Traffic Control and Channel Assignment for Quality Differentiation in Dense Urban LoRaWANs

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***Abstract*—Service quality differentiation is gaining popularity in IoT networks, notably in LoRaWAN, with the rapid widespread of applications on connected devices. There is clearly a business demand for quality in IoT in the context of smart cities and network operators are urged by application designer to offer quality differentiation. However, those types of networks have been designed on the basis of a best effort service model. In particular, Packet Delivery Ratio (PDR) can dramatically decrease in dense scenarios. In this paper, we propose and evaluate traffic control and channel assignment solutions for PDR differentiation in dense deployments. Several performance criteria are defined in order to analyze the gain achieved by a network operator as well as end users. Numerical results show that both players can benefit from quality differentiation with ad-hoc pricing. This proves to be effective if penalizing low requirement devices, as they can create a bottleneck in the system. Namely, we show that in high density settings we can reach a 20% better PDR with one of the proposed policies, improving mean device servicing rate by 10% and the operator gain by 7.5%.**

***Index Terms*—LoRaWAN, Packet Delivery Ratio, Quality Differentiation, Access Control, IoT.**

I. Introduction

In the ever growing Internet of Things (IoT), Long Range Wide Area Networks (LoRaWANs) are rapidly gaining popularity thanks to their cheap and easy-to-operate nature. LoRaWAN is a Low Power Wide Area Network (LPWAN) technology targeting long range sensing and monitoring: use cases are typically in the domain of agriculture (cattle tracking, soil properties monitoring) and smart cities (bicycle pool management, garbage monitoring, air quality monitoring etc.) [1]. Business opportunities have emerged for new and existing operators, interested in understanding its operational limits.

LoRaWAN operates in the unlicensed industrial, scientific, and medical (ISM) bands with a simple communication protocol stack designed to minimize the power consumption of intermittently and sporadically active devices [2]. By design, LoRaWAN is best effort in the sense that the limited radio spectrum, combined with the uncoordinated access to the radio medium, results in a best effort operation and an inefficient resource utilization [3]. While a device duty-cycle limitation is present on the band, collisions are still frequent in device-dense deployments making PDR a key performance metric for an application using LoRaWAN [4].

To overcome this problem, transmission parameters can be dynamically managed through primitives in the LoRaWAN protocol. Many algorithmic propositions exist in the technical literature to obtain improved exploitation of radio resources [5], [6]. In particular, a growing body of literature, boosted by recent interest in the network slicing paradigm in 5G, studied the problem of introducing differentiated quality in LoRaWAN [7]–[14]. Clusters of devices are assigned to separate interference domains, i.e., disjoint sets of frequencies, to enforce traffic isolation. Then, transmission parameters are optimized according to the traffic requirements of the clusters (reliability, throughput, latency, and energy consumption).

While operators have a clear interest in achieving and maintaining differentiated quality levels requested by emerging applications, quality does degrade when a high number of devices transmit in the vicinity of a radio gateway [15], [16]. Resource allocation algorithms currently proposed for quality differentiation do not consider limiting device access and/or traffic to prevent from performance degradation. Such actions may be in contradiction with the openness and best effort principles of LoRaWAN, but seem to be inevitable in light of the expected densification of connected objects in urban environments and quality demanding applications.

In this paper, we study the feasibility of quality differentiation for dense LoRaWANs and we consider the enforcement of realistic PDR requirements for clusters. To limit interference in clusters, we introduce and compare two traffic control solutions (via access control and duty-cycle control). Then, to evaluate the performance impact of using independent interference domains, we define three distinct frequency assignment policies (priority to high requirements, proportional-fairness, traffic maximization) spanning over the fairness spectrum.

We design our techniques to work on pre-existing transmission parameter allocations, such that further requirements and optimization objectives may be subsequently integrated. For evaluation purposes, we define several performance metrics to measure the efficiency of the proposition in terms of requirements satisfaction for devices and gain for the network operator. Numerical results show that significant improvements to PDR levels can be achieved at the expense of penalizing devices with low requirements. Also, to achieve comparable gains operators have to charge for quality differentiation with the exception of high density scenarios.

The paper is organized as follows. We review some basic element of LoRaWAN, and compare our study to the state of the art, in Section II. We introduce our framework for packet delivery control as well as the traffic control policies and the performance criteria used in the evaluation in Section III. We detail the techniques considered for frequency allocation in

ISBN 978-3-903176-49-2 © 2022 IFIP

Section IV. Simulation results are presented in Section V. Concluding remarks are presented in Section VI.

II. Related Work

A. Basic Elements of LoRaWAN

LoRaWAN uses spread-spectrum modulation on the frequency channels in the unlicensed industrial, scientific, and medical (ISM) bands. Devices are assigned to a common pool of frequency channels and they must randomly select one for each new transmission. This behaviour is referred to as *Frequency Hopping* and is introduced to mitigate the impact of external interference [2]. Uplink transmissions are received by LoRaWAN gateways in range and forwarded to a network server. In turn, the server sends downlink configuration frames through the gateway measuring the best reception.

