Applicability of Listen Before Talk for LoRaWAN Deployments with Multiple Gateways

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***Abstract*—The Internet of Things is revolutionizing our daily lives by enabling numerous new applications. Low Power Wide Area Network solutions are pivotal in this transformation, facilitating long-distance data transmission with minimal energy consumption and extended battery life. Particularly suitable for simple temperature sensors, environmental monitoring, and metering applications in Smart Cities, Long Range Wide Area Network (LoRaWAN) has gained popularity due to its adaptability. However, the use of random channel access in current systems presents a significant challenge, as simultaneous data transmissions can lead to message collisions and data loss. To address collisions, alternative channel access methods like Listen Before Talk (LBT) are being explored, showing promising results in efficient collision avoidance. However, optimizing parameter configurations for LBT is challenging due to the varying transmission airtimes of LoRa messages. Our comprehensive simulation-based study examines various parameters for LBT to enhance message transmission quality in LoRaWANs. Our approach significantly reduces message delay compared to existing methods, eliminating the need for additional re-transmissions.**

***Index Terms*—LoRa, IoT, Network Planning, MAC**

I. INTRODUCTION

With the increasing adoption of interconnected smart devices across various industries, cities, and individuals, ranging from simple environmental monitoring applications to complex automation tasks, the Internet of Things (IoT) is becoming integral to our daily lives. However, not all IoT applications have identical network access requirements. In recent years, specialized wireless technologies designed for IoT access networks have been introduced, offering different characteristics compared to existing technologies such as Wi-Fi and mobile networks. Among these, Low Power Wide Area Networks (LPWANs) have emerged as cost-effective alternatives for specific IoT applications. These technologies are particularly suited for applications requiring low data rates, long-distance transmission, and extended battery life. As a result, the LPWAN market, which already exceeds $ 5 billion, is projected to grow to $ 350 billion by 2032 [1]. With a market share of over 42 %, LoRaWAN is one of the most prominent LPWAN technologies [2], commonly used in applications such as smart metering and smart parking [3]. Therefore, it is crucial to study the general performance of LoRaWAN in detail and address the shortcomings of its current usage. Numerous studies have analyzed current deployments and discussed potential improvements.

Although LoRaWAN offers several advantages, such as low energy consumption, robustness against interference, and long transmission distances, its reliance on random channel access introduces a significant drawback: unreliable data transmissions. Methods like re-transmitting lost packets or sending acknowledgments to confirm packet status can mitigate this issue, but these extensions to the random channel access mechanism increase energy consumption and computational overhead, compromising the long battery life that distinguishes LoRaWAN. Addressing these limitations is crucial for end users and network operators. Operators must ensure specific service level agreements for packet transmissions, ideally minimizing the need to re-transmit lost packets to optimize device battery life and reduce operational costs. Consequently, various alternative channel access approaches are currently under investigation in the literature. Time-scheduled channel access approaches [4] and Listen Before Talk (LBT) solutions [4], [5] have shown potential as alternatives. However, the ideal parameter settings and usage potential in large networks with various influencing factors are not yet fully understood.

We conduct a comprehensive large-scale simulation study to identify optimal parameter settings for listen times and back-off configurations using LBT, demonstrating its feasibility across various LoRaWANs. Expanding our investigation as discussed in [4], beyond small single-gateway setups, to larger deployments with multiple gateways, we provide insights into the scalability of LoRaWANs using LBT. Our results show that LBT can significantly reduce collision probability in LoRaWANs without substantially increasing packet transmission delays. Additionally, using our settings, LBT minimizes the need for transmission back-offs when multiple devices access the channel simultaneously, reducing the number of re-transmission attempts for blocked packets.

To this end, the contribution of this work is the answers to the following three research questions:

RQ1: What are the optimal parameter settings for listen times and back-off configurations in LBT for general LoRaWAN deployments?

RQ2: Do state of the art gateway placement approaches from the literature need to be adjusted when LBT is used?

RQ3: Can the parameter selections determined from a synthetic network be generalized to various network configurations?

In the remainder, Sec. II presents the background and related work. Sec. III introduces the used methodology, the ideal parameters used for LBT, and defines the scenarios. Sec. IV presents the evaluation and Sec. V concludes.

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II. BACKGROUND

This section summarizes information required to understand the remainder of this work. The main focus is placed on channel access methodologies in LoRaWAN.

