Bachelor Thesis

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Simulative Collision Study for Different Channel Access Approaches in LoRaWAN

Simulative Kollisionsanalyse von verschiedenen Kanalzugriffs-methoden in LoRaWAN

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Deutsche Zusammenfassung

Der Markt für Internet of Things (IoT)-Anwendungen und -Geräte wächst sowohl in der Industrie als auch in der Wissenschaft stark. Prognosen gehen davon aus, dass die Anzahl von IoT-Geräte bis 2025 30 Milliarden erreichen wird und dass IoT-Geräte 75 % aller weltweit vernetzten Geräte ausmachen werden. Viele dieser IoT-Geräte sind für einfache Monitoraufgaben wie zum Beispiel Feuchtigkeits- oder Parkplatzsensoren. Für diese Anwendungen benötigen Sie keine hohen Datenraten, sondern hohe Energieeffizienz und eine große Flächenabdeckung. Low-Power-Wide-Area-Networks (LPWANs) sind für diese Anforderungen konzipiert. In den letzten Jahren hat sich LoRaWAN zu einem der am häufigsten verwendeten LPWANs in der IoT-Branche entwickelt. Allerdings hat LoRaWAN einen grundsätzlichen Nachteil: Die Datenübertragung basiert auf Random Access Kanalzugriff, was zu einer großen Anzahl von Kollisionen, verlorenen Nachrichten und der Reduzierung der maximalen Anzahl von Geräten führt. Die Verwendung alternativer Protokolle wie Listen Before Talk (LBT), Slotted ALOHA und Scheduled MAC kann die Kollisionswahrscheinlichkeit und den Kaneldurchsatz verbessern.

LBT hat das Potenzial, die Kollisionswahrscheinlichkeit um mehr als 50 % zu verbessern. Mit die Nutzung von Slotted Aloha steigt der theoretische Durchsatz im Vergleich zu Random Access um 50 %. Die Verwendung von Scheduled MAC als Kanalzugriffsprotokoll kann Kollisionen vollständig vermeiden. Aus diesem Grund ist das Ziel um LoRaWANs zukunfsfähig zu machen, die Gesamtkollisionswahrscheinlichkeit drastisch zu reduzieren. Eine Möglichkeit, dieses Ziel zu erreichen, ist die Verwendung geeigneter Kanalzugriffsmechanismen. Diese benötigen jedoch zusätzliche Komplexität. Mit Slotted ALOHA und ScheduledMAC wird die Zeitsynchronisation der Endgeräte zu einer Voraussetzung und LBT erfordert ein zusätzliche Abhören des Übertragungskanals. Durch die Verringerung der Kollisionswahrscheinlichkeit ergeben sich jedoch mehrere Vorteile: Netzbetreiber können ihren Netzwerkdurchsatz erhöhen und Endgeräte gewinnen an Zuverlässigkeit für erfolgreiche Datenübertragung.

Diese Arbeit untersucht die Performance von LoRaWAN in eine Netwerken mit mehreren Kanälen und für verschiedene Kanalzugriffsansätze. Eine Simulation von Mehrkanal-LoRaWAN-Netzwerken mit Endgeräten, die gemischte Kanalzugriffsschemata verwenden, wird entwickelt, um Leistungsmetriken wie Kollisionswahrscheinlichkeit und Energieeffizienz zu vergleichen. Diese Ergebnisse dieser Simulationen werden verwendet, um die Zugriffsprotokolle in Netwerken mit einem Kanel zu vergleichen, das optimale Kanalauswahlverfahren in einem Mehrkanalnetz zu bestimmen, zu untersuchen ob bestimmten Kanälen spezifische Aufgaben zuzuweisen die Leistung verbessern kann, und um verschiedene LBT-Backoff-Methoden zu vergleichen.

Der Beitrag dieser Arbeit ist vielfaltig: Zunächst erweist sich Slotted ALOHA als brauchbares Kanalzugriffsprotokoll, allderings nur wenn die Länge aller Übertragungen nahe beieinander liegt. Ansonsten ist die Kollisionswahrscheinlichkeit höher als bei Random Access. Zweitens bestätigen die Ergebnisse, dass das Zuweisen von Scheduled MAC Geräten auf einen dedizierten Kanal die durchschnittliche Kollisionswahrscheinlichkeit signifikant verbessert. Drittens wird gezeit, dass das optimale Kanalauswahlverfahren für Random Access Geräte eines ist, bei dem die Geräte perfekt über die Kanäle verteilt sind, was durch Verwendung einer zufälligen Kanalauswahl ausreichend gegeben ist. Viertens bietet das Random-Channel-Hop-Backoff-Verfahren die niedrigste Backoff-Zeit für LBT-Geräte, während die Kollisionswahrscheinlichkeit gleich bleibt. Zuletzt wurde festgestellt, dass der Energieverbrauch des LoRa-Transceivers pro Gerät für Scheduled MAC-Geräte um 64 % höher ist als für Random Access- und LBT-Geräte.

Contents

1 Introduction

The market of Internet of Things (IoT) applications and devices is rapidly growing in both industry and academia. Forecasts predict IoT devices to reach 30 billion by 2025 and make up 75 % of all global connected devices [1]. Many of these IoT devices are responsible for simple monitoring tasks like the detection of moisture or tracking of empty parking lots. For their applications, they do not require high data rates but high energy efficiency and large area coverage. Low-power wide-area networks (LPWANs) are designed as a solution to fit these requirements. In recent years, LoRaWAN has become one of the prominently used LPWANs in the IoT industry. However, LoRaWAN as one fundamental drawback: Its data transmission is based on random channel access which leads to a large number of collisions, lost messages, and the reduction of the maximum number of devices that can be serviced in one LoRaWAN. Using alternative protocols like Listen Before Talk (LBT), Slotted ALOHA, and Scheduled MAC can improve the collision probability and throughput [2].

