

The Impact of CSMA on LoRaWAN Communication Efficiency: A Diffusion Approximation Model

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Abstract—This paper investigates the impact of Carrier Sense Multiple Access (CSMA) on the communication efficiency of LoRaWAN systems using a queueing-theoretic diffusion approximation model. The original ALOHA-based access mechanism allows only one attempt to access a free channel; CSMA allows multiple attempts. We are investigating the effect of the number of attempts on reducing collisions and improving transmission reliability. The system is modeled as a $G(n)/G/N/N$ loss queue with state-dependent admission even though free service capacity may exist, where N represents the maximum number of simultaneous transmissions. Since no exact analytical solution exists for this model, a diffusion approximation is adopted. The proposed approach enables the analysis of transient system behavior and supports general interarrival and service-time distributions. The model parameters are adapted to represent the CSMA access procedure and allow quantitative evaluation of throughput, channel occupancy, and transmission reliability under different traffic intensities and retry limits.

Index Terms—Diffusion approximation, queueing models, LPWAN, LoRa, CSMA, transmission reliability

I. INTRODUCTION

LoRa (Long Range) and its protocol layer LoRaWAN [1] are widely adopted LPWAN (LoW Power Wide Area Network) standards for various IoT applications [2]–[4] offering long-range (up to several tens of kilometers) connectivity at the cost of low data rates (up to several tens of kbps) compared to short-range technologies such as Zigbee or Bluetooth. It is designed to wirelessly connect battery-powered devices while addressing key IoT requirements. LoRaWAN is a prominent,

widely used LPWAN technology that is increasingly gaining popularity [5] due to its versatility in various IoT applications, e.g., telemetry, logistics, and smart cities [2]–[4]. Operating in ISM bands, LoRa employs a robust modulation scheme that is resilient to interference; however, simultaneous transmissions often lead to collisions, resulting in packet loss [6].

In telecommunication systems, collision avoidance is essential for reliability and network efficiency. While LoRaWAN originally employed ALOHA (where devices transmit without checking channel availability) as its MAC protocol, the LoRa Alliance introduced CSMA for LoRaWAN [7], allowing multiple attempts to access a free channel with the aim of improving collision avoidance. The LoRaWAN protocol operates over frequency channels specified for different regions, e.g., EU (EU868MHz) [8], based on a standardized plan that ensures compliance with regional requirements and allocated frequency bands. According to it, the network operator can freely assign the network channels; however, the implementation of the three default channels is obligatory in every EU868MHz end-device. Those channels are the minimum set that all network gateways should always monitor. The total number of channels available is relatively limited - e.g., 8 in most countries in Europe. Thus, in this paper, we consider the eight-channel model for investigating CSMA in the LoRaWAN protocol. The CSMA procedure begins with a device performing channel checks, which are determined by a random backoff counter (NumbBackoff) and the interval T_{BO} . If the channel stays clear, the device transmits; otherwise, it switches to a new channel and repeats the process several times, the maximum number of attempts is defined by the protocol but it cannot exceed the number of channels. After repeated failures, the device reverts to ALOHA. Each device executes this independently, introducing a random pre-transmission delay

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T , whose distribution will be analyzed in the next sections.

The objective of this paper is to introduce an analytical model based on diffusion approximation to evaluate how the CSMA protocol affects the probability of successful transmission in LoRaWAN. We introduce the adaptation of $G(N)/G/N/N$ model to the gateway model. Our study analyzes channel occupancy to estimate the likelihood of accessing a free channel in both single trials and in a series of trials, also considering mixed device populations that use either CSMA or ALOHA protocols.

The rest of this paper is organized as follows: In Section II, we present the state-of-the-art. In Sections III and IV, we introduce a $G(N)/G/N/N$ diffusion model, and its adaptation to the gateway model, respectively. The latter section also presents a few numerical results. Finally, we conclude the paper in Section V.