A. General LoRaWAN Background

LoRa is a proprietary modulation technology developed by Cycleo and later acquired by Semtech [3]. It offers a physical layer connection with low power consumption, enabling up to 10 years of battery life and supporting low data rates. In Europe, LoRa primarily operates in the ISM bands between 863.0 MHz and 870 MHz, with the 433 MHz band available for more recent devices [6]. LoRa uses different spreading factors (SFs) to balance transmission time on air (ToA) and transmission distance [7]. SFs range from SF7 to SF12, where SF7 has the shortest ToA but also the shortest transmission distance. This trade-off is crucial due to the restricted duty cycle on the ISM band, limiting transmission time for single devices to 0.1 %, 1 %, or 10 % of the total available time, depending on the channel [6]. LoRaWAN provides the MAC layer for LoRa, with a network organized in a star-of-stars topology. A centralized network server connects to one or multiple gateways, which in turn connect to end devices [3].

B. LoRaWAN Channel Access

To manage channel access in LoRaWAN, a variation of the ALOHA [8] protocol is used. End devices can transmit data whenever they are ready, without synchronization or checking if the channel is free. While this protocol is simple for the client, it can lead to many packet collisions and limits channel capacity usage to a maximum of 18.6 % [9]. Due to these limitations, alternative channel access methods are being investigated. One such method is slotted ALOHA, where fixed or variable-length time slots are defined, allowing devices to initiate transmissions only at the start of these slots. This approach halves the collision time window and increases maximum channel utilization to 37.2 % [10]. However, slotted ALOHA is impractical for networks with varying payload sizes and SFs, which lead to significant variance in transmission ToA and necessitate different slot sizes [4]. The usage of a fully time-scheduled channel access can eliminate collisions by assigning each end device a specific slot, allowing transmissions only during these slots. The methodology to determine parameters for this approach is detailed in [4]. However, pre-planning time slots results in an inflexible solution that is unsuitable for event-based transmission, despite achieving high performance with collision-free transmissions [11].

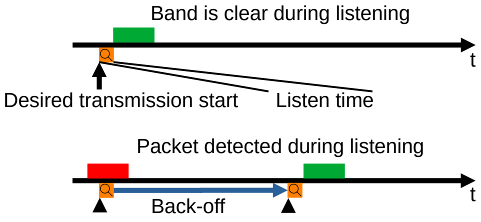

Fig. 1: LBT mechanism overview

Finally, Listen Before Talk (LBT) offers an alternative channel access method where devices listen for a configurable period before transmitting, avoiding the need for synchronized devices or predefined time slots. If the channel is busy, the device defers transmission and waits for a configurable back-off duration before retrying. Various approaches to calculating this back-off duration exist. One approach uses fixed-length time slots similar to IEEE 802.15.4 [12], while others use a random times based on distributions, such as exponential or uniform [4]. Using a random back-off duration, instead of a fixed offset, helps prevent repeated collisions. A constant back-off can cause synchronized retransmissions and subsequent collisions if two devices attempt to transmit simultaneously and both sense a busy channel. Randomly distributed back-offs help mitigate this issue and can be extended to multiple channels [13]. The general LBT mechanism for collision avoidance is illustrated in Figure 1. At the intended transmission start (black arrow), the device listens on the channel for a short predetermined time (orange). If no transmission is detected, the device starts transmitting (green). If a transmission is detected (red), a random back-off is initiated (blue arrow). After this back-off, the process repeats until successful transmission. While LBT reduces collision probability, it is limited by the hidden node problem, particularly in LoRaWAN with its long transmission ranges. This issue can degrade LBT performance to that of ALOHA when devices are out of range of each other but within range of the same gateway [5]. While the more advanced CSMA/CA with RTS/CTS, implemented in Wi-Fi [14], presents a mitigation for the hidden node problem, it requires additional transmissions from both, the gateway and end device, reducing the available duty cycle and further consuming power, making it unsuitable for LoRaWAN.

C. Gateway Placement

Despite LoRa's extensive transmission range, strategically placing gateways is essential to ensure coverage of large areas while minimizing the number of gateways. Given the varying SFs and their corresponding transmission distances, specialized placement approaches are developed. These approaches prioritize positioning gateways in regions with a high density of end devices, thereby reducing the average distance between end devices and gateways. This minimizes the required average SF and the ToA for packet transmissions [7], [15]. A common configuration parameter is the maximum allowable distance between any end device and its gateway [7], [15]. Studies indicate that the SF significantly impacts collision probability in the network, more so than other parameters [7].