LBT has the potential to improve the collision probability by more than 50 % [2]. Furthermore, the theoretical throughput increases with the usage of Slotted Aloha compared to Random Access by 50 % [2]. In addition, the usage of Scheduled MAC as channel access protocol avoids collisions completely. For that reason, the goal of future proofing LoRaWANs is to reduce the overall collision probability drastically. One possibility to achieve this goal is the usage of appropriate channel access mechanisms. However, additional complexity must be added. For Slotted ALOHA and Scheduled MAC time synchronization of the end-devices becomes an essential factor and LBT requires additional channel sensing. However, multiple benefits are gained by reducing the collision probability: Network operators are able to increase their network throughput and end-devices gain reliability for successful data transmission.

This work investigates the performance of LoRaWAN in a multi-channel environment for different channel access approaches. A simulation of multi-channel LoRaWAN networks with devices using mixed channel access schemes is developed to compare performance metrics such as collision probability and energy efficiency. They are used to compare the access protocols in a single channel environment, determine the optimal channel selection method in a multi-channel network, investigate the potential of assigning certain channels specific tasks, and compare different LBT backoff techniques.

The contribution of this thesis is manifold: First Slotted ALOHA is found to be a viable channel access protocol, only if the length of all transmissions is very close to each other. Otherwise, the collision probability is higher than even Random Access. Secondly, the results confirm that the assigning Scheduled devices to a dedicated channel improves the average collision probability significantly. Thirdly, the optimal channel selection method for Random Access devices is found to be one where devices are perfectly spread across the channels, which is well approximated using random channel selection. Fourth, the Random Channel hop backoff method provides the lowest backoff time for LBT devices while keeping the collision probability the same. Last, the energy usage per device of the LoRa transceiver is found to be 64 % higher for Scheduled MAC devices than for Random Access and LBT devices.

The remainder of this work is organized as follows. Chapter 2 presents background information to LoRa, LoRaWAN, and different channel access methods and summarizes related works. Chapter 3 describes the methodology for the simulations used in this thesis. After laying out important parameters, it presents the concept, implementation, and restrictions of the simulation. Lastly, it lists the different scenario configurations simulated for this thesis. Chapter 4 presents and analyzes the simulation results. Finally, Chapter 5 concludes this thesis and discusses potential future works.

2 Background and Related Work

In this chapter important or relevant background information to understand this thesis are given and related works are presented.

2.1 Background

The following section summarizes fundamental information about LoRa and LoRaWAN. Furthermore, an overview over different channel access techniques is given, since they are the main focus of this thesis.

2.1.1 LoRa

LoRa is a low power wide area modulation technique developed by Cycleo and later acquired by Semtech. It uses a spread-spectrum modulation technique and operates in sub gigahertz frequency ranges [3]. LoRa offers low power communication with ranges of up to 15km, although the data rate is limited. Its advantages make it very popular in the internet of things (IoT) sector when data rate is less important than energy efficiency and large area coverage [4].

The basis of LoRa's signal modulation is a spread-spectrum technique that encodes a set number of bits in one symbol. The number of bits in each symbol is defined by the spreading factor (SF) used by the transmitting device. For LoRa SFs from SF7 to SF12 are used [5]. The symbol length in a transmission depends on the SF used by the device and increases exponentially with 2^{SF}.

$$T_s = \frac{2^{SF}}{BW} \tag{2.1}$$

The transmission time of one symbol can be calculated using the SF and the bandwidth (BW). The longer symbol length of large SFs allows the transmission to be decoded with less signal strength and thus allows transmissions across longer distances than using smaller SFs. The drawback of using large SFs is the lower data rate and long transmission time caused by the longer symbol lengths T_s [3]. Because of this, the SF for each device should be carefully chosen to be the lowest possible while still guaranteeing a successful messages transmission.

A LoRa transmission is composed of the preamble and the payload. The time on air (ToA) for each LoRa transmission can be calculated as the sum of preamble and payload time $ToA = T_{preamble} + T_{payload}$.

The transmission time for the preamble can be calculated using the symbol time T_s, the number of preamble symbols $n_{preamble}$, and 4.25 symbols for synchronization.

$$T_{preamble} = (n_{preamble} + 4.25) \cdot T_s \tag{2.2}$$

To calculate the transmission time of the payload the number of symbols for the payload is needed which depends on the size of the payload and multiple LoRa configuration variables.

$$n_{payload} = 8 + max\left(0, ceil\left(\frac{8 \cdot PL - 4 \cdot SF + 28 + 16 \cdot CRC - 20 \cdot H}{4 \cdot (SF - 2 \cdot DE)}\right) \cdot (CR + 4)\right) \tag{2.3}$$

PL = Payload in Bytes
CR = Coding rate
CRC = Optional CRV field
H = Header enabled
DE = Low data rate optimization
Then the transmission time of the payload $T_{payload}$ can be calculated.

$$T_{payload} = n_{payload} \cdot T_s \tag{2.4}$$

On the ISM bands that LoRa operates on, devices are subject to duty cycle restrictions [6]. The duty cycle of a device is the percentage of time that it occupies a band. This means the total ToA of a device's transmissions may not succeed a set limit. For the Europe ISM 868 MHz bands 10 channels with duty cycle restriction of 0.1 %, 1 %, and 10 % are defined. They are listed in Table 2.1. This is especially important for gateways, which are subject to the same restrictions but have to handle downlink transmissions to all LoRa nodes.

