Resource Allocation for Long Range Wide-Area Network

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Abstract. *People in smart cities tend to be constantly connected, and wireless connection technologies have become necessary in their routines. The Long Range Wide-Area Network protocol provides a resource allocation mechanism called Adaptive Data Rate that allocates the transmission parameters to increase scalability and reduce the devices' power consumption. However, ADR prioritizes scalability at the cost of low reliability. In this paper, we propose the PRA and APRA resource allocation mechanisms. Both aims to hierarchy ensure better performance for devices in Long Range networks. While PRA aims to reduce transmission delay and power consumption, APRA reduces packet loss and power consumption while increasing the devices' battery life. The results showed that the PRA mechanism reduced the ToA and power consumption of high-priority devices by up to 85%. APRA increased up to 5% in packet delivery and 85% in energy savings. Furthermore, APRA's transmission power allocation mechanism has increased the device's battery life by up to 28 years.*

1. Introduction

Internet of Things (IoT) is expanding its portfolio to include a wide range of IoT applications, mainly due to the advances in different areas, such as embedded systems, microelectronics, communication, and sensing [Kassab and Darabkh 2020]. IoT applications require low energy consumption (to address maximum battery time), high coverage, and cost-effectiveness [Zeadally et al. 2020]. Hence, the communication technology used to transmit the collected IoT data plays a vital role in the massive adoption and deployment of IoT applications. To satisfy IoT applications' requirements, the Low-Power Wide-Area Network (LPWAN) emerged as a promising communication technology for supporting many IoT applications in rural and urban areas. Over the last few years, LPWAN has been increasingly used on a large scale by the industry. Recent market data shows an increase of 109% per year of connected LPWAN devices and an annual investment of more than US$4.5 billion from 2018 to 2023.

Instead of common cellular infrastructures such as 4G and 5G, LPWAN solutions implement a communication technology with lower operating costs, low bit rate, long-range, and low energy consumption [Gaddam and Rai 2018]. According to Haxhibeqiri et al. [Haxhibeqiri et al. 2018], the number of publications on Long Range (LoRa) areas has grown tremendously in recent years. LoRa enables the devices to transmit over distances up to hundreds of kilometers. LoRaWAN offers a cost-effective way to enable large-scale deployment of End Devices (ED) that require less-complex medium access control mechanisms at the expense of low throughput. However, the densification of LoRaWAN generates a severe problem when more connected devices coexist in the same area with limited radio resources [Matni et al. 2020].

This issue significantly impacts the number of packets lost due to collision and interference, affecting network scalability and efficiency [Georgiou and Raza 2017]. In this context, the LoRaWAN physical layer considers a set of radio parameters that can be adjusted on the fly to provide a trade-off among transmission range, bit rate, airtime, energy consumption, and interference [Kufakunesu et al. 2020]. Existing works have demonstrated that an efficient combination of these radio-related parameters configured by a resource allocation mechanism significantly impacts the IoT applications, resulting in better coverage, data delivery, and robustness with lower energy consumption [Sanchez-Iborra et al. 2018].

The default LoRaWAN resource allocation mechanism selects parameters such as SF, BW, and TP of each device on the network. Thus, the network becomes scalable, resistant to packet loss, and saves energy. However, current algorithms are not sensitive to the device's priority. As a result, LoRaWAN resources are not assigned to devices following a pre-established hierarchy, potentially causing losses of essential packets. This paper presents two resource allocation mechanism detailed in the master thesis [L. Eduardo 2022]. The resource allocation mechanism selects the devices' transmission parameters according to their priority to maximize network scalability, reliability, and energy saving. We can divide the research steps as follows:

- Propose two resource allocation mechanisms to select transmission parameters according to the priority of devices in LoRaWAN networks.
- Generate devices and random priority in simulation environment to evaluate the mechanisms performance according to each priority.
- Simulate state-of-the-art resource allocation mechanisms to compare all the resource allocation mechanisms.

2. Related Works

This section presents a brief summary of state-of-the-art research results on resource allocation algorithms and discusses their strengths and weaknesses. Existing resource allocation approaches focus on improving the LoRaWAN scalability and reliability by adjusting different radio parameters. However, the diversity of IoT applications in QoS requirements has yet to receive commensurate attention.