D. Related Work

Several simulation-based studies have already explored LoRaWAN channel access performance, including slotted ALOHA [16] and comparisons among slotted ALOHA, LBT, and scheduled MAC [4]. The consensus is that scheduled MAC can outperform other approaches if the network can be pre-planned and is not overly populated. Scheduled MAC has been analyzed through various synchronization and planning methodologies [17]–[19]. In contrast, simulative comparisons between LBT and ALOHA have been conducted [13], and studies on the coexistence of these approaches have been examined [20]. LBT generally shows a lower collision probability than ALOHA, studied both independently [13] and in combination [20] but a detailed analysis of LBT is still required and done in this paper. Beyond single-cell LoRaWAN deployments with one gateway, analyzing larger networks and how gateway placement impacts network quality is crucial, as explored in the literature [15]. Utilizing concepts from graph theory, overall network quality can be enhanced [7]. These approaches can be pre-clustered to handle larger problem instances, at the cost of additional gateways [21]. Previous works have already applied clustering techniques for gateway placement in LoRaWAN [22]–[24], addressing very large networks, including state-wide deployments [24]. Despite individual research on gateway placement and LBT optimization, a combined study has yet to be conducted. The back-off behavior in LBT is significantly influenced by gateway placement, particularly the distance between end devices and gateways, and the resulting packet transmission duration, which affects how long a single packet blocks a channel. Therefore, this paper addresses optimizing the listening time for individual devices during LBT and the back-off behavior, incorporating various gateway placement strategies.

III. METHODOLOGY

This section outlines the methodology for investigating and optimizing LBT for various gateway placements. We provide an examination of the LBT back-off parameters and analyze how gateway placement decisions influence the effectiveness of LBT within a LoRaWAN. Additionally, we describe our simulation for evaluating LBT, define the key performance metrics, and outline the scenarios used in the evaluation.

A. Back-off Parameters

The configurable parameters vary based on the selected back-off methodology. This study examines random back-off strategies using either exponential or uniform distributions.

a) Exponential Distribution: The exponential distribution is characterized by the rate parameter λ, which directly determines the expected delay by

$$A \approx EXP(\lambda) : E[A] = \frac{1}{\lambda}. \tag{1}$$

b) Uniform Distribution: The uniform distribution offers a defined range for the interval with equal probabilities for all values. However, for an easier analysis of the back-off duration, the input of a fixed mean value would be preferable. Consequently, to directly describe the mean back-off duration, the interval for the uniform distribution is chosen as

$$U(L-(W/2), L+(W/2)) \tag{2}$$

with the parameters L as mean back-off (similar to $\frac{1}{\lambda}$ for the exponential distribution case) and W as maximum deviation from the mean back-off value L. Note, to indicate a difference to the standard notation for a uniform distribution, we use U_m with the parameters $U_m(L, W)$ in the following describing a uniform back-off with a mean value L and maximal positive and negative deviation of $W/2$ around the mean.

B. LoRa Network Setup Effects on Listen Before Talk

LoRaWAN enables a trade-off between transmission ToA and transmission distance through the use of different SFs. Consequently, the optimal back-off configuration is anticipated to vary based on the ToA distribution within the network.

a) Network Topology and SF: As discussed in Sec.II, the SF required for an end device to successfully communicate with a gateway is directly related to the distance between the device and the gateway. Therefore, the SF distribution within a network depends on the geographic distribution of end devices and gateways. In practice, this distribution is unlikely to follow a standard pattern and is influenced by the chosen gateway placement strategy and the locations of end devices. Common gateway placement methods can affect the SF distribution by setting a maximum allowable distance between any end device and its associated gateway, thus constraining the maximum SF in the network [7]. In this study, we model real-world networks by positioning end devices at the centroids of buildings in various cities using data from OpenStreetMap, similar to the approach in [15]. We also employ a well-established gateway placement strategy from the literature [7]. Due to the challenges in precisely controlling the SF distribution, a more controlled network setup is necessary for studying LBT first. In this work, we use synthetic networks to achieve this. We position a single gateway at the center of a circle and uniformly distribute a specified number of end devices within this circle, following the methodology described in [25]. The circle's radius serves as the maximum distance between end devices and gateways in a real-world network. To determine the transmission distance for each end device, and consequently the SF, we apply the Hata path loss model, ensuring consistency with the used gateway placement approach [7].

b) Payload and Time on Air: Key LoRaWAN parameters, as defined in [26], are kept constant for this study. Specifically, the number of preamble symbols is set to eight, the coding rate to 4/8, both header and CRC are enabled, and data rate optimization is disabled. With these settings and a given SF for an end device, only the payload size needs to be specified to determine the required ToA. Since payload size varies by application, we use a random payload size ranging from $1\,\mathrm{B}$ to $51\,\mathrm{B}$ in this study, covering the full range of possible payload sizes for all SFs.