Table 2.1: Maximum duty cycles for LoRa channels in the EU [7] [6]

Channels	Maximum duty cycle
867.1 MHz	1 %
867.3 MHz	1 %
867.5 MHz	1 %
867.7 MHz	1 %
867.9 MHz	1 %
868.1 MHz	1 %
868.3 MHz	1 %
868.5 MHz	1 %
868.8 MHz	0.1 %
869.525 MHz	10 %

2.1.2 LoRaWAN

LoRaWAN is a MAC layer protocol built on top of the LoRa signal modulation that enables higher layer access [5]. It has been developed and is being maintained by the LoRa Alliance. LoRaWAN enables LoRa end devices to transmit and receive data from network servers via gateways. For this, uplink messages are sent from the end devices to the gateway using the LoRa physical layer and then relayed to the network server using existing IP connections. The gateway can also transmit downlink data to LoRa end devices.

2.1.3 Current LoRaWAN Channel Access

In its current specification, LoRaWAN uses a Random Access based channel access method similar to Pure ALOHA.

Pure ALOHA ALOHA was developed at the University of Hawaii in 1968 and was one of the first MAC protocols [8]. Thanks to its low overhead and simplicity it is still one of the prominently used protocols in communication networks.

In ALOHA, a transmission is initiated as soon as a packet is available. For each transmission, an acknowledgement by the receiver is expected. If this isn't received, the transmission is regarded as failed and will be retransmitted after an exponential random backoff time. This simple channel access method without the need for synchronization between devices leads to the advantages of low overhead and high energy efficiency [4].

However, because of the random nature of the access and the lack of any collision avoidance, this leads to a low theoretical maximum channel utilization of 18.6 %.

Random Access in LoRaWAN In its base specification LoRaWAN uses a channel access method similar to Pure ALOHA. Identical to Pure ALOHA packets in LoRaWAN are transmitted as soon as they are ready. However because of the duty cycle restrictions on the frequencies used by LoRaWAN acknowledgement messages by the gateway are not feasible. Using acknowledgement messages would limit the maximum number of total transmissions to the number of acknowledgement messages that can be sent without violating the duty cycle restrictions of the gateway. Instead, potential data loss is accepted in LoRaWAN, but can be minimized using further channel access logic. Collisions can be handled by listening to the medium while sending and triggering a retransmission in case of a detected collision. Next to handling collisions, they can also be actively avoided using alternative channel access protocols. Since LoRaWAN does not restrict devices from using additional MAC logic, protocols with active collision avoidance can be used instead of Random Access to minimize the chance of collisions and thus maximize the chance for successful transmissions.

2.1.4 Listen Before Talk

Devices using the Listen Before Talk (LBT) protocol sense the medium for ongoing transmissions before starting a transmission themself. In case a transmission is sensed, the device executes a backoff procedure where it retries at a later time or on a different channel.

Advantages The collision probability can be greatly reduced by using this protocol [2]. Since it does not require any special logic on the side of the gateway LBT devices can coexist in LoRaWAN networks with devices using any other channel access methodology.

Disadvantages In certain cases, the transmissions of other devices can not be detected but still lead to collisions at the gateway. The transmissions can be blocked by walls and other obstacles, also known as the hidden node problem, or the two devices can simply be too far away. Since LoRaWANs are often spread across a large area, both scenarios are likely to happen and will degrade the performance of LBT. In the worst case scenario where no collisions can be prevented, the performance will degrade to that of Random Access. Since energy efficiency is very important for LoRaWAN devices, the extra energy consumption for the sensing and backoff also needs to be taken into consideration when using LBT.

2.1.5 Slotted ALOHA

For Slotted ALOHA, the channel gets split into different slots with a fixed length. A device is only allowed to start a transmission at the start of a slot.

Advantages Because devices can only start a transmission at the beginning of a slot, the only theoretical collision case is when multiple devices choose the same slot. This reduces the chance of collisions compared to Random Access by up to 50 % [2]. Since the protocol does not need to listen to other transmissions to achieve the reduced collision chance hidden nodes are not a problem.

Disadvantages The clocks between all devices need to be synchronized to deploy the protocol in a working manner. This requires devices to receive additional transmissions, thus increasing energy consumption [2]. The maximum number of devices using Slotted ALOHA in a LoRaWAN network is limited by the duty cycle of the gateway. For every device that drifts over a defined threshold the gateway has to send a synchronization message.

$$\frac{n \cdot P(sync) \cdot T_{sync}}{3600} \leq d$$

n = number of sensors
$P(sync)$ = probability synchronization is nessecary
T_{sync} = ToA of sync message

d = maximum duty cycle
The total percentage of time the channel is used for synchronization messages has to stay below the duty cycle of the used channel. In case of multi channel LoRaWAN, multiple channels can be used for re-synchronization of devices which increases the maximum number of possible Slotted ALOHA devices.

2.1.6 Scheduled

Scheduled MAC also divides the time into multiple slots. However devices are assigned slots by the gateway instead of choosing their own. They are only allowed to transmit in their own slots.

Advantages In a fully scheduled network with proper time drift handling, the theoretical collision probability is zero [9]. Furthermore the length of each slot can be adjusted to the device allowing more slots to be fitted into a channel than with Slotted ALOHA. The maximum number of sensors in a scheduled network is limited to the number of slots that fit into all channels.