II. RELATED WORK

In recent years, several studies have been conducted on adapting CSMA for use in the LoRaWAN protocol [9]–[12]. These studies examine the performance of various approaches to CSMA adoption in LoRaWAN that differ from each other in the case of carrier-sensing technique, as well as reaction to the idle or busy channels. These CSMA proposals have been evaluated experimentally or theoretically in comparison to pure ALOHA, the MAC protocol originally used in LoRaWAN.

Most existing studies evaluate CSMA adaptations for LoRaWAN using simulations [9], [13]–[15] or experiments using physical devices [10], [11], [16], [17]. Several studies have proposed theoretical models to evaluate the performance of LoRaWAN. The study in [18] applies Markovian analysis to evaluate the performance of Class B devices, while Georgiou et al. introduce a theoretical framework using stochastic geometry in [19] to determine the uplink outage probability in LoRaWAN. The studies [15], [20] propose mechanisms for carrier sensing in LoRaWAN and evaluate their performance. Markov chains are used to model the backoff, sensing, and transmission states of the end device.

However, research on the analytical modeling of the officially specified CSMA protocol for LoRaWAN [7] remains very limited, and to date, no analytical model has been developed for this recently released specification. The authors proposed, yet unpublished, a Markov model of LoRaWAN gateway using $M(n)/M/N/N$ queueing station [21], but the diffusion approximation used in this study allows us to capture more details. This method, e.g. [22], was applied in network performance studies, e.g. [23]–[25]. Previous studies demonstrate its versatility, as it has been used to model the ALOHA protocol [26], the IEEE 802.11 medium access [27], and multi-hop wireless networks with scheduling algorithms that ensure end-to-end delay guarantees [28]. These examples highlight that diffusion approximation can provide a powerful framework for analyzing diverse network protocols. Therefore, it appears to be a promising framework for developing analytical

tools for evaluating the efficiency of the CSMA protocol in LoRaWAN.

III. $G(N)/G/N/N$ DIFFUSION MODEL

Following Kendall's notation [29], the $G(n)/G/N/N$ station is a service system with interarrival and service-times generally distributed; the number of parallel servers is N , the maximum number of customers is also N (no queueing). We assume that the population of customers is infinite because the number of devices communicating with the gate is large. The interarrival time distribution depends on the number of customers in service.

The model extends the single-server $G/G/1/N$ model [30] and its modifications, which have been investigated, e.g., in [31], [32]. Diffusion approximation uses the analogy between the random process $N(t)$, which is the number of tasks at the service station, and the real-valued diffusion process $\{X(t)\} \in [0, N]$.

The incremental changes of $\{X(t)\}$, $dX(t) = X(t+dt) - X(t)$ are normally distributed with the mean βdt and variance αdt where β, α are coefficients of the diffusion equation. The increments of the process $\{N(t)\}$ during an interval θ tend to normal distribution with mean $(\lambda - \mu)\theta$ and variance $(\sigma_A^2 \lambda^3 + \sigma_B^2 \mu^3)\theta$ where $1/\lambda$ and $1/\mu$ are the mean interarrival and service-times, and σ_A^2, σ_B^2 are the variances of the interarrival and service-times, respectively. The choice

$$\beta = \lambda - \mu \quad \text{and} \quad \alpha = \sigma_A^2 \lambda^3 + \sigma_B^2 \mu^3 = C_A^2 \lambda + C_B^2 \mu$$

where C_A^2, C_B^2 are squared coefficients of variation of interarrival and service-times, ensures that the changes of both processes $\{X(t)\}$ and $\{N(t)\}$ have normal distributions with the same parameters.

At the ends $x = 0$ and $x = N$ of the diffusion interval, the absorbing barriers are placed, so that when $\{X(t)\}$ reaches a barrier, it stays there for a random time and jumps from $x = 0$ to $x = 1$ with intensity λ and from $x = N$ to $x = N - 1$ with intensity μ .

