standard ADR consumes 2.33 j and 1.51 j for single and two gateways.

The results enhance SG-ADR by 3% for a single gateway and 15.89 % for two gateways in an urban context relative to standard ADR.



(a)

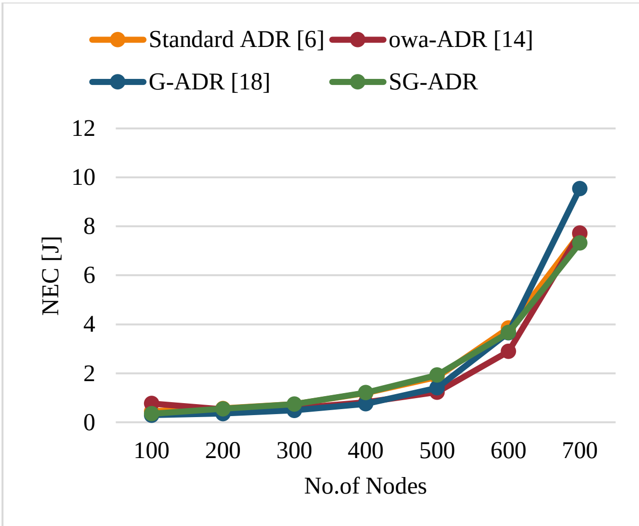


(b)

Fig. 6 PDR sub-urban Scenario: (a) Single gateway, and (b) Two gateways.

6.2.2. NEC in Sub-Urban Scenario

within a deployment geographical range of 9.8km x 9.8km, the LoRaWAN network's efficacy in suburban regions was demonstrated. The node count increased from 100 to 700 by adding one and two gateways.



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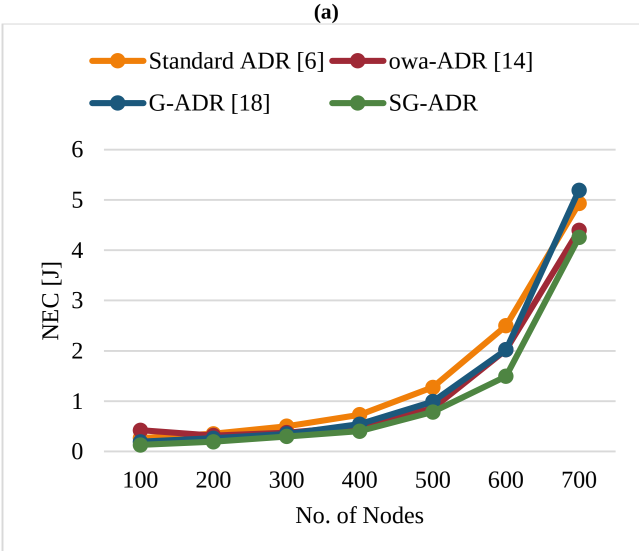
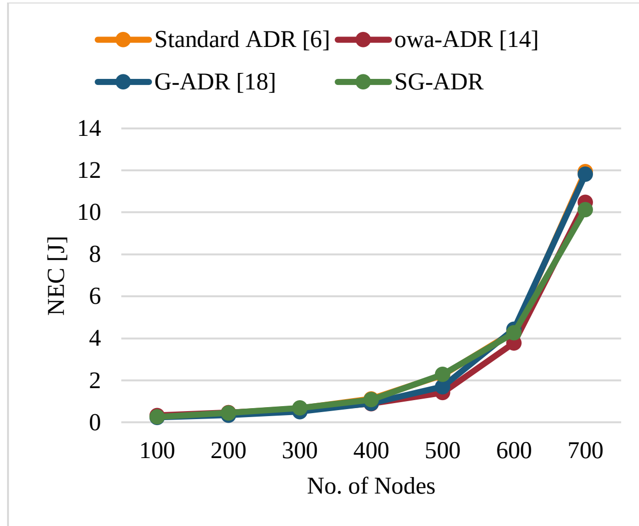


(b)

Fig. 7 NEC in urban Scenario. (a) Single gateway, and (b) Two gateways.