Disadvantages Identical to Slotted ALOHA, the clocks of Scheduled devices need to be synchronized. This means the same duty cycle limitations and energy consumption drawbacks as Slotted ALOHA apply.

2.2 Related Work

With LoRaWAN becoming widely used in the IoT field over the last few years, a lot of research papers regarding it and its channel access have been published. This section presents an overview over related works.

The LoRaWAN technology has been analyzed in a number of papers. In [4] the authors describe and then analyze LoRaWAN regarding its network capacity, scale limitations, and use cases. After comparing it to other low-power, wide-area technologies like SigFox, they give LoRaWAN a slight preference thanks to being a more flexible and open architecture. By analyzing the functionality of LoRa and LoRaWAN, they come to the conclusion that a networks size is limited by collisions and the maximum duty cycle. Many other papers outline the LoRaWAN technology and also find it to be one of the most promising emerging low-power, wide area technologies for IoT devices (e.g. [10], [11], [12]). In [12], the authors suggest that other channel access mechanisms, like CSMA may improve on the collision probability and energy efficiency. In other papers like [13] that specifically investigate the performance of LoRaWAN, the authors also suggest that alternative channel access schemes may reduce collisions.

The performance of LoRaWAN can be evaluated using different methods. While some real world measurements have been conducted [14] most papers analyze the performance of LoRaWAN by models or simulations. Next to writing custom simulations, some authors expanded existing network simulators for LoRaWAN (e.g. [15], [16]).

To improve on the limitation of its channel access, many authors focused on investigating LoRaWAN's MAC protocol and comparing it to alternative approaches. In [2], Beltramelli *et al.* compare Random Access, Slotted Aloha, and Listen Before Talk as MAC protocols for LoRaWAN using simulations. They find both Slotted Aloha and Listen Before Talk have a lower collision probability compared to Random Access in all cases. This leads the channel throughput to be significantly higher for Slotted Aloha and Listen Before Talk. Furthermore, they measured the energy efficiency and found it to be better in most cases for Slotted ALOHA and always better for Listen Before Talk. In the same paper, they investigated the capture effect which has also been modeled in [17]. The authors of both papers find that for some collisions, the gateway can still correctly decode the transmission with a higher signal strength.

Increasing LoRaWAN performance using Slotted ALOHA has also been the goal of the authors of [18]. In their paper, they suggest their own method for synchronizing the time of LoRa devices and show that Slotted Aloha can improve the channel throughput by means of simulations. To synchronize the time of end devices when their clocks drift, the authors use predefined acknowledgement packets of LoRaWAN. When acknowledgements are required the authors find a two times increase in channel capacity using Slotted ALOHA. A similar channel access- and time synchronization method has been implemented and tested on 20 low cost sensor nodes by the authors of [19] who have found the same two time increase in channel throughput.

Listen Before Talk is the most investigated MAC protocol as an alternative for Random Access in LoRaWAN. This is most likely because it does not require any synchronization which might create large overhead in channel occupancy and energy usage. In [20], the authors propose a way to adapt the CSMA protocol to LoRaWAN and show in experimental tests that it can decrease the collision probability in large scale LoRaWAN networks. Using matlab simulations, the authors of [21] demonstrate a significantly improved channel utilization for LBT with a slight increase in energy usage per device. The authors of [22] evaluate two LBT approaches: energy detection on the physical layer and layer-2 frame decoding on the MAC layer. They propose a framework to model the performance of a network with mixed channel access in terms of collision probability and transmission delay. Using a simulation, they confirm the accuracy of their model. Their model shows the physical layer approach to only be better than Random Access in some cases while the MAC layer approach delivers consistently better results. As explanation for the worse performance of the physical layer approach they find that the probability for channel access failure is higher than the collision probability for small SFs. For the average delay, their model shows the MAC layer approach to be significantly lower than the physical approach leading to a better energy efficiency. Taking into account the regulative channel limitations, the authors of [23] compare the performance of Random Access and Listen Before Talk using simulations of realistic scenarios. They confirm

LBT to perform better under high traffic loads. Furthermore, they conclude that the use of downlink acknowledgement messages should be avoided in large scale LoRaWAN deployments. To study how LBT affects performance in LoRaWAN with some nodes still using Random Access, the authors of [24] develop a mathematical model for the data extraction rate and average backoff delay. Using a simulation, they confirm their model to be accurate. They find that LBT devices in the network always improve the data extraction rate of Random Access devices. However, for networks with a small number of nodes and a small SF they find a higher number of Random Access devices to improve the data extraction rate of the LBT devices. This is caused by an increased channel access failure probability for LBT devices with a low SF. Another approach to improve Random Access would be a scheduled channel access. One proposal for such a solution is made by the authors of [25]. With their approach, the network server schedules SFs, frequency channels, and time slots for all links in the network. Because the slot lengths are adjusted for each device based on their SF more transmissions than with a fixed slot length can be fit. In their proposed system acknowledgements for uplink transmissions on multiple channels are combined into group acknowledgements. This improves channel efficiency and lessens the duty cycle of the gateway. Comparing their solution to Random Access, they are able to accommodate 60 % more end devices in their network while keeping the packet success rate over 90 %.

3 Methodology

For this thesis, a simulation of a LoRaWAN with devices using the channel access protocols Random Access, LBT, Slotted ALOHA, and Scheduled is used. In this section, the methodology behind the simulation is introduced. At first essential simulation parameters are listed, and then an explanation of the implementation is given, and restrictions are explored. Lastly, an overview of the scenarios is presented.

3.1 Simulation Parameters

This section presents different parameters used to configure the simulation, which is essential for later assessing the results.