Six Spreading Factor (SF) configurations that range from SF_7 to SF_{12} are used. The SF is a parameter that controls the spreading of symbols at modulation time. With a higher SF, transmission range is increased at the expense of longer transmission time on the air interface. Moreover, transmissions that are on the same SF and on the same frequency channel collide, while different SFs are almost orthogonal [17]. In addition, Transmission Power (TP) can be configured to improve capacity as in cellular networks [16].

A 1% duty cycle limitation is introduced to maintain fairness in the ISM band [18] and can be additionally lowered by using LoRaWAN primitives. If the duration of packet transmission is τ time units, then the transmission starting times of two consecutive packets must be separated by $\frac{\tau}{\delta}$ time units, where δ is the duty cycle [2].

To enable collision detection, the LoRaWAN standard provides the option of using 'confirmed' (acknowledged) traffic. Precisely, a downlink acknowledgment is sent back to the devices after every uplink transmission, hence possibly triggering re-transmissions. However, as this can halve the network capacity, it is considered viable only in small networks [19].

In dense deployments, the increase of network traffic leads to a high number of collisions. This can be mitigated by distributing traffic over multiple SFs and regulating TP, with the so called Adaptive Data Rate (ADR) algorithms. Many propositions exist to tackle this problem, improving network scalability, throughput or energy consumption [6]. Existing implementations minimize the SF of each device according to the measured Signal to Noise Ratio (SNR) of transmissions [5]. TP is lowered only if a device is already using SF_7. In our proposition we consider SFs and TP as pre-assigned.

B. Quality Differentiation

In [7]–[14], the authors propose to introduce network slicing in LoRaWAN. They provide a high level view of the end-to-end architecture and put more attention on the radio parameter assignment problem. Specifically, the assignment of independent interference domains allow them to achieve differentiated traffic quality. These works follow a common methodology consisting of two steps as follows.

a) Channel Allocation: In each gateway, a portion of the available frequencies is reserved for each cluster. In [7], this is done proportionally to the average device throughput of each cluster. In [8], [11], the methodology is refined by considering, for each gateway, only nodes in range instead of the total number of devices for the average device throughput calculation. In [13], this method is compared with an approach based on mini-batch gradient descent to obtain the portion of frequencies for each cluster. In [9], bankruptcy games and matching theory are used in frequency allocation algorithms.

b) SF and TP Allocation: An assignment of SFs and TP to devices is achieved for the different clusters, according to their needs. In [9], [11], this task is done with a multi-criteria decision analysis approach proposed in [10]. In [7], [8], a further step is specified to find for each device the best path to a gateway. In [12], this problem is addressed via a 'transfer learning-based multi-agent deep deterministic policy gradient' algorithm, and in [14] via deep reinforced learning.

To address cluster quality requirements, authors adopt 5G Machine Type Communications (MTC) ones, classified as ultra-high, high, and low levels of latency and reliability requirements. Latency and reliability bounds are used to guide the cluster optimization. Such tight targets are in the order of hundreds of ms (or less) for latency, and 99.9% (and higher) packet delivery ratios; they may, however, be difficult to meet in LoRaWAN, since this technology has very specific bandwidth, transmission speeds and medium access control conditions. Indeed, such targets are actually not met in the numerical results reported in [1], [3], [4], [17], [20].

C. Contributions

Our study focuses on traffic control and frequency allocation policies for PDR differentiation, and differs from previous works above in the following aspects:

- The share of radio resources, i.e., the number of channels, assigned to each cluster is scaled according to the PDR requirement and input traffic. In [8], [9], [13] this share is only based on input traffic, not considering the impact of requirements.
- We limit traffic in a cluster according to the number of channels assigned. This is important to allow more precise control over the satisfaction of requirements, and to address network congestion if the population of devices around a gateway increases. For example, this could happen in a smart city scenario due to bicycle tracking. To the best of our knowledge, this has not been considered before in LoRaWAN literature.

In this paper we define classes of services in terms of PDR. Latency is a secondary metric because LoRaWAN use cases are not time-critical [1], and throughput is closely related to PDR due to duty-cycle and packet size constraints [21]. Energy considerations are out of the scope of this paper and can be addressed in further studies. We still adopt an ultra-high, high, and low classification as in 5G MTCs for the Industrial IoT [13], yet rescaling the requirements to more realistic 97% PDR, 90% PDR, and 70% PDR levels, as of experimental results in [20].

We consider cluster membership as predetermined, based on the cluster PDR-requirements. For evaluation purposes, we design two metrics to determine device satisfaction and operator gain with an allocation scheme.

III. Packet Delivery Control

Our objective is to separate and control levels of PDR for different groups of devices by means of parameter allocation schemes. For this purpose, we introduce an estimation of the PDR in a cell, followed by two methods of enforcing a desired level of PDR. Finally, we introduce two metrics to evaluate the utility of devices and the operator gain with an allocation scheme.