The resulting diffusion equations, including balance equations for probabilities of the process at barriers, are

$$\begin{aligned} \frac{\partial f(x, t; x_0)}{\partial t} &= \frac{\alpha}{2} \frac{\partial^2 f(x, t; x_0)}{\partial x^2} - \beta \frac{\partial f(x, t; x_0)}{\partial x} + \\ &\quad + \lambda p_0(t) \delta(x - 1) + \mu p_N(t) \delta(x - N + 1), \\ \frac{dp_0(t)}{dt} &= \lim_{x \rightarrow 0} \left[\frac{\alpha}{2} \frac{\partial f(x, t; x_0)}{\partial x} - \beta f(x, t; x_0) \right] - \lambda p_0(t), \\ \frac{dp_N(t)}{dt} &= \lim_{x \rightarrow N} \left[-\frac{\alpha}{2} \frac{\partial f(x, t; x_0)}{\partial x} + \beta f(x, t; x_0) \right] - \mu p_N(t), \end{aligned}$$

where $\delta(x)$ is the Dirac delta function, $p_0(t), p_N(t)$ are probabilities that the process is at the barriers at $x = 0$ or $x = N$, respectively, and $f(x, t; x_0)$ is probability density function (pdf) of the process $\{X(t)\}$

$$f(x, t; x_0) dx = P[x \leq X(t) < x + dx \mid X(0) = x_0],$$

which approximates the queue distribution, $p(n, t; n_0) \approx f(n, t; n_0)$.

In the $G/G/1/N$ model, the parameters α, β are state-independent, because the input and output processes do not

depend on the state of the queue. In the present model, the input process is influenced by losses, which depend on the number of occupied channels. Also, the output process depends on the number of busy channels.

We assume that in the interval $[n-1, n]$, $(n = 1 \dots N)$, n channels are busy, therefore

$$\begin{aligned}\beta(n) &= \lambda(n) - n\mu, \\ \alpha(n) &= \lambda(n)C_A^2(n) + n\mu C_B^2, \quad n = 1, \dots, N.\end{aligned}\quad (1)$$

The jumps from N to $N-1$ have intensity $N\mu$, as N channels are busy.

The equations are solved in N intervals, with the corresponding parameters, assuming absorbing barriers at their extremities. The interactions between processes in neighboring intervals are expressed by probabilities of crossing the boundary between two intervals.

The density $\phi_n(x, t; \psi_n)$ for the interval n with absorbing barriers at $n-1$ and n , and initial condition ψ_n , is known [33]

$$\phi_n(x, t; x_0) = \frac{e^{\frac{\beta_n}{\alpha_n}(x-x_0) - \frac{\beta_n^2}{2\alpha_n}t}}{\sqrt{2\pi\alpha_n t}} \left[e^{-\frac{(x-x_0)^2}{2\alpha_n t}} - e^{-\frac{(x+x_0)^2}{2\alpha_n t}} \right]. \quad (2)$$

and allows us to compute the density of entering either of the barriers using the densities of first passage times from any point in the interval to the barriers.

The density of the first passage time of a diffusion process that starts from the point $x = \xi$ given by a density function $\psi(\xi)$ and is absorbed at the barrier at $x = B$ is, [33]

$$\gamma_{\psi \rightarrow B}(t) = \int_0^B \frac{B - \xi}{\sqrt{2\pi\alpha t^3}} e^{-\frac{(B-\xi-\beta t)^2}{2\alpha t}} \psi(\xi) d\xi. \quad (3)$$

These densities reappearing on the other side of a barrier define the dynamics of the process in the neighboring interval. The flows generated by the process $f_n(\cdot)$ at interval n generates flows $g_{n-1-\varepsilon}(t)$ and $g_{n+\varepsilon}(t)$. The distance ε behind the barrier is added for numerical reasons.