3.1.1 Time on Air

The ToA of a LoRaWAN message can be calculated using the payload size, the device's SF, and some general LoRa configuration values as described in Equation 2.4. Because legal duty cycle regulations limit the maximum ToA, a limited number of bytes can be transmitted depending on the SF of the transmitted message. An overview of the maximum payload sized depending on the used SF can be found in Table 3.1. To simplify the simulation configuration and to ease the interpretation of the simulation results, all devices in the simulation will use a maximum payload of 51 B.

Table 3.1: Maximum payload according to EU 863 - 870 for bandwidth 125 kHz [26]

SF	maximum payload
7	222 B
8	222 B
9	115 B
10	51 B
11	51 B
12	51 B

3.1.2 Channel Count and Selection

The number of channels in a LoRaWAN is set by the network operator and limited by region-specific regulations [7]. The channels can differ in bandwidth, maximum duty cycle, and uplink/downlink usage. In this simulation uses a bandwidth of 125 000/s for all channels. A LoRaWAN sensor communicates only on one channel, while a gateway can simultaneously handle transmissions on all channels. Since LoRa channels do not interfere with each other increasing the channel count linearly increases the theoretical maximum number of supported devices in a LoRaWAN network. The channel selection can influence the performance of a LoRaWAN network greatly. Same as the channel configuration, the channel selection is a region-specific parameter [26]. Currently, it is only defined explicitly for North America and Australia, where a random channel selection is specified. This thesis investigates the impact of channel selection, and alternative methods like assigning channels specific jobs are tested.

3.1.3 Device Energy Usage

Energy efficiency is an essential metric for LoRaWAN devices since they are often used in battery-powered IoT sensors. To compare the energy efficiency between different scenarios, the simulation tracks the sleep time, idle time, sending time, and receiving time of all LoRaWAN nodes. Those values are written to the output as percentages used to calculate the actual energy the mean node would have used. Percentages are used to be able to calculate the concrete energy consumption for different devices. In the simulation, every device is considered in sending state while transmitting data. This is tracked as the total ToA of its messages. Using Slotted ALOHA and Scheduled, the device is deemed to be in the receiving the remainder of its slot time to simulate it waiting for and optionally receiving a clock-sync message. The sensing action of LBT devices is tracked for each message as $T_s(SF) \cdot 1.9$ [20]. Random Access does not enter the receiving state. waiting during backoff actions they are considered idling. All other times that the device is not idle, sending or receiving it is tracked as sleeping. An overview of the states tracked in the simulation can be found in Table 3.2. The columns

Table 3.2: Times tracked during simulation

	Random	LBT	Slotted	Scheduled
Sending	Total ToA	Total ToA	Total ToA	Total ToA
Receiving	0	Sensing: $T_s(SF) \cdot 1.9$	Rest of slot	Rest of slot
Idle	0	Backoff time	0	0
Sleep	other	other	other	other

Table 3.3: Lopy 4 LoRa transceiver energy usage [27]

State	Energy usage
Sleep	0.004 95 mW
Idle	5.28 mW
Receiving	39.6 mW
Sending	297 mW

in the table are the different protocols and the rows are the various states. Each cell lists the value tracked for a state using a specific protocol. To get concrete values for the comparisons in this thesis, the energy usage of the Lopy4 LoRa transceiver module is used. The specific values for the states are listed in Table 3.3.

3.2 Protocol Specific Simulation Parameters

In this section, simulation parameters specific to certain protocols are introduced.

3.2.1 Backoff Procedure

For LBT, the backoff procedure is an important parameter. It defines how the device acts when another transmission is detected. The most common backoff procedure is waiting a randomly selected time before retrying the transmission. Here, the length of the backoff time is crucial for its performance. If the chosen value is too small, the retry will interfere with the same transmission it did before. But if the value is selected unnecessarily large, the device will sit idle for an extended amount of time, negatively influencing energy efficiency. Another backoff procedure is retransmitting on a separate channel. The backoff channel selection can be random, or a channel can be explicitly defined for LBT backoff. What a sensible backoff time is and if using a separate channel to backoff to is more efficient will be explored in this thesis.

3.2.2 Clock Drift

All devices using oscillator crystals are bound to express some amount of clock drift due to the imperfect nature of the crystals. The resulting deviation in frequency is measured in parts per million (ppm) [18]. A clock drift of 1 ppm is equal to a drift of 3.6 ms per hour. Because LoRaWAN nodes are usually low-cost IoT sensors with low-quality crystals, a large amount of clock drift can be expected. Periodical synchronizations are required to prevent the clock drift from becoming too large and impacting the timings in a Slotted or Scheduled network. Large clock drifts necessitate more frequent re-synchronizations or larger slot lengths. If the synchronization is done via individual messages by the gateway, the size of Slotted and Scheduled networks is limited by the number of synchronization messages that can be sent during the maximum duty cycle. To prevent this limitation, some works suggest using self-calibration approaches [28]. This thesis uses an average clock drift of 25ppm with a maximum clock drift of 50ppm.