C. Simulating Listen Before Talk

To evaluate the performance of LBT, we use a custom simulation tool designed to model a single LoRa channel. This tool not only simulates channel access and back-off for LBT but also incorporates geographic distribution and transmission ranges of end devices to accurately reflect collisions in larger networks and address the hidden node problem. The simulation begins by loading end device locations, the nearest gateway, and the SFs from either a predefined gateway placement or an synthetically generated network, depending on the scenario specified. The main simulation process follows a three-step routine, similar to that described in [7]. The source code and data is available on GitHub[1].

a) Step 1: Packet Generation: Each end device generates one transmission per hour with a random start timestamp t_{start} between $0\,\mathrm{s}$ and $3{,}600\,\mathrm{s}$. The transmission is then represented by an interval $[t_{start}, t_{start} + ToA]$ for the rest of the simulation. After all end devices generate their transmission, all transmissions are sorted chronologically by t_{start}.

b) Step 2: Listening on the Channel and Back-off: For LBT, each end device must listen on the channel before transmitting. To simulate this process, all transmissions are handled chronologically. Initially, a short listening interval is introduced before each transmission. During this interval, overlapping transmissions are identified, reflecting simultaneous activity from a global perspective. The distance between the devices these overlapping transmissions are coming from is then calculated to determine if the listening end device can hear the transmission or is out of range. If the listening end device is within range, a back-off is triggered, and the original transmission is removed. A new transmission is scheduled with the same ToA but delayed by the back-off period. Finally, the listening interval is removed, and the remaining transmissions are reordered to maintain chronological accuracy.

c) Step 3: Transmission: After processing all transmissions, their chronological order reflects what would occur in a real system. This allows for the simulation of actual data transmission, including collision events. Collisions are identified when a gateway receives multiple transmissions simultaneously. Note, that this check does not consider potential orthogonality of different SFs, representing a worst case. This is assessed similarly to Step 2, but with the closest gateway as the reference point. To extend the simulation beyond one hour, the entire process can be repeated. To handle end devices attempting to transmit at the end of one specific hour and overlapping into the next one, these transmissions are transferred to the subsequent hour before starting the next simulation cycle.

D. Listen Before Talk Performance Metrics

To evaluate the performance of LoRaWAN using LBT, several metrics are essential. Each metric is defined in the following and calculated upon completion of the simulation.

a) Collision Probability: The collision probability is a critical metric for evaluating channel access procedures in LoRaWAN. It measures the ratio of lost transmissions due to collisions to the total number of transmissions. Minimizing collision probability is crucial because collisions either result in data loss or necessitate re-transmissions, which increase energy consumption and reduce overall service quality. This metric is determined by analyzing the collisions identified in Step 3 of the simulation.

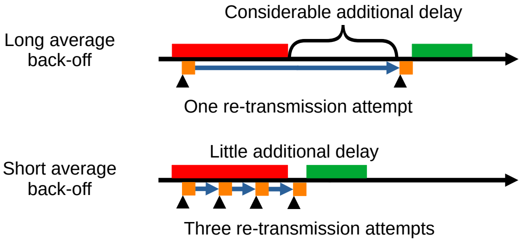

Fig. 2: Delay and re-transmission trade-off

b) Delay: In the context of LBT, delay refers to the time elapsed between the initiation of listening on the channel and the actual start of data transmission. This delay includes the initial listening time, any subsequent back-offs, and additional periods of listening if necessary. The significance of delay varies with the application: for instance, long-term monitoring applications may tolerate longer delays, whereas fault detection systems require minimal delay. The delay for each transmission is also recorded during Step 2 of the simulation.

c) Re-Transmission Attempts: The number of re-transmission attempts indicates how frequently the process of listening and back-off must be repeated. If the channel is free during the initial transmission attempt and no back-off is needed, the re-transmission count is zero. Each subsequent failed attempt adds to the total number of re-transmissions. Re-transmissions require additional listening on the channel, leading to increased energy consumption for the end device. Like delay, the number of re-transmission attempts for each transmission is recorded in Step 2 of the simulation.

d) Delay and Re-Transmission Relationship: The delay and number of re-transmission attempts represent a trade-off, as illustrated in Figure 2. This figure uses the same event representation as Figure 1. In the top scenario, a longer back-off duration is chosen to reduce the number of re-transmissions, but this can lead to increased overall delay by extending the time before the transmission starts. Conversely, the bottom scenario prioritizes minimizing the delay by using shorter back-offs, which often results in more re-transmission attempts, as also already illustrated in [4]. To quantify this trade-off, we introduce a new metric that combines the number of re-transmission attempts with the total delay, since these two factors are not directly comparable. Normalization is performed by varying the listen time and back-off configuration to establish bounds for both delay and re-transmission attempts. The minimum and maximum back-off values are selected for normalization based on the chosen back-off configuration to

$$M_c = \frac{r - r_{min}}{r_{max} - r_{min}} \cdot w_r + \frac{d - d_{min}}{d_{max} - d_{min}} \cdot w_d$$

where r and d are the number of re-transmission attempts and the delay of the same configuration of listen time and back-off. The minima and maxima are denoted by d_{min}, d_{max}, and r_{min}, r_{max} for the delay and number of re-transmission attempts, respectively. The weights, w_r and w_d allow for different priorities when comparing configurations. Applied over a range of configurations, the minimum value