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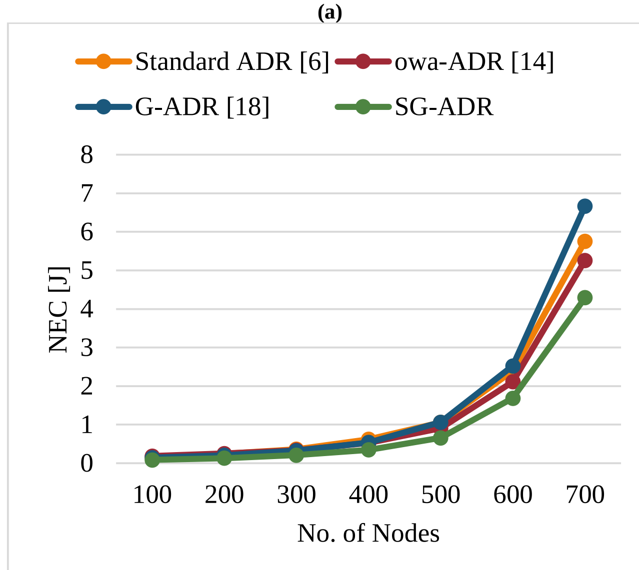


(b)

Fig. 8 NEC in sub-urban Scenario: (a) Single gateway, and (b) Two gateways.

Figure 8 exhibits an increase in energy use for both the standard ADR and the SG-ADR as the quantity of EDs escalates. The proposed ADR (SG-ADR) utilizes an average of 2.82j and 1.41j for one and two gateways, respectively, whereas the standard ADR consumes 2.96j and 1.59j for one and two gateways. These results indicate a 4.73% improvement for a single gateway and an 11.32% enhancement for two gateways in an urban setting about the proposed ADR compared to the traditional ADR.

6.3. Final SF Allocation Used by each ED

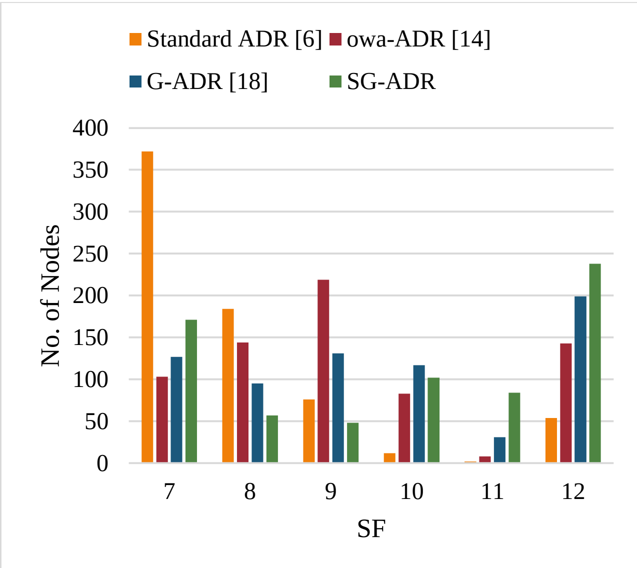
The final SF allocation utilized by the EDs with N = 700 for ADR algorithms in urban and suburban scenarios for single and two gateways is presented in this section. Equation (11) demonstrates that the communication distance for LoRaWAN increases according to the spreading factor [24].

$$D = \left(\frac{PL(d)}{\left(\frac{4\pi f}{c}\right)^2}\right)^{\frac{1}{n}} = \left(\left(\frac{c}{4\pi f}\right)^2 . \frac{P_{tr.}.2^{SF}}{SNR_0.NF.k.T.BW}\right)^{\frac{1}{n}} \qquad (11)$$