3.2.3 Slot Length

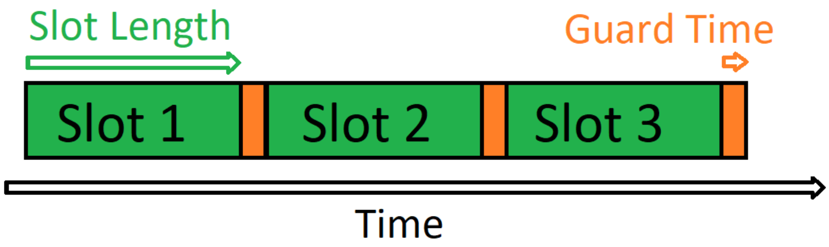

Figure 3.1: Slot length and guard time visualization

The slot length defines the start time between two transmissions for devices using Slotted ALOHA or Scheduled as their MAC protocol. Figure 3.1 visualizes the slot length and guard time for three slots on a single channel. The slots are represented by the three green boxes, which are directly followed by three guard time slots. Both slot length and guard time are values defined in the network configuration. The slot length is determined by the maximum time a communication with the gateway takes. The guard time is added to deal with the clock drift of devices. In the simulation for this thesis, slot length and guard time are defined as one value L_s. It is calculated as the sum of the maximum ToA of any message in the network $max(ToA_{payload})$, the maximum ToA of a synchronization reply of the gateway $max(ToA_{sync})$, and double the maximum hourly clock drift $max(T_{drift})$. A randomness variable r is added to deal with additional random clock drift.

$$L_s = max(ToA_{payload}) + max(ToA_{sync}) + 2 \cdot max(T_{drift}) + r$$
$$L_s = 3.023s + 0.926s + 2 \cdot 0.36s + 0.036s = 4.705s$$

This gives a slot length of 4.705 s which is used throughout this thesis for Slotted ALOHA and Scheduled devices.

3.3 Simulation Concept and Implementation

The simulation for this thesis models the traffic between multiple sensors and multiple gateways on multiple channels in a LoRaWAN. It is split into two logic parts: the initialization and iteration stages. In the initialization stage, the network with gateways and sensors is set up, and transmissions are generated. In the iteration stage, the transmissions are iterated, checked for collisions, and further protocol-based logic is run.

Configuration Gateways are configured with an x and y coordinate and a percentage of nodes around it. Channel count is globally defined as an integer, and channel selection is configured for uplink messages, sync messages, and LBT backoff separately. Sensors have MAC protocol, transmissions per hour, maximum time drift, and minimum/maximum payload as parameters.

General The simulation is built using object-oriented programming in python. Each gateway, sensor, and transmission is represented by an object. The transmissions are saved in a sorted array. The time drift for Slotted ALOHA and Scheduled is modeled as an offset value saved to each sensor that is always increased for the subsequent transmission. Transmissions are initialized with an origin and target device, a start time, ToA, SF, and a channel. When time drift is modeled, the start time and end time of the transmission object are shifted. For resetting the time drift, once a sync message is received, the start time is saved unchanged a second time.

Initialization In the initialization stage, the sensors are generated and randomly assigned to a gateway taking into account the gateways node percentage. They are then spread around their gateway uniformly, and their SF is chosen based on the Hata model. Based on the configured selection method, a channel is chosen, the sensor's payload size is randomly selected, and the ToA is calculated. The sensors are also assigned a random initial time drift. After the sensors have been created and configured, the transmissions for the sensors are generated and saved into an array. For Random Access and LBT devices, random transmission times each hour are selected. For devices using Slotted ALOHA, random slot starts are chosen as transmission start times. The time drift for the first transmission is increased. For devices using the Scheduled protocol, a random slot selection is generated for each channel on each gateway. The slot selection is generated using the "random.sample" function, which chooses items from a sequence without replacement. Each scheduled device is assigned one of the slots in which a transmission is created each simulated hour. After their transmissions have been created, the time drift for the first transmission is increased. Once all transmissions have been created, they are sorted by their start time.

Iteration In this stage, the sorted transmissions list is iterated. The most essential thing in the iteration stage is the collision check. Simply checking the start time of the current transmission with the end time of the previous transmission is not enough to handle all cases. This is because another transmission might have drifted into the current one and would not be checked against. It can also happen that when three or more transmissions collide, one of them would not be found as a collision. Figure 3.2