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[1] https://github.com/lsinfo3/lora_LBT_simulation

TABLE I: Scenario overview

Scenario	Listen time	Back-off method	Research goal
S1	1 ms - 3,023 ms stepsize variable	$U(400\,\mathrm{ms}, 1{,}750\,\mathrm{ms})$	Determine ideal listen time
S2	1 ms	$EXP(\frac{1}{X})$, $X = [400\,\mathrm{ms}, 1{,}750\,\mathrm{ms}]$	Analyze behavior for λ
S3.1	1 ms	$U_m(1{,}110\,\mathrm{ms}, X)$, $X = [50\,\mathrm{ms}, 2{,}150\,\mathrm{ms}]$	Determine ideal W
S3.2	1 ms	$U_m(L, W)$, $L = [35\,\mathrm{ms}, 3{,}023\,\mathrm{ms}]$, W based on S3.1	Analyze behavior of L

Scenario	Back-off method	Dataset	Research goal
S4	$U_m(L, W)$, W based on S3.1, L based on S3.2	Würzburg	Study behavior of LBT compared to ALOHA
S5	$U_m(L, W)$, W based on S3.1, L based on S3.2	Various cities	Study approach for different locations and compare to related work

for M_c represents a Pareto point, as neither the delay nor the number of re-transmission attempts can be improved without increasing the other value, as we will see in the evaluation. The specific Pareto point depends on the value of w_r and w_d. Varying the ratio between w_d and w_r allows each point on the Pareto front to be selected. For the remainder, these values are set to $w_r = w_d = 1$ for an unbiased optimization.

E. Scenario Definition

To analyze LBT for LoRaWAN and determine optimal parameter combinations, we have defined the scenarios listed in Table I. The following sections provide a detailed explanation of each scenario and the reasoning behind its design.

a) S1: Listen Time Analysis: The objective of the first scenario is to identify the optimal listening duration for detecting other transmissions on the channel. This scenario employs a synthetic network with a maximum range of $1{,}960\,\mathrm{m}$, which is $90\,\%$ of the maximum possible transmission range as estimated by the Hata model [7]. This range is selected to achieve a more uniform distribution of SFs compared to using the absolute maximum range. To ensure network load and potential collisions, the network is populated with 700 end devices. A preliminary study showed a $10\,\%$ collision probability using ALOHA in this setup. The listening time is varied from $1\,\mathrm{ms}$ (the minimum possible value in this simulation) to $3{,}023\,\mathrm{ms}$, which corresponds to the maximum ToA for a LoRaWAN packet with the described parameter settings. Although the maximum value is unlikely to yield optimal results, it provides a broad range for evaluation. Additionally, since the end device must continuously receive during the entire listening period, longer listen times will result in higher energy consumption, significantly impacting battery life. For this reason, a step size of $1\,\mathrm{ms}$ is used up to $100\,\mathrm{ms}$, and $50\,\mathrm{ms}$ increments are used for longer listening durations. This coarser step size for longer durations is based on previous research, which indicates that shorter listening times generally yield better results [4], [13]. The back-off duration is uniformly varied between $400\,\mathrm{ms}$ and $1{,}750\,\mathrm{ms}$, reflecting findings from [4] that suggest this range is effective.

b) S2: Exponential Back-off: To examine the behavior of an exponential back-off, the same network configuration as in scenario S1 is used. $E(A)$ is varied between $400\,\mathrm{ms}$ and $1{,}750\,\mathrm{ms}$ with a step size of $10\,\mathrm{ms}$, aligning with the effective back-off range identified in the literature [4].

c) S3: Uniform Back-off: To further refine the uniform back-off strategy recommended in the literature [4], additional configurations for $U_m(L, W)$ are examined in scenario S3.

d) S3.1: Back-off Window Size Analysis: In this scenario, the optimal back-off window length W is identified. Since there are no existing references in the literature for this parameter, the analysis explores a broad range of synthetic networks. Consistent with the previous scenario, the same synthetic network is used, along with networks covering the maximum range limits for all SFs. The listen time is fixed at $1\,\mathrm{ms}$, in line with findings suggesting that shorter listen times yield better performance [4], [13]. The average back-off L is set to $1{,}075\,\mathrm{ms}$, which is centrally located within a known effective interval [4]. Although the specific value for L is not anticipated to significantly affect the results for W, as the average back-off delay and the number of re-transmission attempts exhibit predictable patterns according to related studies, it is crucial to maintain consistency. The back-off window length W is varied from $50\,\mathrm{ms}$ to $2{,}150\,\mathrm{ms}$. A minimum value of $50\,\mathrm{ms}$ is chosen to avoid collisions caused by deterministic back-offs, while the maximum of $2{,}150\,\mathrm{ms}$ ensures that the average back-off remains consistent. Increasing W beyond this range would require adjusting the average back-off delay L to prevent negative back-off values or necessitate shifts in the average back-off duration.