Table 1. Summary of resource allocation mechanisms analyzed for a scenario with heterogeneous IoT applications

Resource allocation mechanisms	**Year**	**Optimization goal**	**Energy**	**Application requirements**	**LoRa parameters**		
					SF	TP	BW
ADR LoRaWAN	2016	Maximize the transmission range and energy-saving	✓		✓	✓	✓
Khaled *et al.* [Abdelfadeel et al. 2018]	2018	Address the unfair LoRaWAN characteristic	✓		✓	✓	
Alenezi *et al.* [Alenezi et al. 2019]	2019	Reduce collisions		✓			
Dawaliby *et al.* [Dawaliby et al. 2019]	2019	Maximize QoS	✓	✓	✓	✓	
El-Asser *et al.* [El-Aasser et al. 2018]	2018	PDR and throughput			✓		
Babaki *et al.* [Babaki et al. 2020]	2020	Improve the noise resilience and PDR	✓		✓	✓	
PRA [Lima et al. 2020]	2020	Improve scalability		✓	✓		✓
APRA [Lima et al. 2021]	2021	Improve scalability and energy optimization	✓	✓	✓	✓	✓

Table 1 summarizes the main characteristics of the analyzed resource allocation mechanisms based on the following characteristics: optimization goal, energy efficiency, requirement-based differentiation decisions, and LoRaWAN radio parameters considered, meaning their strengths and weaknesses as supported and not supported feature. Such characteristics can significantly improve the system's performance in terms of reliability and energy. Based on our state-of-the-art analysis, we conclude that only a few works [Abdelfadeel et al. 2018, Dawaliby et al. 2019, Cuomo et al. 2017, Babaki et al. 2020] provide energy-efficiency through TP adjustment or SF allocation. Also, existing works [Abdelfadeel et al. 2018, Cuomo et al. 2017, El-Aasser et al. 2018, Zorbas et al. 2018, Moraes et al. 2020, Babaki et al. 2020] do not deliver application requirements for resource allocation.

3. Priority-Aware Resource Allocation

We can conclude that the state-of-the-arts resource allocation mechanisms are not sensible to the application QoS requirements and do not prioritize important devices. To solve these issues, our proposed resource mechanisms limits the number of the devices in each SF level.

Priority-aware Resource Allocation mechanism describes a LoRaWAN resource allocation that manages the available SFs on the network and distributes them to the EDs. This distribution considers a limited number of EDs in each SF, the device priority given by the application, and the ToA of each SF. The PRA aims to decrease the ToA of high and medium-priority EDs and reduce packet collision of low-priority devices.

PRA considers that the network starts all EDs in the highest SF available to maximize transmission range. From the first packet received from each ED, PRA creates a matrix $RSSI_{mat}$ to represent the packet RSSI of each ED in each GW. Each row of $RSSI_{mat}$ represents a GW, and each column represents an ED and its RSSI values from each GW. From $RSSI_{mat}$, we can associate EDs to the best GW and sort them according to RSSI to allocate its SF. PRA uses an array $Prior_{arr}$ for each GW containing EDs with the highest RSSI value from each column in $RSSI_{mat}$. We multiply each value in $Prior_{arr}$ by the priority level of the respective ED. The priority levels are 1, 2, and 3 for high, medium, and low-priority EDs.

From $Prior_{arr}$, PRA calculates the limit of EDs in each SF, considering their respective priority and RSSI values. The ToA between the SFs must be balanced to reduce collision, preventing the EDs from occupying a GW in a specific SF for a long time. Therefore, PRA limits the number of EDs in each SF according to the average SF ToA. We compute the limit of EDs in each SF by the array lim_{arr} in Equation 2, W_{arr} is an array of weights given by Equation 1, ToA_{arr} is the array of ToA for each SF (as in the example of Table 2), $ToASum_{arr}$ is the sum of all elements of ToA_{arr}, $WSum_{arr}$ is the sum of all elements of W_{arr} and n is the size of $Prior_{arr}$, *i.e.,* , the number of EDs for the respective GW.