A. PDR Estimation for Urban Environments

Scenarios with a high density of End-Devices (EDs) are very likely to happen in many use cases, notably smart cities. Before considering the effect of interference in the calculation of PDR, fading caused by dense building environments has to be considered and is typically modeled by using Rayleigh fading. This effect has a significant impact on PDR independently of interference [16], [17]. The coverage probability is expressed as

$$\mathbb{P}_H = exp\Big(-\frac{Nq_j}{Pg(d)}\Big), \quad (1)$$

where $N = -117$dBm is the constant thermal noise for a 125 kHz-wide band [17], [22], q_j is the SNR threshold for reception at SF j [16], P is transmission power, and $g(d)$ is average path loss at distance d.

Therefore in the following we assume that EDs are placed at a maximum distance from gateways such that $\mathbb{P}_H \geq 0.98$ on SF_{12} at 14dBm ERP power (max in Europe [18], [21]). With the Okumura-Hata path loss model for large urban environments (widely used in the literature [16]) we obtain a maximum distance of 2.5 km. Assuming ADR is used, the SNR margin for SF and TP assignment can be increased [5]. Thus, we derive the margin from Equation (1) to grant $\mathbb{P}_H \geq 0.98$ and benefit from the usage of multiple SFs and TP combinations.

We base our PDR estimation on the model proposed in [16], correlating the effects of fading with co-SF interference. Depending on the SF $j = 7, \ldots, 12$, the model formula is

$$e^{-g_t-2\nu_j} + \frac{1+\gamma(1-e^{\frac{1}{\gamma}-g_t})}{\gamma+1}\cdot 2\nu_j e^{-g_t-2\nu_j} \stackrel{\text{def}}{=} h(\nu_j), \quad (2)$$

where $h(\nu_j)$ is the PDR as a function of ν_j, offered traffic per frequency on SF j, $g_t = \frac{Nq_j}{Pg(d)}$ is the maximum thermal noise gain that allows successful reception, and $\gamma = 1$dB is the difference in received power necessary to capture one of two overlapping transmissions for a given SF [23]. Under the established condition $\mathbb{P}_H \geq 0.98$, from Equation (1) we can set $g_t = -\log(\mathbb{P}_H)$ for every SF.

By inverting Equation (2) we obtain the maximum frequency offered traffic ν for a SF to respect the desired PDR

$$h^{-1}(PDR) = -\frac{1}{2}\cdot\mathcal{W}(-\frac{\xi}{e^{\xi}}\cdot e^{g_t}\cdot PDR) - \frac{\xi}{2} = \nu_j, \quad (3)$$

where $\mathcal{W}$ is the Lambert function and

$$\xi = \frac{\gamma+1}{1+\gamma(1-e^{\frac{1}{\gamma}-g_t})}. \quad (4)$$

The offered traffic of a single ED is usually considered to be $\delta = 0.01$ because, with duty-cycle limitations, they cannot transmit for more than 1% of time and thus their arrival rate λ will always be $\frac{\delta}{\tau}$. The problem with this approach is that in real LoRaWAN scenarios EDs usually transmit much less than a δ fraction of time. Thus, supposing to know a priori the bit rate β in bit/s of an ED, we can obtain a better estimate of the offered traffic with

$$\delta = \frac{p}{dr_{SF}}\lambda = \frac{\beta}{dr_{SF}}, \quad (5)$$

where p is the packet length in bit and dr_{SF} is the data-rate in bit/s of the SF used by the ED.

We use the above estimate for allocating resources in the proposed technique, which constrains traffic on each SF so that the total offered traffic is less than $h^{-1}(PDR)$ times the number of frequencies assigned.

B. Traffic Control Schemes

We consider two alternative techniques to constrain traffic: the first one consists of limiting the population of active EDs, and the second one of uniformly lowering the duty-cycle.

1) Access Control: Assuming that a group of EDs can transmit on m frequencies with a desired PDR value, we can formulate the following problem to maximize the global amount of traffic under the PDR constraint: for all SFs $j = 7, \ldots, 12$,

$$\max \sum_{i=1}^{N^j} d_i^j \delta_i^j, \quad (6)$$

$$\sum_{i=1}^{N^j} d_i^j \delta_i^j \leq m \cdot h^{-1}(PDR), \quad (7)$$

$$d_i^j \in \{0,1\}, \qquad i = 1, \ldots, N^j, \quad (8)$$

where N^j is the number of EDs using SF j, δ_i^j is the duty-cycle of ED i using SF j, and d_i^j is a binary variable that indicates whether a ED is enabled to transmit.

2) Duty-Cycle Control: Alternatively, we consider a solution exploiting the LoRaWAN primitives to constrain the duty-cycle of EDs. The parameter `MaxDutyCycle` $= [0:15]$ sets the maximum duty-cycle to $\delta = 1/2^{\texttt{MaxDutyCycle}}$. In the EU 863-870MHz band, only values between 7 and 15 are useful because they yield $\delta < 1\%$, from 0.0078 to $3.05 \cdot 10^{-5}$.

We lower the maximum duty-cycle of all EDs using SF j to the same value δ^j as follows: for all $j = 7, \ldots, 12$,

$$\delta^j = \max\left\{\delta \in \overline{\delta} : \delta \leq \min\left\{\delta^j_{\text{max}}, \frac{m \cdot h^{-1}(PDR)}{N^j}\right\}\right\}, \quad (9)$$

where $\overline{\delta} = \left\{\delta^j_{\text{max}}, \frac{1}{2^7}, \ldots, \frac{1}{2^{15}}\right\}$ and δ^j_{max} is the maximum offered traffic value among the EDs using SF j. The latter is introduced as an upper bound indicating no duty-cycle limitation.