e) S3.2: Average Back-off Duration Analysis: This scenario examines the impact of the average back-off duration L on the performance metrics. To thoroughly investigate L, which is anticipated to be a significant factor, 38 synthetic networks are created, each with 700 end devices. The maximum geographic range of these networks varies from $300\,\mathrm{m}$ to $2{,}150\,\mathrm{m}$ in $50\,\mathrm{m}$ increments. This leads to the usage of different SFs and different ToAs for transmissions. For each network, L is adjusted from $35\,\mathrm{ms}$ to $3{,}023\,\mathrm{ms}$ in $10\,\mathrm{ms}$ increments. The minimum of $35\,\mathrm{ms}$ is selected to ensure a back-off delay of at least $10\,\mathrm{ms}$ and to avoid frequent state transitions by the end devices. The maximum value corresponds to the maximum ToA for a LoRaWAN packet again, ensuring that the original transmission concludes before a re-transmission attempt. It is expected that longer back-off delays will not yield improvements. To determine whether the optimal configuration is influenced by the number of end devices, a second set of 38 networks is evaluated. Each network in this set includes 1,000 end devices, reflecting a higher network load similar to the configuration in S1 of [7]. Apart from this increase in device count, these networks are identical to the corresponding networks with 700 end devices.

f) S4: Real World Network Analysis: This scenario evaluates the performance of LBT and the optimized parameters

TABLE II: Evaluated cities

City	**District**	**Country**	**Number of Gateways**	**Number of end devices**	**End devices per km^2**
Würzburg	entire city	Germany	25	10,000	114
Bangkok	entire city	Thailand	284	14,443	4.7
London	City of London	UK	4	1,959	412
Munich	Schwabing-West	Germany	6	3,094	489
Shanghai	Pudong	China	239	17,210	5.8
Sydney	City of Sydney	Australia	3	1,058	193.1
New York City	Manhattan	USA	38	11,592	46.2
San Francisco	entire city	USA	62	20,048	19.2

in a realistic network setting. The network under consideration includes 10,000 end devices distributed around Würzburg, Germany. The placement of end devices and gateways follows the configuration from scenario S1 in [7] to ensure consistency. Thus, the maximum distance between end devices and gateways is varied from $300\,\mathrm{m}$ to $2{,}600\,\mathrm{m}$ in $50\,\mathrm{m}$ increments. LBT parameters are configured based on the best-performing results from scenarios S1 and S3. Specifically, the listen time is set according to the optimal performance identified in S1, while the values for W and L are derived from scenario S3. For networks where the maximum distance exceeds $2{,}150\,\mathrm{m}$, a lookup table aligns the maximum distance in the network with the closest maximum distance evaluated in scenario S3.2.

g) S5: Comparison to Related Work: In this final scenario, the ideal parameter configuration identified in S3 is compared with approaches from related work [4]. To cover a wide range of real-world network conditions, networks are generated for various cities listed in Table II according to our methodology from Section III-B0a. These cities were also evaluated in the literature [7] and represent different end device densities to conduct a comprehensive study and comparison. For this comparison, the maximum gateway distance is set to $1{,}173\,\mathrm{m}$, consistent with findings from [7], and each gateway supports up to 1,000 end devices. The parameters for our approach are based on the optimal values from S1 and S3, with the listen time, back-off window (W), and average back-off delay (L) set accordingly. For comparison with the literature [4], the listen time is fixed at $1\,\mathrm{ms}$, and the back-off duration is varied between $400\,\mathrm{ms}$ and $1{,}750\,\mathrm{ms}$.

IV. EVALUATION

This section comprehensively summarizes the results obtained during the studies of the scenarios defined above.

A. S1: Listen Time Analysis

Scenario S1 determines the optimal listen time that minimizes both delay and re-transmission attempts. The results indicate that delay and re-transmission attempts increase exponentially with longer listen times. Specifically, the delay rises from $81.304\,\mathrm{ms}$ with a listen time of $1\,\mathrm{ms}$ to $4{,}536.475\,\mathrm{ms}$ with a listen time of $3{,}023\,\mathrm{ms}$. Similarly, the number of re-transmission attempts increases from 0.074 with a listen time of $1\,\mathrm{ms}$ to 0.377 with a listen time of $3{,}023\,\mathrm{ms}$. The collision probability remains stable across different listen times, averaging $5.044\,\%$ with a $99\,\%$ confidence interval of less than $0.1\,\%$ at a listen time of $1\,\mathrm{ms}$. Therefore, the results suggest that the listen time should be as short as possible, as it effectively minimizes delay and re-transmission attempts without significantly affecting the collision probability.