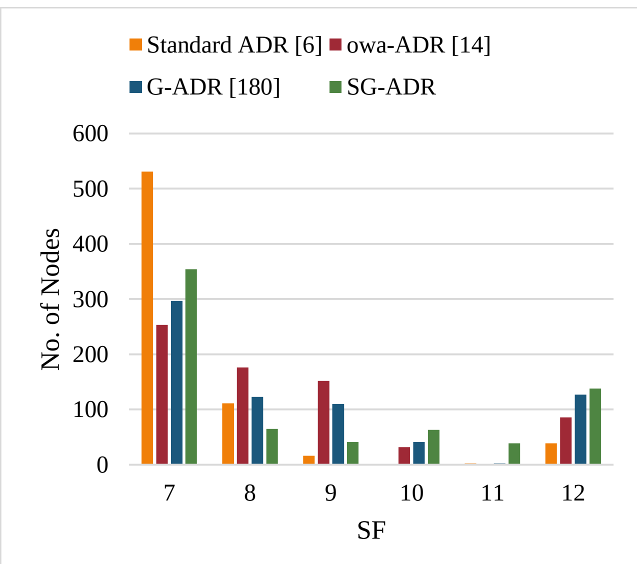
Where,

- $PL(d)$; *path loss between transmitter and receiver.*
- SF; Spreading Factor.
- c; speed of light.
- f; communication frequency.
- $P_{tr.}$; transmit power.
- BW; bandwidth.
- n; path loss exponent.
- SNR_0; signal – to – noise ratio.
- NF; noise figure.
- T; temperature.
- k; Kelvin constant.

Figure 9 and Table 4 depict that only 7.7% and 5.57% of the total number of nodes = 700 EDs assigned SF 12 in case of standard ADR in single and two Gateway, respectively, while 34% and 19.7% of the total number of nodes = 700 EDs assigned SF 12 in case of SG-ADR for single and two Gateway respectively in urban scenario.



(a)



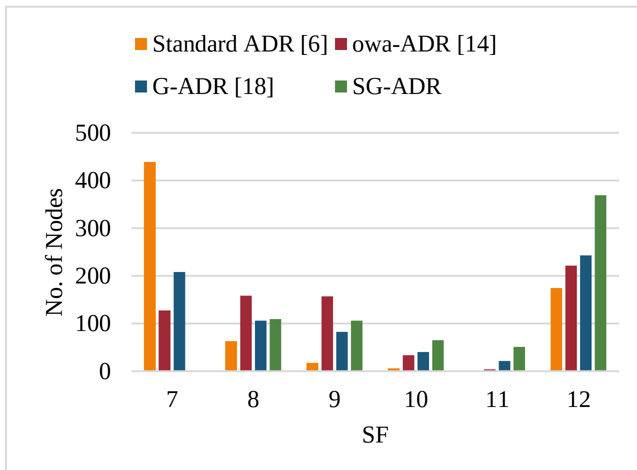
(b)

Fig. 9 Final allocation of SF per Nodes (EDs=700) urban scenario: (a) Single gateway, and (b) Two gateway.

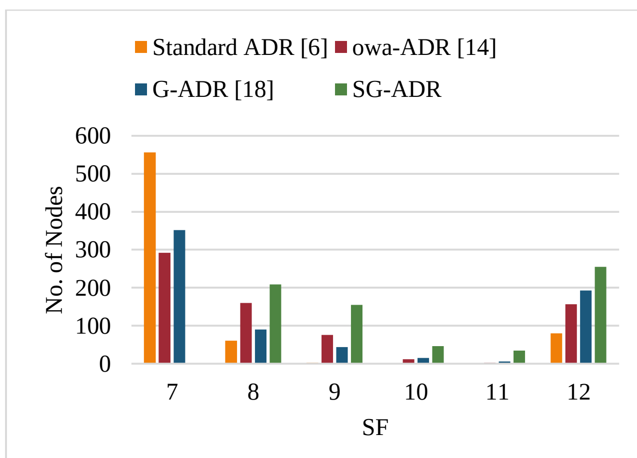
Figure 10 and Table 5 depict that only 22.9% and 13.7% of the total number of nodes = 700 EDs assigned SF 12 in case of standard ADR in single and two Gateway, respectively, while 34.6% and 15% of the total number of nodes = 700 EDs assigned SF 12 in case of SG-ADR for single and two Gateway respectively in a sub-urban scenario.