The density functions $f_n(x, t; \psi_n)$, $n = 1, \dots, N$, for the intervals $x \in]n-1, n[$ are:

$$\begin{aligned}f_n(x, t; \psi_n) &= \phi_n(x, t; \psi_n) + \\ &+ \int_0^t g_{n-1+\varepsilon}(\tau) \phi_n(x, t-\tau; n-1+\varepsilon) d\tau \\ &+ \int_0^t g_{n-\varepsilon}(\tau) \phi_n(x, t-\tau; n-\varepsilon) d\tau,\end{aligned}\quad (4)$$

with slight modifications in the first and last interval: there are no flows appearing at points $x = 0 + \varepsilon$ and $x = N - \varepsilon$; the flow $\lambda p_0(t)$ is added to $g_{1+\varepsilon}(t)$ and the flow $N\mu p_N(t)$ to $g_{N-1-\varepsilon}(t)$.

The initial conditions at each interval result in

$$\phi_n(x, t; \psi_n) = \int_{n-1}^n f(x, t; \xi) \psi_n(\xi) d\xi. \quad (5)$$

The probability density functions, e.g. $g_{n-1+\varepsilon}(t)$, $g_{n-\varepsilon}(t)$ for the interval $[n-1, n]$ are the probability flows coming to

this interval from $[n-2, n-1]$ and $[n, n+1]$, absorbed at these intervals by barriers at $n-1$ and n ; e.g., the flow entering the barrier at $x = n$ from its left side is

$$\begin{aligned}\gamma_n^L(t) &= \gamma_{\psi_n, n}(t) + \int_0^t g_{n-1+\varepsilon}(\tau) \gamma_{n-1+\varepsilon, n}(t-\tau) d\tau + \\ &+ \int_0^t g_{n-\varepsilon}(\tau) \gamma_{n-\varepsilon, n}(t-\tau) d\tau,\end{aligned}$$

where γ_{ij} are due to Eq. (3),

In practice, the above system of equations is transformed into the Laplace domain and solved analytically. The results are then numerically inverted to the real domain, using Stehfest's algorithm [34]. In the steady state, this solution converges to simple formulas based on exponential functions.

IV. ADAPTATION OF THE $G(n)/G/N/N$ QUEUEING MODEL TO THE LoRaWAN GATEWAY MODEL AND NUMERICAL RESULTS

A. Admission of customers

In a standard queueing loss model, such as $G(n)/G/N/N$, an arriving customer is admitted whenever at least one service channel is available. Thus, if n out of N channels are occupied and $n < N$, the arriving customer enters service; blocking occurs only when $n = N$. The situation at a LoRaWAN gateway is different. Even when $n < N$, so that one or more channels are free, an arriving packet may fail to access a free channel and consequently be rejected.

Assume that n out of N channels are occupied. In ALOHA only one access attempt is allowed and the channel is selected uniformly at random, the probability of selecting an occupied channel, and hence of being rejected, is $r^1(n) = n/N$. In CSMA, up to a access attempts are allowed, where $a = 2, \dots, N$ is a parameter determined by the operator. The channel found to be occupied is not selected again in subsequent attempts.

The access procedure can therefore be compared to sampling without replacement from an urn containing n black balls, representing occupied channels, and $N - n$ white balls, representing free channels. Admission occurs if at least one white ball is drawn within at most a attempts. For example, if two attempts are allowed, the probability that both selected channels are occupied, and hence that the packet is rejected, is, for $n \geq 2$,

$$r^2(n) = \frac{n}{N} \frac{n-1}{N-1}.$$

More generally, for a allowed attempts,

$$r^a(n) = \prod_{j=0}^{a-1} \frac{n-j}{N-j}, \quad n \geq a,$$

whereas $r^a(n) = 0$ for $n < a$ because if fewer than a channels are occupied, a free channel must necessarily be found within a distinct attempts.

Hence, the probability that an arriving packet is admitted when n channels are occupied is $z^a(n) = 1 - r^a(n)$. If the

external arrival rate is λ , the effective admitted arrival rate in state n is therefore $\lambda^a(n) = \lambda z^a(n) = \lambda[1 - r^a(n)]$.