B. S2: Exponential Back-off

This scenario investigates whether using a negative exponential distribution for the back-off improves the performance characteristics of LBT. The results are illustrated in Figure 3, where the x-axis represents the parameter λ of the exponential distribution. The y-axis is divided into two sections: delay on the left and re-transmission attempts on the right. The mean delay is depicted by the black solid line, with the shaded area indicating the $99\,\%$ confidence interval. Similarly, the solid orange line and the shaded area show the re-transmission attempts. The data reveal that delay decreases exponentially as λ increases, while the number of re-transmission attempts rises linearly with a larger λ, accompanied by a broader confidence interval. As observed in scenario S1, the collision probability remains consistent regardless of λ, showing no significant difference from scenario S1.

To determine the optimal trade-off, the metric M_c is computed for these results and displayed in Figure 4. The x-axis is kept as in Figure 3, while the y-axis shows M_c as a percentage. The plot reveals a parabolic, though left-skewed, shape. The minimum point on this curve represents the Pareto optimal configuration, with $\lambda \approx 1.22$ being ideal for balancing both performance metrics. Deviations from this value result in either a disproportionate increase in delay for lower λ values or a rise in re-transmission attempts for higher λ values. If minimizing delay is the primary goal, an exponential back-off might be preferable to a uniform back-off, as the exponential decrease in delay affects re-transmission attempts linearly.

C. S3: Uniform Back-off

This scenario further investigates a uniform back-off. According to related work [4], a uniform back-off exhibits a trade-off similar to that of an exponential back-off, however, with the delay increasing linearly and re-transmission attempts decreasing exponentially. Given that minimizing energy consumption is crucial for end devices, reducing re-transmission attempts often takes precedence, making an exponential decrease in this metric preferable. Therefore, identifying the optimal configuration for a uniform back-off is essential for improving the performance of a LoRaWAN using LBT.

a) S3.1: Back-off Window Size Analysis: The results for the back-off window size reflect those observed in S1. Across all SFs, a shorter back-off window consistently reduces delay and re-transmissions. However, as discussed in Section II, a minimal random interval is necessary to avoid systematic

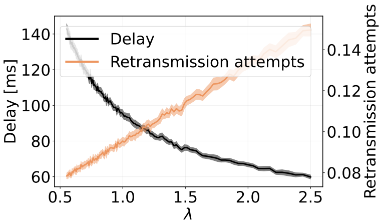

Fig. 3: Delay and re-transmission attempts for different λ

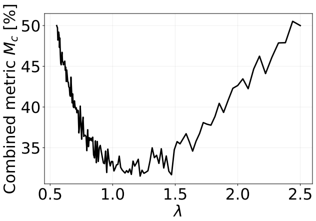

Fig. 4: M_c for different λ

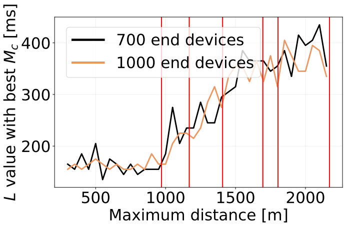

Fig. 5: Ideal L for different maximum gateway distance

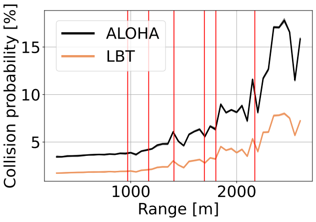

Fig. 6: Collision probability for different maximum gateway distance

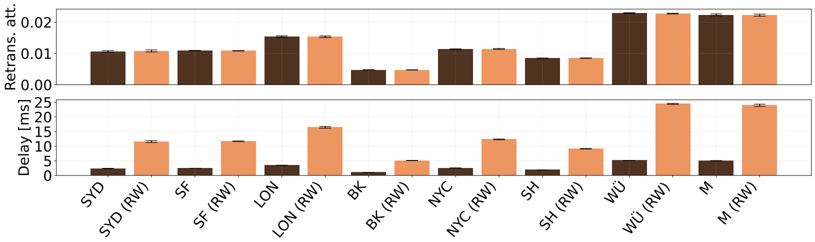

Fig. 7: Delay and re-transmission attempts compared to related work

collisions if two end devices initiate a back-off simultaneously. To prevent such collisions in the remaining scenarios, the back-off window size W is set to $50\,\mathrm{ms}$. As with S1 and S2, variations in W do not influence the collision probability.