Table 4. Final allocation of spreading factor per node in percentage (EDs=700) in urban scenario

Single Gateway						
Algorithm	**SF7**	**SF8**	**SF9**	**SF10**	**SF11**	**SF12**
Standard ADR [6]	53.1	26.3	10.9	1.7	0.3	7.7
Owa-ADR [14]	14.7	20.6	31.3	11.9	1.1	20.4
G-ADR [18]	18.1	13.6	18.7	16.7	4.4	28.4
SG-ADR	24.4	8.1	6.9	14.6	12	34
Two Gateways						
Algorithm	**SF7**	**SF8**	**SF9**	**SF10**	**SF11**	**SF12**
Standard ADR [6]	75.9	15.9	2.3	0.1	0.3	5.6
Owa-ADR [14]	36.1	25.1	21.7	4.6	0.1	12.3
G-ADR [18]	42.4	17.6	15.7	5.9	0.3	18.1
SG-ADR	50.6	9.3	5.9	9	5.6	19.7



(a)



(b)

Fig. 10 Final Allocation of SF per Nodes (EDs=700) in sub-urban scenario: (a) Single gateway, and (b) Two gateway.

Table 5. Final allocation of spreading factor per node in percentage (EDs=700) in sub-urban scenario

Single Gateway						
Algorithm	**SF7**	**SF8**	**SF9**	**SF10**	**SF11**	**SF12**
Standard ADR [6]	62.7	9.0	2.4	0.9	0.1	24.9
Owa-ADR [14]	18.1	22.6	22.4	4.7	0.6	31.6
G-ADR [18]	29.7	15.1	11.7	5.7	3.0	34.7
SG-ADR	0.0	15.6	15.1	9.3	7.3	52.7
Two Gateways						
Algorithm	**SF7**	**SF8**	**SF9**	**SF10**	**SF11**	**SF12**
Standard ADR [9]	79.4	8.7	0.4	0.0	0.0	11.4
Owa-ADR [14]	41.7	22.9	10.9	1.7	0.4	22.4
G-ADR [18]	50.3	12.9	6.3	2.1	0.9	27.6
SG-ADR	0.0	29.9	22.1	6.6	5.0	36.4

The figures also show that using the SG-ADR algorithm gives a better allocation of SF to ED to improve both the ToA and communication range for LoRaWAN.

7. Conclusion

This research presents a new adaptive data rate mechanism called SG-ADR for LoRaWAN networks, aimed at enhancing packet delivery ratios and minimizing network energy usage. Typical ADRs experience high rates of losing packet loss due to interference. Therefore, NS-controlled ADRs (SG-ADR) were presented to improve the PDR and NEC. The proposed approach includes two steps. First, the SNR values for each ED were smoothed by convolving the SNR values of 20 Packets with the convolution coefficient of Savitzky-Golay. In the second stage, after finding the smoothed SNR for each node, the determination of new SF and TP at each node was achieved through the adaptive data rate method. The evaluation of the performance of the SG-ADR algorithm against the conventional ADR implementation through comprehensive simulations and analysis performed. The findings demonstrate that the SG-ADR method attains substantial enhancements in critical performance parameters. The findings collected demonstrate the superiority of the suggested approach compared to the standard ADR in terms of energy usage and PDR. Additionally, the offered approaches are appropriate for IoT applications, necessitating a high PDR and reliability without excessive energy usage.

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