However, if the input flow is not Poisson, removing some customers changes the variance of the interarrival times. The density $f_A^n(x)$ of the times between accepted calls may be expressed as

$$f_A^n(x) = f_A(x)z^a(n) + f_A(x) * f_A(x)(1 - z^a(n))z^a(n) + \dots$$

The Laplace transform of this series is

$$\bar{f}_A^n(s) = \bar{f}_A(s)z^a(n) + f_A(s)^2(1 - z^a(n))z^a(n) + \dots = \frac{\bar{f}_A(s)}{(1 - z^a(n))\bar{f}_A(s)} \quad (6)$$

$$= \frac{\bar{f}_A(s)}{(1 - z^a(n))\bar{f}_A(s)} \quad (7)$$

and the expression $\frac{d^2 \bar{f}_A^n(s)}{ds^2}$ at $s = 0$ yields the second moment of this distribution For each a giving

$$C_A^2(n) = z^a(n)(C_A^2 - 1) + 1. \quad (8)$$

A different distribution $p^a(n, t)$ is obtained for each a , as well as a different effective flow and efficiency factor $\eta(t)$

$$\lambda_{eff}^a(t) = \sum_{n=1}^N p^a(n, t)\lambda(t)z^a(n), \quad \eta(t) = \frac{\lambda_{eff}^a(t)}{\lambda(t)}. \quad (9)$$

B. Additional variation of interarrival times

Additional variation of effective interarrival times is due to the time T needed to find an unoccupied channel. It is a product of two independent variables: X , the time spent multiple-sensing the channel during one trial, and Y , the number of trials.

X is composed of the phase DIFS (two CAD slots) to assess a clear channel and one to six (with equal probability) CAD (Channel Activity Detection) slots. This time depends on SF and transmission channel width, as defined in [35], eg, for SF=12 and a 125 kHz channel, it is 16.5 ms. In this case $E[X] = 82.510^{-3}$ s and $\sigma_X^2 = 51.210^{-6}$ s².

Y depends on the number of occupied channels, which in turn depends on the traffic intensity. Given the distribution $p^a(n)$, we may determine the unconditional probability r_i^a of rejection at a trial $i \leq a$ and the distribution of the number of trials. At each trial i , the distribution of the number of channels and of the number of occupied channels $p_i^a(n)$ is different. At the first trial the distribution is $p_1^a(n) = p^a(n)$, $n = 1 \dots N$. An occupied channel is chosen and removed from the list with probability.

$$r_1^a = \sum_{j=1}^N r^a(j)p_1^a(j). \quad (10)$$

In the second trial, there are $N - 1$ channels, and $n - 1$ occupied ones: the new distribution of the number of occupied channels:

$$p_2^a(n) = \frac{p_1^a(n+1)}{1 - p_1^a(0)}.$$

λ	2.5	5	10	15	20	40
$E[T]$ [s]	0.0825	0.0836	0.1041	0.1381	0.1728	0.2790
$\text{Var}[T]$	0.0001	0.0011	0.0240	0.0726	0.1321	0.3339
C_T^2	0.0086	0.1620	2.2144	3.8060	4.4257	4.2890

TABLE I
MEAN AND VARIANCE OF THE DISTRIBUTION OF T , TIME OF A SINGLE TEST, $SF = 12$, VARIOUS TRAFFIC λ , MEAN[S], VAR [s²]

The probability of failure at the second trial is

$$r_2^a = \sum_{j=1}^{N-1} r^a(j)p_2^a(j). \quad (11)$$

In this way, we determine all probabilities r_i^a of failures at trial i if a trials are permitted, the probability of success at exactly the i -th trial, and the distribution of the number of trials

$$p_Y^a(i) = (1 - r_i^a) \prod_{j=1}^{i-1} r_j^a \quad i = 1, \dots, a-1,$$

$$p_Y^a(a) = 1 - \sum_{i=1}^{a-1} p_Y^a(i), \quad (12)$$

giving us the distribution of T , cf. Table I. If we compare the computed variance of T with the variance of interarrival times measured in a network we studied (composed of approximately 6,500 water meters and transmitting their measurements via 16 gateways, Table II), the computed variance of T is insignificant.