C. Performance Metrics

1) Device Utility: To understand the satisfaction of EDs with a resource allocation we model their utility. The utility of a ED is the ratio of the amount of radio resources received to the expected amount of resources, which depends on the PDR specified in the Service Level Agreements (SLAs) and the ED maximum offered traffic δ.

Maximum utility of a ED is achieved when the actual PDR^* of the ED is equal or greater than the PDR requirement of its cluster. Otherwise, we model utility as the ratio of radio resources used at PDR^* to the resources needed for PDR. The exponential decrease of resource needs at low PDRs introduces a strong penalty for not complying with SLA when compared, for instance, with modeling utility as the direct ratio of PDR^* to PDR. Also, under duty-cycle control described in the previous section, some EDs have lower offered traffic δ^* than the one they expected, δ, and consequently use less resources.

Radio resources are estimated with the capacity model $h^{-1}(\cdot)$ and expressed in terms of bandwidth. There is no direct way of obtaining the bandwidth occupied by a single ED because in LoRaWAN multiple EDs concurrently transmit on the same bandwidth with different traffic patterns. We derive the fraction of bandwidth b traceable to each ED from the proportion of ED offered traffic to maximum carried traffic on a same-PDR bandwidth:

$$b = \frac{\delta}{J \cdot h^{-1}(PDR)} \cdot B, \tag{10}$$

where δ is the ED offered traffic, and $J \cdot h^{-1}(PDR)$ is the maximum carried traffic on a frequency channel of bandwidth $B = 125$kHz. This is obtained by considering $J = 6$ SFs, each contributing $h^{-1}(PDR)$ to the channel capacity. From Formula 10 we obtain b, the bandwidth of the ED according to desired PDR and desired offered traffic δ, and b^*, computed from the achieved PDR^* and offered load δ^*.

We can thus define ED utility u in terms of bandwidth requirement satisfaction,

$$u = \frac{\min\{b^*, b\}}{b}, \tag{11}$$

where again $\min\{b^*, b\}$ is the amount of bandwidth directly contributing to requirement satisfaction (the above ratio is equal to 100 % if $b^* \geq b$).

2) Total Operator Gain: To evaluate the impact of resource allocations on the operator, we define a metric to measure the gain he receives from the network. Assuming that the operator is fairly charging users according to their resource demand and satisfaction, we define the total gain as the sum of $u \cdot b = \min\{b^*, b\}$ over all EDs in the network. This is the amount of well-assigned bandwidth, directly contributing to the satisfaction of requirements. Thus, it corresponds to the resources that the users are charged for by the operator. Then we divide it by the total bandwidth used by the network (B times the number of frequency channels) to obtain a metric for resource allocation efficiency directly related to the operator gain.

With the PDR estimation (2) and the presented traffic control policies, our proposal consists of allocating frequencies to clusters. Different policies can be adopted to achieve this task as described in the next section.

IV. Frequency allocation policies

Our proposal aims at differentiating the PDR of EDs depending the cluster they belong to. Differentiation is achieved by assigning disjoint sets of frequencies to EDs according to clusters present around a gateway. We group EDs according to the gateway measuring the best radio conditions (SNR) of its transmissions, and we define the frequency allocation problem for the group of EDs around to a gateway.

We grant a minimum level of service by assigning at least one frequency to each cluster. Formally,

$$\sum_{k=1}^{K} m_k = F \tag{12}$$

$$m_k \geq 1,\, m_k \in \mathbb{N}, \quad k = 1, \ldots, K, \tag{13}$$

where K is the number of clusters, F the total number of frequencies, and m_k represents the number of frequencies assigned to cluster k.

We quantify the resource demand of clusters through the parameters w_k for $k = 1, \ldots, K$ defined by

$$w_k = \max_{j \in \{7,\ldots,12\}} \left\{ \frac{\sum_{i=1}^{N_k^j} \delta_{k,i}^j}{h^{-1}(PDR_k)} \right\}, \tag{14}$$

where N_k^j is the number of EDs using SF j in cluster k and $\delta_{k,i}^j$ is the duty cycle of ED i using SF j in cluster k. For the resources to be enough independently of the SF, we select the maximum frequency requirement among the SFs $j = 7, \ldots, 12$ in a cluster. We obtain the estimated frequency requirement by dividing the total offered traffic on the SF by $h^{-1}(PDR_k)$, the SF estimated capacity on a single frequency. For each cluster k, PDR_k is the required PDR level.

In the following, we introduce three different frequency allocation policies: (i) giving priority to clusters with strict requirements, (ii) doing a proportional-fair allocation with right to resource demands of clusters, and (iii) maximizing the amount of network traffic. It is worth noting that it is possible to host sufficiently more EDs at lower PDR to result in higher global traffic [16]. Intuitively, such techniques can be placed on a concave fairness curve going from being biased towards high PDR demands to favouring low resource consuming EDs.