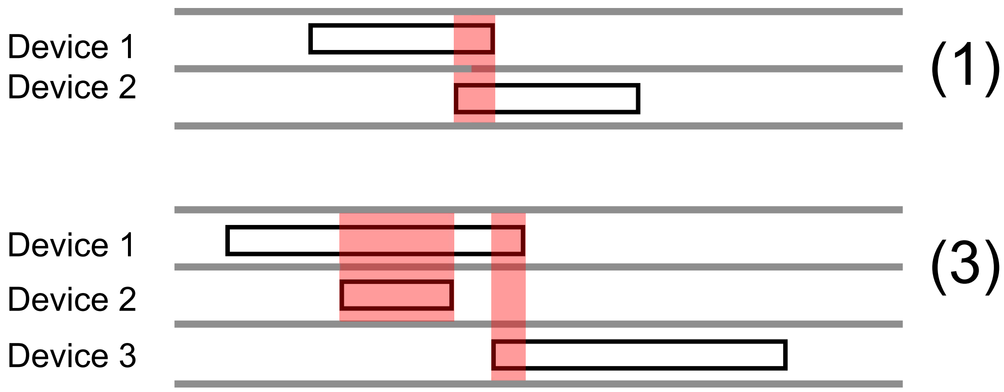

Figure 3.2: Examples of collisions

shows an example for one of those cases. In the figure, two situations are depicted where multiple devices (1-3) are transmitting on the same channel. Transmissions are shown as black boxes, and the rectangular red overlays indicate colliding transmissions. In case (1), a simple collision between two transmissions is depicted. This could be detected by a simple end-start time comparison of following transmissions. Case (2) shows a situation where the transmission of device two is shorter than that of device one and happens entirely during device one's transmission. Thus, there is one collision between device one and device two and one collision between device one and device three. If the transmissions were only checked against their predecessor, the transmission of device three would only be checked against that of device two, resulting in the collision between device one and device three not being detected. To correctly detect all collisions, all transmissions that end less than a slot length before the current transmission starts are checked for collisions. If a collision is found and the device uses LBT, it is checked if the device can detect the other transmission and if detectable the backoff procedure is executed. For devices using the Slotted ALOHA or Scheduled protocol, it is checked if the time drift exceeds the maximum time drift threshold. If it does, a new sync transmission from the gateway to the sensor is enqueued in the transmission list. Furthermore, the time drift of the sensor and its subsequent transmission is increased. If the current transmission is a time sync message and does not collide, the time drift of the target sensor and its subsequent transmission is reset to zero. An overview of all important variables set and conducted during the simulation process is summarized in Table 3.4.

Restrictions The collision detection of the simulation is making some assumptions. First, this simulation assumes that any overlap of transmissions on the same channel leads to failed transmissions. But LoRaWAN SFs are quasi-orthogonal, which means transmissions using different SFs appear as noise, and only intense noise will lead to a loss of the transmission [29]. Secondly, this simulation also does not take into account the capture effect. In some instances, a LoRaWAN gateway can still receive and decode the stronger transmission of a collision [30].

Because of both of these effects, the actual transmission success rate of LoRaWAN transmissions should be higher in real-world conditions. But modeling and implementing either of these effects would significantly increase the complexity of the simulation while not significantly impacting the comparison of different access methods and possibly making interpreting the simulation results more difficult.

Table 3.4: Important variables for the simulation

name	description
#sensors	total number of sensors
#random	number of sensors using Random Access
#lbt	number of sensors using LBT
#scheduled	number of sensors using Scheduled
#slotted	number of sensors using Slotted ALOHA
#transmissions	number of transmissions per hour
#collisions	number of collisions per hour
collisions prob	probability of a transmission to collide
#sync-try	number of synchronization attempts
#sync-succ	number of successful synchronizations
#backoff	number of backoffs per hour
avg backoff	mean backoff time
time sleep	percentage of time a device was sleeping
time idle	percentage of time a device was idle
time sending	percentage of time a device was sending
time receiving	percentage of time a device was receiving

3.4 Pre-Study: Slotted ALOHA with Random Payloads

During initial testing, the collision probability results of Slotted ALOHA were significantly higher than expected, even doubling those of Random Access. The reason for this is the random payload size and spread out SFs used during the simulations, which leads to an average transmission time significantly shorter than the slot length. The used slot length directly drives the collision probability in Slotted ALOHA. A longer slot length decreases the number of slots and thus increases the chance multiple transmissions are started at the same slot. This makes the collision probability mostly independent of the ToA of the individual transmissions. In contrast, the collision probability of Random

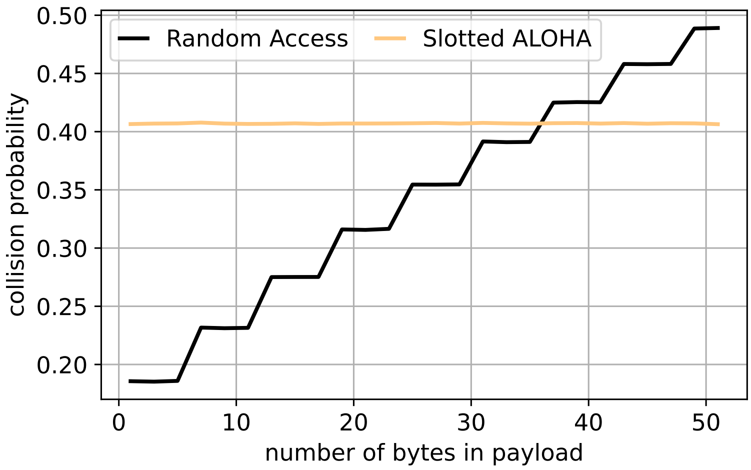

Figure 3.3: Collision probability using Random Access and Slotted ALOHA

Access is directly affected by the ToA of individual transmissions. Slotted ALOHA can deliver a collision probability of almost half of Random Access if most transmissions' ToA is close to the used slot length. However, if the ToA is shorter, the collision probability of Slotted ALOHA will stay the same while the collision probability of Random Access will improve.

To confirm this theory, a LoRaWAN with 400 devices is simulated where the average ToA is varied. The SF of all devices is set to 12, while the payload size is increased gradually from 1 B to 51 B. This raises the message ToA from 925.696 s to 3.023 s. At a ToA of 3.023 s, the message takes up all of the slot dedicated to the uplink transmission, a 0.64 % usage of the slot time. The rest of the slot is reserved for the synchronization messages and padding for clock drift. The clock-drift is set to zero in the simulation, creating optimal conditions for Slotted ALOHA. This simulation is run once for Random Access devices and once for Slotted ALOHA devices.

The results of the simulation are shown in Figure 3.3. The x-axis shows the payload size of all transmission in bytes, the y-axis the collision probability. The black line represents the Random Access simulations, the orange line the Slotted ALOHA simulations. The collision probability of Slotted ALOHA stays constant at 41 %. This is the exact theoretical value of Slotted ALOHA for 400 devices using the slot length 4.704 s. This slot length has been chosen based on the maximum transmission length, sync message length, and guard time 3.2.3. Random Access starts with a collision probability of less than 20 % and gradually increases with larger payload sizes. Only at a payload size of 37 B with a ToA of 2.498 s does Random Access have a higher collision probability than Slotted ALOHA. In LoRa, one symbol encodes multiple bytes depending on the coding rate, SF, and multiple LoRa configuration values. This causes the staircase-like increase that can be seen for the Random Access collision probability.