$$W_{arr} = \left(\frac{ToA_{arr}}{ToASum_{arr}} \right)^{-1} \tag{1}$$

$$lim_{arr} = \frac{W_{arr}}{WSum_{arr}} \cdot n \tag{2}$$

Table 2. ToA for packets of 20 bytes, CR=4/5 e BW=125 kHz

SF	7	8	9	10	11	12
ToA (ms)	56.576	102.912	185.344	370.688	741.376	1318.912

4. Adaptive Priority-Aware Resource Allocation

Adaptive Priority-aware Resource Allocation considers the $RSSI_{j,i}$ and the ED's priority $p_{l,i}$ to determine the configuration of radio parameters, *i.e.,* , SF, BW, and TP. Initially, APRA considers all EDs configured with the highest SF SF_k available because a high SF increases the transmission range and the probability of reaching a GW_j. As Equation 3 shows, a matrix R represents the $RSSI_{j,i}$ value perceived by a given GW_j from each ED_i, where each row in R represents a GW_j, each column represents an ED_i, and each value represents $RSSI_{j,i}$ measurement.

$$R = \begin{pmatrix} RSSI_{1,1} & RSSI_{1,2} & \cdots & RSSI_{1,n} \\ RSSI_{2,1} & RSSI_{2,2} & \cdots & RSSI_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ RSSI_{m,1} & RSSI_{m,2} & \cdots & RSSI_{m,n} \end{pmatrix}. \tag{3}$$

Next, APRA creates a priority matrix $Prior_{mat}$ based on the values from the R. Where each $Prior_{mat}$ column is the result of multiplying each $R_{l,c}$ column by the respective EDs' priority value $p_{l,i}$, as Equation 4 shows. Hence, the high value in $Prior_{mat}$ represents the highest priority, using the highest DR_r configuration.

$$Prior_{mat} = \begin{array}{c} \\ GW_1 \\ GW_2 \\ \vdots \\ GW_m \end{array} \begin{array}{c} \begin{array}{cccc} ED_1 & ED_2 & \cdots & ED_n \end{array} \\ \begin{pmatrix} R_{1,1} \times p_{l,1} & R_{1,2} \times p_{l,2} & \cdots & R_{1,n} \times p_{l,n} \\ R_{2,1} \times p_{l,1} & R_{2,2} \times p_{l,2} & \cdots & R_{2,n} \times p_{l,n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m,1} \times p_{l,1} & R_{m,2} \times p_{l,2} & \cdots & R_{m,n} \times p_{l,n} \end{pmatrix} \end{array}. \tag{4}$$

APRA uses an array lim_{SF_k} to limit the number of EDs in each SF_k. The lim_{SF_k} array depends on W_1, W_2, n, and a constant WF. W_1 aims to provide EDs uniformly distributed in SFs SF_k (*i.e.,* , 16.6% EDs in each SF), as Equation 5 shows. W_2 aims to provide EDs distributed in SFs based on the b_{rate} inverse to reduce packet collision in lower SFs SF_k, as Equation 6 shows. The constant WF adjusts the distribution and APRA adaptive characteristics, where values close to 1 result in a uniform EDs distribution on SFs, and $WF = 0$ results in an unfair distribution (more EDs in high SF).

$$W_1 = \frac{1}{\sum\limits_{SF_k=7}^{12} 1}, \quad \forall SF_k \in SF \tag{5}$$

$$W_2 = \frac{b_{rate}^{-1}}{\sum\limits_{SF_k=7}^{12} (b_{rate})^{-1}}, \quad \forall SF_k \in SF \tag{6}$$

$$lim_{SF_k} = n \times [W_1 \times WF + W_2 \times (1 - WF)], \quad \forall SF_k \in SF \tag{7}$$

APRA sets the ED_i with the highest $Prior_{mat}$ value to the highest DR_r, by considering the $RSSI_{j,i}$ perceived by a given GW_j from such ED_i, receiver sensitivity $Sensitivity_{DR_r}$ for each DR_r, and also limits the number of EDs in each SF_k (*i.e.,* , lim_{SF_k}). Specifically, as soon as the SF limit lim_{SF_k} for a given SF_k value has been reached, the limit or the $RSSI_{j,i}$ of a given ED_i is lower than or equal to the receiver's sensitivity in the calculated DR, APRA decreases the DR_r until ED_i can communicate with GW_j without exceeding the maximum number of EDs in each SF_k. Therefore, if any high-priority ED has connection problems, it will be set to a low DR (high SF).