A. Priority to High Requirements

After reserving one frequency channel per cluster, we assign the remaining frequencies starting from the cluster demanding highest PDR. We select the minimum number of frequencies in order to fully satisfy the capacity demands of the considered cluster $k = 1, \ldots, K$ as

$$m_k = \min \begin{cases} \lceil w_k \rceil, \\ F - \sum_{k' < k} m_{k'} - (K - k), \end{cases} \tag{15}$$

where clusters are ordered by descending PDR.

Equation (15) also recursively ensures that conditions (12) and (13) are respected. Finally, we maximize traffic in each cluster by using the policies of Sections III-B1 and III-B2.

B. Proportional-fair Allocation

We adapt the optimization problem for proportional fairness described in [24]. In our case, we assume that clusters are charged proportionally to the expected resource consumption to serve all EDs. The optimization problem becomes:

$$\max \sum_{k=1}^{K} w_k \cdot \log m_k \tag{16}$$

$$\sum_{k=1}^{K} m_k = F \tag{17}$$

$$m_k \geq 1,\, m_k \in \mathbb{N}, \qquad k = 1, \ldots, K. \tag{18}$$

This problem presents a non-linear objective that is usually solved with heuristic algorithms. In our case, however, the solution space size $\binom{F-1}{K-1}$, being a K-composition of F elements, is fairly small due to the limited number of frequencies (rarely $F \geq 8$, with a maximum of 18 channels fitting in the EU 863-870MHz band at 1% duty-cycle [18]). Therefore, we can always tackle the problem directly in reasonable time (i.e., $O(2^F/\sqrt{F})$ iterations using Stirling's approximation of the factorial to bound binomial coefficients [25]). After determining m_k, $k = 1, \ldots, K$, we can optimize traffic as detailed in Sections III-B1 and III-B2.

C. Network Traffic Maximization

In this policy, we set the optimization objective to maximize the amount of network traffic, considering the effect of expected PDR on traffic. Therefore, we integrate the traffic optimization in the problem. It follows from Section III-B1, detailing access control,

$$\max \sum_{k=1}^{K} \left(PDR_k \sum_{j=7}^{12} \left(dr_j \sum_{i=1}^{N_k^j} d_{k,i}^j \delta_{k,i}^j \right) \right) \tag{19}$$

$$\sum_{i=1}^{N_k^j} d_{k,i}^j \delta_{k,i}^j \leq m_k \cdot h^{-1}(PDR_k), \begin{cases} j = 7, \ldots, 12, \\ k = 1, \ldots, K, \end{cases} \tag{20}$$

$$\sum_{k=1}^{K} m_k = F, \tag{21}$$

$$m_k \geq 1,\, m_k \in \mathbb{N}, \qquad k = 1, \ldots, K, \tag{22}$$

$$d_{k,i}^j \in \{0, 1\}, \qquad \text{for} \qquad \begin{cases} j = 7, \ldots, 12, \\ k = 1, \ldots, K, \\ i = 1, \ldots, N_k^j. \end{cases} \tag{23}$$

To obtain the total bit-rate on each SF, the cumulative offered traffic is multiplied by dr_j, the fixed data-rate of SF j.

When considering duty-cycle control (Section III-B2), the problem can be rewritten as

$$\max \sum_{k=1}^{K} \left(PDR_k \cdot \sum_{j=7}^{12} \left(dr_j \cdot N_k^j \cdot \sum_{l=0}^{9} x_{k,l}^j \overline{\delta}_l \right) \right), \tag{24}$$

$$\sum_{l=0}^{9} x_{k,l}^j \overline{\delta}_l \leq \min \left\{ \delta_{k,\max}^j, \frac{h^{-1}(PDR_k)}{N_k^j} \cdot m_k \right\}, \quad k = 1, \ldots, K,\ j = 7, \ldots, 12, \tag{25}$$

$$\sum_{l=0}^{9} x_{k,l}^j = 1, \qquad k = 1, \ldots, K,\ j = 7, \ldots, 12, \tag{26}$$

$$\sum_{k=1}^{K} m_k = F, \tag{27}$$

$$m_k \geq 1,\, m_k \in \mathbb{N}, \qquad k = 1, \ldots, K, \tag{28}$$

$$x_{k,l}^j \in \{0, 1\}, \qquad \begin{cases} j = 7, \ldots, 12, \\ k = 1, \ldots, K, \\ l = 0, \ldots, 9, \end{cases} \tag{29}$$

where $x_{k,l}^j$ are binary variables used to indicate whether a duty-cycle setting l is used on SF j of cluster k.

V. Numerical Results

For evaluation purposes, we developed a lightweight simulator for the LoRa uplink traffic physical layer in the Ns-3 simulation environment[1]. Interference computations follow the state of the art model from [15]. Path loss follows the Okumura-Hata model for large urban environments with Rayleigh fading. Solutions to integer programming problems are obtained using the CBC solver in the OR-Tools suite[2].