b) S3.2: Average Back-off Duration Analysis: To analyze the average back-off, additional synthetic networks are analyzed, to represent different maximum distances from the gateway. Individual networks in this scenario show a similar behavior, as observed in [4]. This results in a similar behavior for M_c, compared to S2. Individual networks show a parabolic curve for M_c in relation to the average back-off L. As a result, each individual network results in a single optimum for L. This ideal value for L is shown on the y-axis of Figure 5. The x-axis shows the maximum distance between end devices and gateway of the corresponding network. The red lines delimit the individual SFs. The leftmost line corresponds to SF7, while the rightmost line to SF12. The colors differentiate the different number of end devices in the network. The network with 700 devices is shown in black and with 1,000 devices, it is shown in orange. Both results show a similar behavior. Up to a maximum distance from the gateway of $950\,\mathrm{m}$, where only SF7 is present, the ideal value for L remains close to $150\,\mathrm{ms}$. Larger maximum distances show a limited growth up to an ideal value for L of $435\,\mathrm{ms}$. The variability observed in the results is a direct consequence of the sensitivity of M_c to variability in both delay and re-transmission attempts. However, as both 700 and 1,000 end device networks share a similar behavior, the identified values for L are universally applicable. Thus, we can answer our first research question: *A short listen time, and uniform back-off distribution show the best results. The average back-off should be set between* $200\,\mathrm{ms}$ *and* $400\,\mathrm{ms}$ *depending on the maximum distance from the gateway, with a small variation of* $50\,\mathrm{ms}$.

D. S4: Real World Network Analysis

To evaluate the performance of LBT and the optimized uniform back-off configuration in a real network, S1 from [7] is replicated using LBT with the determined values for listen time, W, and L. The results for this scenario are presented in Figure 6. The x-axis represents the maximum distance between the gateway and end devices, while the y-axis shows the collision probability. The orange line indicates the mean collision probability for the network using LBT, with shaded areas representing the observed minimum and maximum values. The $99\,\%$ confidence interval is too narrow to be visible, suggesting that the solid line effectively captures more than $99\,\%$ of the data. The results for the same networks using ALOHA are shown in black, following the same format as the LBT results. The red lines delineate the individual SFs, similar to Figure 5. As expected, the ALOHA results align with those from S1 in [7]. The LBT results display a similar trend but with a reduced collision probability, irrespective of the maximum distance. The delay and re-transmission attempts both exhibit trends consistent with the collision probability results with more pronounced variations in magnitude. These results demonstrate that the parameters identified in scenario S3 are applicable to real networks, achieving similar performance to ALOHA and confirming that the ideal gateway placement configuration for LBT aligns with that of ALOHA.

This answers our second research question: *The collision probability, delay, and number of re-transmission attempts exhibit behavior similar to ALOHA. Therefore, the optimal gateway placement is consistent between ALOHA and LBT,* *meaning that strategies optimized for ALOHA can also be effectively applied to networks using LBT.*

E. S5: Comparison to Related Work

This scenario compares the listen time and back-off parameters identified in this work with those from a state-of-the-art approach for LBT presented in [4]. The parameters used in this work are a uniform back-off with $U_m(225ms, 50ms)$, while the related work uses a back-off with $U(400ms, 1750ms)$. Both approaches use a listen time of $1\,\mathrm{ms}$. The comparison results are illustrated in Figure 7 where the x-axis represents the cities listed in Table II, the top y-axis shows re-transmission attempts, and the bottom y-axis displays delay. The results are presented as bar graphs, with $99\,\%$ confidence intervals indicated by error bars. Results from this work are shown in brown, while those from related work are in orange. The comparison reveals no significant difference in re-transmission attempts across the cities. However, the parameter combination from this work significantly reduces the delay, achieving more than a fourfold improvement. This indicates that the parameter selection process presented here can substantially enhance delay performance without increasing re-transmission attempts. This addresses the final research question with *Yes, the parameter combinations derived for a synthetic network also yield comparable results in various real-world applications and demonstrate improvements over the related work.*

V. CONCLUSION

As IoT applications become increasingly diverse, ranging from simple environmental monitoring to complex automation tasks, the need for effective connection technologies is growing. LPWANs, particularly LoRaWAN, are favored for their low energy consumption, which extends battery life in these devices. However, the standard ALOHA-based channel access mechanism can result in high collision rates and potential data loss. To address this issue, we explore LBT as an alternative to ALOHA. Through simulations of synthetic networks, we identify optimal parameters for listen time and back-off behavior to enhance delay and minimize re-transmission attempts. Our findings indicate that LBT significantly reduces collision probability in LoRaWAN networks by up to $50\,\%$, with only an average increase of less than $25\,\mathrm{ms}$ in delay and fewer than 0.03 re-transmission attempts in real world scenarios. While there is a trade-off between delay and re-transmission attempts with varying back-off durations, we demonstrate that an optimal configuration, dependent on gateway placement constraints, achieves the best results. Specifically, an average delay of $200\,\mathrm{ms}$ to $400\,\mathrm{ms}$ yields the best performance, depending on the distance from the gateway. Additionally, our optimized parameters can reduce delay by up to four times compared to existing solutions, without increasing re-transmission attempts.

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