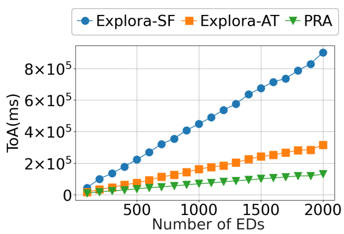
After selecting the DR_r configuration (*i.e.,* , SF and BW), APRA performs the TP adjustment. In this way, APRA must define a minimal $RSSI_{j,i}$ value, called the $RSSI_{threshold}$, where a high $RSSI_{threshold}$ value means a higher chance of losing packets, while low-value results in energy savings. Based on the DR_r value, it is possible to compute the difference between the $RSSI_{j,i}$ and the receiver $Sensitivity_{DR_r}$. As a result, as soon as this difference is higher than $RSSI_{threshold}$, APRA decreases TP_p by a determined value until the difference between the $RSSI_{j,i}$ and the receiver $Sensitivity_{DR_r}$ is less than or equal to $RSSI_{threshold}$. This way, the APRA reduces energy consumption by decreasing the TP without affecting the transmitted packets' integrity.

Table 3. Receiver sensitivity for SX1272 module in each DR and LoRa configuration

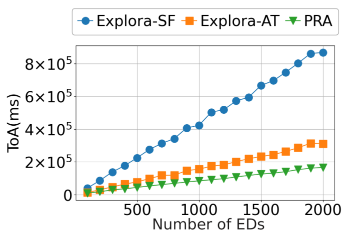
DR	LoRa configuration	Sensitivity
DR_0	SF_{12} **and** BW_{125}	-137
DR_1	SF_{11} **and** BW_{125}	-134
DR_2	SF_{10} **and** BW_{125}	-132
DR_3	SF_9 **and** BW_{125}	-129
DR_4	SF_8 **and** BW_{125}	-126
DR_5	SF_7 **and** BW_{125}	-123
DR_6	SF_7 **and** BW_{250}	-120

5. Experimental Results

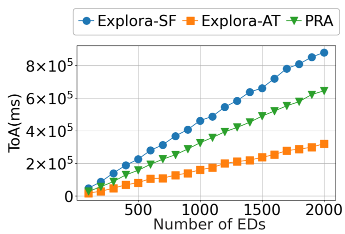
As expected, PRA set the medium and high-priority EDs to the low SFs. This strategy guarantee that PRA obtains the lowest ToA for these EDs. Compared to EXPLoRa-SF, the PRA reduces the ToA by up to 85% and 80% for high and medium-priority groups, respectively. Compared to EXPLoRa-AT, the PRA reduces 58% and 46% for the high and medium priority groups, respectively (Figures 1(a) and 1(b)). Due to setting the best SFs to medium and high-priority EDs and because low-priority EDs are set to higher SFs, PRA obtains higher ToA than EXPLoRa-AT for low-priority EDs (Figure 1(c)). However, PRA is a superior allocation mechanism to EXPLoRa-SF, which does not utilize the lowest SFs to reduce packet collision caused by high ToA.



(a) High priority



(b) Medium priority



(c) Low priority

Figure 1. The total packets ToA according to the resource allocation mechanism used.

The obtained PRA's packets low ToA result in low latency and low packet collision probability. The results show that PRA reduces the ToA of high and medium-priority devices and reduces these groups' delay and energy consumption. Furthermore, PRA improves the reliability by reducing the amount of packet collision in low-priority devices as a cost to increase the ToA and energy consumption of low-priority devices.

Different to PRA, APRA can adapts to a wide variety of environments, thanks to their sub parameters. Otherwise, APRA can select TP parameter to save energy. These features result in low energy, and consequently high battery duration time.

Figure 2 shows the energy consumption of each resource allocation mechanism and each application priority level. Min_Airtime, ADR, and APRA have the lowest energy consumption for high- and medium-priority EDs. For Min_Airtime, this occurs because SF_7 has low ToA. For instance, SF_{11} consumes ten times more energy than SF_7. ADR makes the TP allocation to save energy on EDs with high SNR. APRA has both advantages. Decreasing TP for high RSSI EDs and using BW allocation, APRA reduces the ToA of high-priority EDs (SF_7-SF_8). Even for high-priority EDs, EXPLoRa-SF, EXPLoRa-AT, and CORRECT had the highest energy consumption because these mechanisms do not have TP and BW allocation. APRA has the second highest energy consumption for low-priority EDs because the lowest ToA resources have been used in high-priority EDs. For high-priority EDs, APRA reduces energy consumption by up to 57.2%, 19.1%, 95.0%, 85.6%, and 85.9% compared to Min_Airtime, ADR, EXPLoRa-SF, EXPLoRa-AT and CORRECT, respectively (EDs n = 5000). APRA reduces the energy consumption for medium priority EDs by up to 84.2%, 53.7%, and 55.5% compared to EXPLoRa-SF, EXPLoRa-AT, and CORRECT, respectively (EDs n = 5000). Finally, Min_Airtime, ADR, EXPLoRa-SF, EXPLoRa-AT, and CORRECT mechanisms show similar behavior in terms of energy consumption for all application priorities because they do not consider application priority when allocating the EDs' radio parameters.