A. Simulation Setup

Seven gateways are placed using hexagonal tiling as illustrated in Figure 1, where circle radius is 2.5 km. This results in a total area of 128 km^2, used to obtain densities in the following sections. Devices are uniformly placed in range of gateways, and they transmit with a periodical traffic pattern, interfering with other EDs in the same and other cells. Inter-transmission time and payload of each ED are extracted from a truncated Gaussian random variable with mean 600s and variance 300s, and with mean 31B (13B for headers) and variance 10B, respectively [20]. The EDs transmission parameters are given in Table I.

Packet transmission time is computed following the SX1272/3/6/7/8 LoRa Modem Design Guide [26]. Gateways are modeled on Semtech's SX1301 chips for LoRaWAN outdoor macro-gateways and therefore have 8 parallel reception paths. Sensitivity levels of gateways to SFs are detailed in Table II. In interference calculations, we adopt the empirical Signal-to-Interference thresholds matrix in Table III. SFs and TP are configured with ADR [5], the scheme currently implemented in most LoRaWAN deployments. We simulate the network

[1] https://www.nsnam.org

[2] https://developers.google.com/optimization

TABLE I
END DEVICES TRANSMISSION PARAMETERS [2], [18], [21].

Parameter	Value(s)
Antenna ERP power (dBm)	14, 12, 10, 8, 6, 4, 2, 0
Frequency (MHz)	868.1, 868.3, 868.5, 867.1, 867.3, 867.5, 867.7, 867.9
Spreading Factor	7-12
Bandwidth (kHz)	125
Coding rate	4/5
Preamble length	8
Explicit header	Disabled
CRC	Enabled
Low data rate optimization	Enabled (SF_{11}/SF_{12})

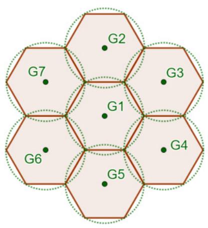


Fig. 1. Placement of gateways and devices in simulations.

TABLE II
SENSITIVITY LEVELS (dBm) REQUIRED FOR CORRECT PACKET RECEPTION ON THE DIFFERENT SFs [22]

SF_7	SF_8	SF_9
-126.5	-129.0	-131.5

SF_{10}	SF_{11}	SF_{12}
-134.0	-136.5	-139.5

TABLE III
SIGNAL TO INTERFERENCE RATIO (SIR) THRESHOLDS (dB) OF REFERENCE SFs (ROWS) AGAINST INTERFERENCE COMING FROM OTHER SFs [23]

	SF_7	SF_8	SF_9	SF_{10}	SF_{11}	SF_{12}
SF_7	1	−8	−9	−9	−9	−9
SF_8	−11	1	−11	−12	−13	−13
SF_9	−15	−13	1	−13	−14	−15
SF_{10}	−19	−18	−17	1	−17	−18
SF_{11}	−22	−22	−21	−20	1	−20
SF_{12}	−25	−25	−25	−24	−23	1

running for 10 hours and we replicate simulations 30 times to be able to draw figures with 95% confidence intervals.

We use three clusters with the PDR requirements at 97%, 90% and 70%, as motivated in Section II-C. Devices assignment to clusters at 10%, 30% and 60%, respectively, follows the one proposed in [8].

B. Result Analysis

To measure the effectiveness of our proposal, we ran simulations of the Access Control (AC) and Duty Cycle Control (DCC) policies of Section III in combination with the proposed Priority, Proportional-fair, and Traffic Maximization frequency allocation policies detailed in Section IV. For bench-marking our solution, we implement the Adaptive Dynamic Slicing (ADS) frequency allocation proposed in [8], which does not limit traffic. Results in [9], [13] show that ADS is comparable to other propositions in terms of PDR optimization. As a baseline, we plot ADR with EDs using all frequencies.

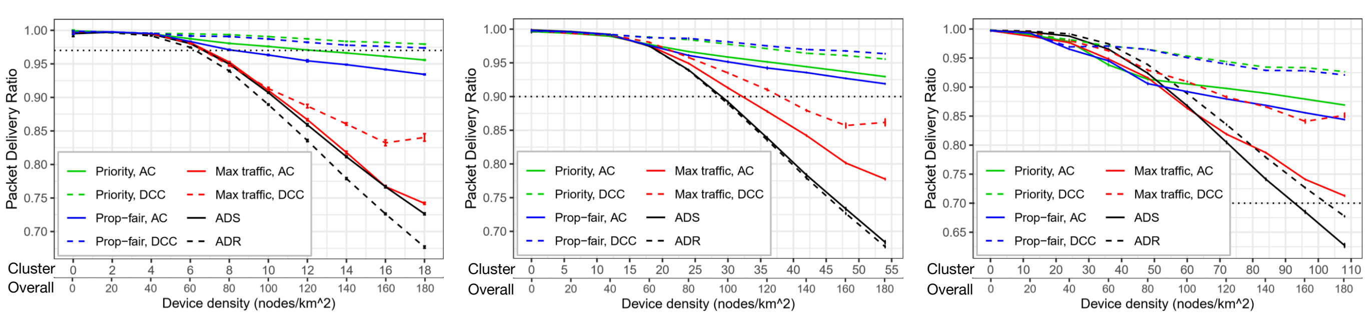
Multiple scenarios are tested, as we progressively increase the density of EDs (nodes) in the network range. As we are interested in the scalability under very heavy loads, we simulate up to 180 nodes/km^2, doubling the highest density studied in [16] for similar cell size. In the following sections, metrics refer to traffic over all 7 gateways, occasionally shown per cluster in the same simulation.