C. Distribution of service times

Following our measurements, transmitted packets are of two fixed sizes: short packets of 10 Bytes (10 % of the flow) and long packets of 52 Bytes (90 % of the flow). The corresponding mean service times are $1/\mu_1 = 1.48s$ and $1/\mu_2 = 2.79s$. The overall mean service time is $1/\mu = 2.659s$ and $\text{var}[B] = 0.15445$ with $C_B^2 = 0.02$. Service times are not exponentially distributed, and the use of the diffusion approximation is justified.

Gateway	$E[A] = 1/\lambda$	$\text{var}[A]$	C_A^2	Count	No. of clients
GW1	16.65	276.2	1	124 822	2288
GW2	15.52	239.6	1	138 352	2053
GW3	10.96	136.9	1.14	199 370	3125

TABLE II
INTERARRIVAL TIMES STATISTICS FOR THREE GATEWAYS, BASED ON DATA COLLECTED FROM REAL-LIFE IoT, MEAN[S], VAR [s²]

D. Two classes of packets

Suppose that two kinds of packets enter the channel; they may have different parameters of input flow and service time, and different number of trials a_1, a_2 . If $a_1 = 1$ and $a_2 > 1$, we may regard them as ALOHA and CSMA packets. The model is capable of handling this case.

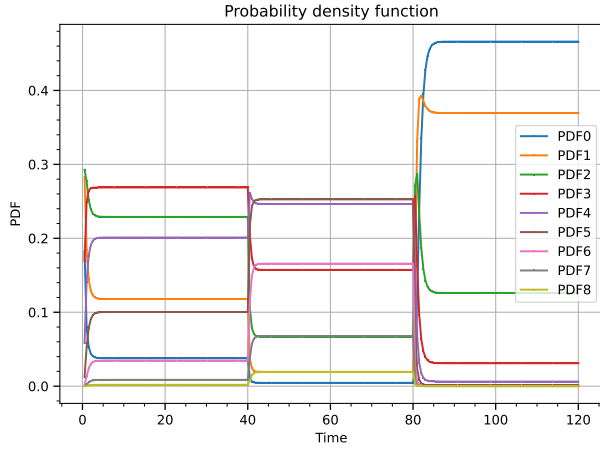


Fig. 1. $p(n, t; 0)$, $n = 0, \dots, 8$, changes of $\lambda(t)$ as in the text

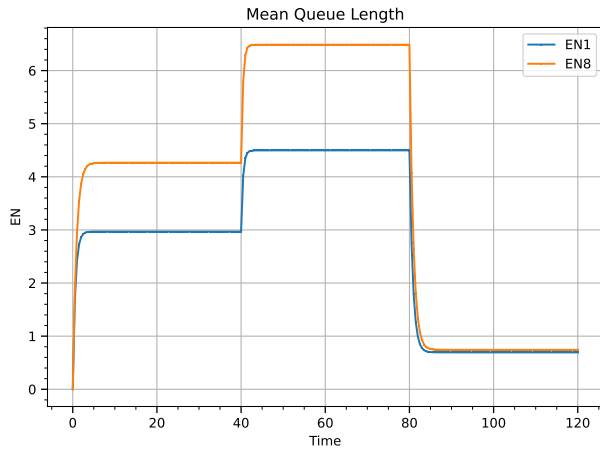


Fig. 2. One class of customers, mean number of busy channels case of one and eight trials, changes of $\lambda(t)$ the same as in Fig. 1

E. Numerical results

Fig. 1 presents an exemplary solution $p(n, t; 0) = f(x, t; 0)$ due to Eq. (4). The flow intensity $\lambda(t)$ is changing in the following pattern: $\lambda = 2.5$ for $t \in [0, 40]$; $\lambda = 5.0$ for $t \in [40, 80]$; $\lambda = 0.5$ for $t \in [80, 120]$. Number of channels is $N = 8$, $\mu = 1$, $C_A^2 = C_B^2 = 1$, i.e., the interarrival and service-time distributions are exponential. As we checked, the results are very close to the output of an analogous Markov model solved numerically. This agreement suggests that the diffusion approximation preserves the dominant statistical characteristics of the multichannel access process while significantly simplifying the analysis.