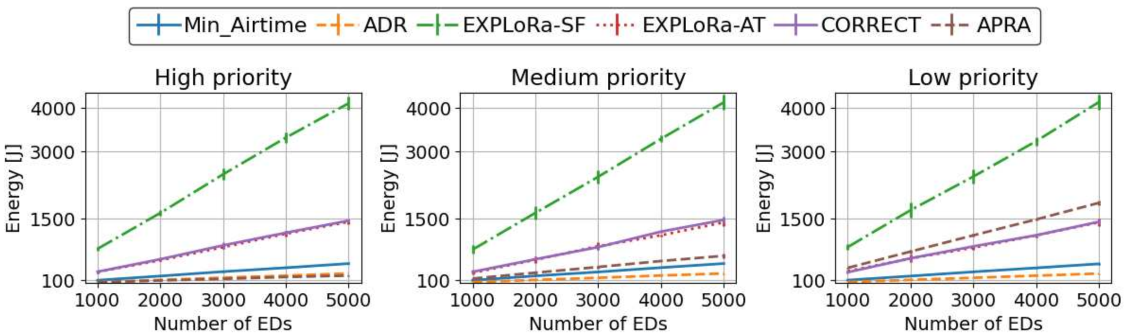


Figure 2. Energy consumption by device priority for each mechanism.

Figure 3 shows the average BDT for each resource allocation mechanism. We note that APRA has the best battery duration due to an optimal TP allocation while also achieving an intelligent SF and BW allocation, which results in minimum packet airtime. ADR performs well because the TP is reduced according to the packet SNR. Min_Airtime has a good BDT result because it sets all EDs to SF_7, which results in a lower ToA at the expense of high packet losses. EXPLoRa-AT and CORRECT mechanisms have similar results because both set EDs in SF based on the ToA. As expected, EXPLoRa-SF configures many EDs in higher SFs, *i.e.,* , SF_{11} and SF_{12}, and incurs the highest energy consumption. In summary, APRA increases the duration time by up to 18.5, 4.4, 28.8, 24.1, and 24.1 years than Min_Airtime, ADR, EXPLoRa-SF, and EXPLoRa-AT

CORRECT, respectively.

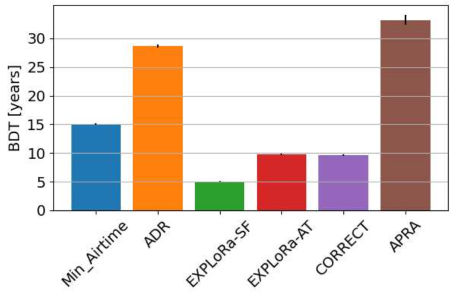


Figure 3. BDT by device priority for each mechanism.

6. Conclusion and Thesis Impact

The massive use of IoT in intelligent spaces is transforming everything worldwide, paving the way for creating smart cities and industry services 4.0. The LoRa and LoRaWAN showed as a solution for wireless communication technology. LoRaWAN protocol can manage LoRa physical resources to transmit packets in high coverage and low power consumption. However, some communication and energy waste issues remain and must be solved. The PRA and APRA mechanisms allocate the SF parameter to reduce packet collision. However, APRA also allocates BW and TP parameters to reduce packet air time and increase device battery life. This can improve device performance in terms of QoS and device battery duration time. Results showed that PRA's SF allocation reduces ToA and energy consumption by 85% for high-priority. Also, APRA increased network performance by 5% in terms of packet delivery and 85% in terms of energy saving for high-priority. In addition, APRA TP allocation increased high-priority EDs' battery life by up to 28 years.

7. Publications

The results of this Master Theses are published on:

Table 4. Summary of Results Published

Works	Qualis	Local
[Lima et al. 2021]	A1	Ad Hoc Networks
[Lima et al. 2020]	B4	SBCUP

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