1) Packet Delivery Ratio: The PDR of the three clusters is shown in Figure 2 with their respective PDR target highlighted. The density range of each cluster reflects the percentage of input EDs assigned to them.

Densities above 60 nodes/km^2 are critical for the network: a difference in the performance of the various policies begins to appear at high densities. Priority and Proportional-fair allocations are actively able to prevent from quality degradation due to interference and limited reception paths, with the exception of the 97% PDR cluster, for which only with duty-cycle control they are able to satisfy the requirement at all densities. As expected, duty-cycle control is more conservative than access control because it lowers traffic in steps defined by the protocol primitive.

With ADR and ADS, the PDR quickly falls down to values lower than 70% at maximum density. The results of ADS show that frequency allocation alone is not enough. Allocating frequencies with Traffic Maximization yields similar results to ADR and ADS in requirement satisfaction. We conclude that traffic control is necessary, but not sufficient to mitigate traffic quality degradation.

To understand why Traffic Maximization is more similar to configurations without traffic limitation, we compare causes for packet loss. As shown in Table IV, under heavy traffic conditions the limited number of reception paths in gateways creates a bottleneck. Higher traffic is obtained with lower PDR constraints [16], so they are favoured by Traffic Maximization.

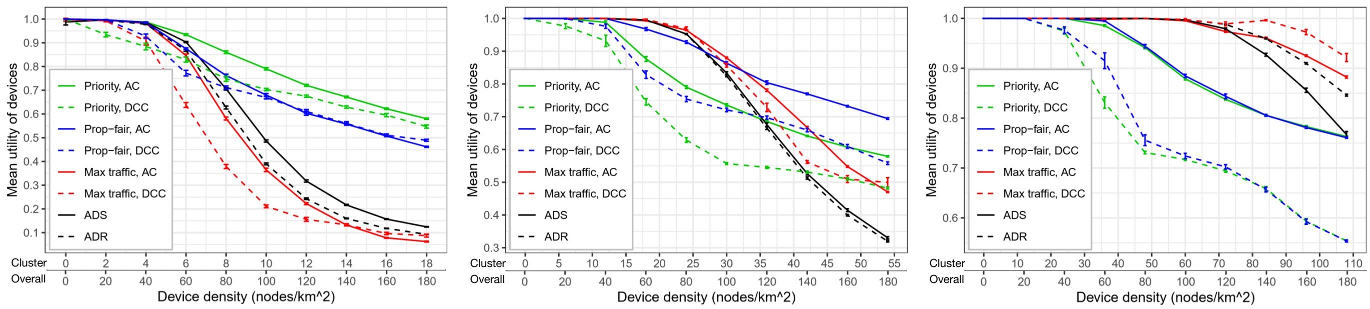


(a) 97% PDR cluster.

(b) 90% PDR cluster.

(c) 70% PDR cluster.

Fig. 2. Packet delivery ratio comparison, per cluster in the same simulation. Horizontal dotted black lines denote the required PDR level.



(a) 97% PDR cluster.

(b) 90% PDR cluster.

(c) 70% PDR cluster.

Fig. 3. Mean utility of EDs, per cluster in the same simulation.

Increase of traffic in the 70% cluster for Traffic Maximization impacts the other clusters by occupying reception paths. Current implementation of LoRaWAN gateways do not allow more than 8 parallel reception paths, limiting the scalability of the technology in dense scenarios. The impact of limited reception paths is mitigated by Proportional-fair and Priority allocations.

TABLE IV
PERCENTAGE OF LOST FRAMES IN Prop-fair, AC, Max traffic, AC, AND ADR. LOSS IS CAUSED BY INTERFERENCE (I), NO AVAILABLE RECEPTION PATHS IN A CONGESTED GATEWAY (C), AND UNDER SENSITIVITY (U) DUE TO FADING. OFFERED TRAFFIC (OT) (IN ERLANG) IS INCLUDED.

Scenario		60 n/km^2	120 n/km^2	180 n/km^2
Prop-fair, AC	I	3.39%	5.10%	6.21%
	C	1.16%	3.63%	5.79%
	U	0.21%	0.25%	0.27%
	OT	7.01	9.66	11.27
Max traffic, AC	I	2.13%	5.18%	7.04%
	C	1.42%	10.07%	18.81%
	U	0.22%	0.23%	0.23%
	OT	7.34	13.57	18.58
ADR	I	0.77%	3.44%	6.97%
	C	1.55%	12.41%	24.94%
	U	0.21%	0.22%	0.21%
	OT	7.51	14.96	22.60

2) Device Utility and Fairness: Mean EDs utility is illustrated in Figure 3. As expected, Priority allocations favor the high PDR cluster while Traffic Maximization favors low requirements with similar results to ADR and ADS. Globally, Proportional-fair allocation with access control is the most balanced and is able to bring higher utility to the 97% and 90% PDR clusters than techniques without traffic control. Duty-cycle control falls behind access control; this was expected because duty-cycle control is more conservative as discussed in the PDR results section. Interestingly, with Traffic Maximization it yields the best results for low PDR requirements; this is due to the more relaxed offered traffic constraints of the cluster.