Fig. 2 presents the impact of a on the mean number of busy channels $E[N(t)] = \sum_{n=1}^N np^a(n, t)$, especially important for higher traffic.

The curves in Fig. 3 show the transmission efficiency for both classes, each curve corresponding to a series of results with $a_1 = 1$ and $a_2 = 1, \dots, 8$. It is visible how the increase of a_2 increases the transmission efficiency of the second class at the expense of the efficiency of the first class. At relatively

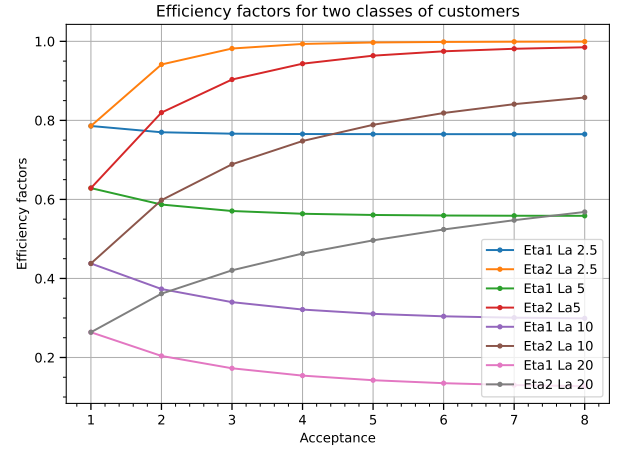


Fig. 3. Efficiency factors η_1, η_2 for two classes of customers as a function of a_2 : $a_1 = 1$, $a_2 = 1, 2, \dots, 8$ (axis x) for flow intensities $\lambda = 2.5, 5.0, 10.0, 20$, and $\lambda_1 = \lambda_2 = \lambda/2$, for steady-state distributions

low traffic, the efficiency of the second class increases faster than the efficiency of the first class decreases. At higher traffic volumes, the rate of change is similar.

V. CONCLUSIONS

The present study intentionally focuses on MAC-layer access dynamics and does not explicitly model hidden terminals, capture effects, imperfect sensing, or regional duty-cycle constraints. These aspects may be incorporated in future extensions of the model.

The proposed model may support preliminary dimensioning of LoRaWAN infrastructures by estimating admissible traffic loads and evaluating the impact of retransmission policies on transmission reliability under transient overload conditions.

The introduction of diffusion approximation allows us to model general interarrival and service-time distributions when evaluating the performance of LoRaWAN gateways. This aspect is important because traffic observed in real IoT networks is usually non-Markovian, while packet transmission times are not exponentially distributed.

The proposed model also enables the analysis of transient states under time-dependent traffic conditions. The numerical results demonstrate that allowing multiple channel-access attempts significantly increases the probability of successful transmission and improves effective throughput, particularly under medium and high traffic conditions. At the same time, the additional delay introduced by channel sensing has only a limited impact on overall system performance.

The proposed analytical framework may support the design and optimization of large-scale IoT deployments by enabling rapid evaluation of MAC-layer strategies under varying traffic conditions. Compared with classical Markov-chain approaches, the diffusion approximation naturally supports general service and interarrival distributions while preserving computational tractability.

The contribution of the paper lies primarily in the development of a transient-state analytical framework for LoRaWAN

CSMA evaluation rather than in demonstrating qualitatively new MAC-layer phenomena. The proposed model assumes statistically independent transmission attempts and does not explicitly represent physical-layer interference effects, capture phenomena, or adaptive spreading-factor allocation. These aspects will be considered in future work together with validation against large-scale simulations and real deployments.

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