Globally speaking, Figure 3 illustrates the distortion introduced by quality differentiation in terms of utility (or satisfaction for EDs). Traffic control and frequency allocation policies can preserve a rather high utility for the higher PDR clusters while the lower PDR cluster is more penalized. The ADR and ADS schemes, which cannot meet the requirements of the high PDR clusters, have the inverse impact. Thus, the price to pay to offer differentiated quality is to penalize a significant fraction of EDs in order to satisfy the fraction of most demanding EDs. This is viable only if the network can benefit of quality differentiation; this point is discussed in the next section. It is worth noting that the fraction of excluded EDs with access control can take significant values (Figure 4).

To better understand how balanced is the utility value between EDs, we evaluate the Jain's Fairness Index of the utility for active EDs. Results are displayed in Figure 5. According to this metric, access control is reasonably fair.

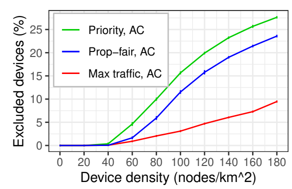


Fig. 4. Percentage of excluded EDs with Access Control (AC).

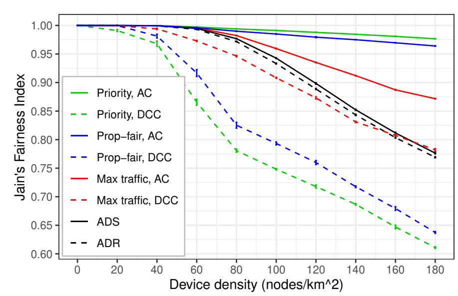


Fig. 5. Jain's fairness index $\frac{(\sum_{i=1}^{N} u_i)^2}{N \cdot \sum_{i=1}^{N} u_i^2}$ of the utility for active EDs.

3) Traffic Quality Differentiation Cost: We evaluate the impact of quality differentiation on the operator by showing the resource allocation efficiency metric defined in Section III-C. This metric, shown in Figure 6, is directly related to how much the operator is charging users (resources and requirements satisfaction) and thus it is an indicator of operator gains that can be expected. We see that access control is able to maintain considerable gains that exceed ADR and ADS at higher density. This is the result of the trade-off of serving EDs with better traffic quality, with Proportional-fair being the best allocation.

We can conclude that with quality differentiation the operator uses resources less efficiently and thus needs to charge a

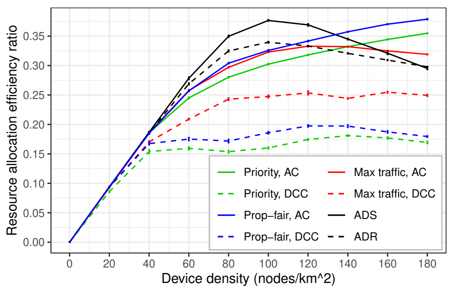


Fig. 6. Share of resources (bandwidth) contributing to satisfaction of requirements. If the operator charges users according to demands satisfaction, higher values indicate higher gain for the operator.

premium to high requirement EDs. Furthermore, network throughput (Figure 7) does not suffer significant degradation with access control. Energy considerations are outside of the scope of this work but can be expected to be on par with the results in [11] for ADR (therein called DA).

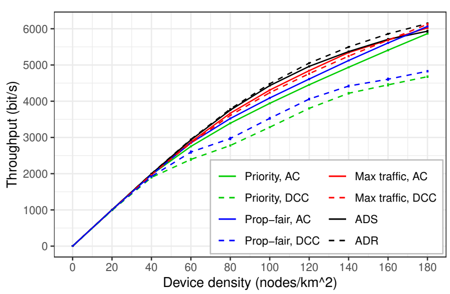


Fig. 7. Total network throughput.

VI. Conclusion

To achieve quality differentiation in dense urban LoRaWANs, we introduced various traffic control and frequency allocation policies for devices in clusters defined in terms of target PDR. It turns out that some policies can meet PDR requirements, even with high levels of PDR (97%) and high network densities, proving the importance of traffic control. In this respect, the proposed policies perform much better (in terms of PDR and utility) than allocations introduced earlier in the technical literature without traffic control. Access control joint with proportional-fair allocation yields the best results overall.

The counterpart of introducing differentiated quality is that the utility (or satisfaction) of devices is worse for low PDR clusters than that offered by existing approaches. Yet, we find that favouring low PDR requirements is not ideal as it causes a bottleneck in the whole system. Finally, the usage of resources of the network can be lower with quality differentiation except in the case of very high device densities. This can be compensated by the network only via ad-hoc pricing. This last point can raise attractiveness issues for potential customers.

Acknowledgment

This work was conducted within the framework of the French ANR-funded INTELLIGENTSIA project (grant nb: ANR-20-CE25-0011).

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