In conclusion, Slotted ALOHA can deliver a better collision probability than Random Access, but the ToA of transmissions needs to be consistent and the slot length chosen accordingly. This means Slotted ALOHA is only a viable MAC protocol for specific LoRaWANs.

The rest of this thesis runs simulations with varying ToA, which is why Slotted ALOHA will not be evaluated.

3.5 Scenarios

To investigate the scenarios of multi-channel LoRaWAN, this thesis first compares the different protocols in a single-channel environment to generate baseline data. Afterward, different multi-channel setups will be tested.

3.5.1 Single Channel Protocol Comparison

To get a baseline for the following multi-channel comparison, first a single channel comparison of the different protocols is made. For this single-channel LoRaWANs using different access protocols are simulated. In all of the scenarios the minimum payload is 1 B and the maximum payload 51 B. This simulates LoRaWANs with a wide range of different devices. All devices are spread uniformly over a circular area around the gateway, with their SF chosen using the Hata model based on their distance.

S1.1 - S1.3 represent networks where all devices use the same access protocol. S1.1 simulates networks from one to 800 devices in steps of 1 using Random Access as MAC protocol. S1.2 simulates networks from one to 800 devices in steps of 1 using LBT as MAC protocol. S1.3 simulates networks from one to 765 devices in steps of 1 with all devices using Scheduled as MAC protocol. The device count only goes to 765 for the Scheduled simulations because it is limited by the maximum number of slots that fit into one hour. These scenarios are used to make a rudimentary comparison of the different protocols, their collisions probability, and their energy efficiency.

S1.4 - S1.7 represent networks where the count of Random Access devices is gradually reduced while the count of devices using an alternative protocol is increased. S1.4 simulates networks of 760 devices where LBT devices gradually replace the Random Access devices. S1.5 simulates networks of 760 devices where Scheduled devices gradually replace the Random Access devices. S1.6 simulates networks of 250 devices where LBT devices gradually replace the Random Access devices. S1.7 simulates networks of 250 devices where Scheduled devices gradually replace the Random Access devices. These scenarios are used to investigate how the collision probability grows when only part of the devices use alternative access protocols and which protocol is the best for a specific percentage. An overview of those scenarios can be found in Table 3.5.

Table 3.5: Protocol comparison scenario definition overview

name	protocol type	SF	#sensor	min. payload	max. payload
S1.1	Random Access	7-12	1-800	1 B	51 B
S1.2	LBT	7-12	1-800	1 B	51 B
S1.3	Scheduled	7-12	1-765	1 B	51 B
S1.4	Random Access, LBT	7-12	760	1 B	51 B
S1.5	Random Access, Scheduled	7-12	760	1 B	51 B
S1.6	Random Access, LBT	7-12	250	1 B	51 B
S1.7	Random Access, Scheduled	7-12	250	1 B	51 B

3.5.2 Sensor Channel Selection

To evaluate the impact of the channel selection on the collision probability, different network layouts with the same ratio of sensors to channels $\frac{\#sensors}{\#channels}$ are simulated. As a baseline, a single channel network with 500 sensors is simulated in S2.1. This is compared to a network with two channels and 1000 devices in S2.2 - S2.4 and a network with six channels and 3000 devices in S2.5 - S2.7. For both multi-channel networks, different channel selection methods are simulated. With "random" channel selection, used in S2.2 and S.2.5, each sensor independently selects a random channel to transmit on. This can lead to an uneven distribution of sensors between channels. To test an even distribution, "Split perfectly" assigns channels to devices using a round-robin approach. "Split Perfectly" is simulated in S2.3 and S2.6. Lastly the method "based on SF" assigns channels based on each devices' SF using the calculation $channel = (sf - 7) \bmod \#channels$. This is simulated in S2.4 for three channels and S2.7 for six channels.

To keep the scenarios as consistent as possible only Random Access is used as a protocol, and the sensor positioning and thus the SF distribution is kept uniform. The maximum clock drift is also kept at 50ppm, and the minimum payload size is kept at 1 B. The maximum payload size is kept at 51 B respectively.

An overview of those scenarios can be found in Table 3.7 with an overview of the general configuration in Table 3.6.

Table 3.6: General configurations

Channel count	3
Simulation time	24 hours
Payload minimum	1 B
Payload maximum	51 B
Maximum drift	50 ppm
Sensor distribution	Uniformly around gateway

Table 3.7: Protocol comparison scenario definition overview

name	protocol type	channels	#sensor	channel selection
S2.1	Random Access	1	1-500	Random
S2.2	Random Access	2	1-1000	Random
S2.3	Random Access	2	1-1000	Split perfectly
S2.4	Random Access	2	1-1000	Based on SF
S2.5	Random Access	6	1-3000	Random
S2.6	Random Access	6	1-3000	Split perfectly
S2.7	Random Access	6	1-3000	Based on SF

3.5.3 Using Channels for Protocols

In this scenario, channels are assigned based on the devices' used channel access protocol. The goal is to investigate if assigning them a certain way can improve the collision probability or energy efficiency. For this, the same network with three channels is simulated multiple times, with the only variation in the setup being the distribution of protocol. The payload size is kept random between 1 B to 51 B and the maximum drift is kept at 50 ppm. The devices are distributed uniformly by area around the gateway and are assigned their SF according to the Hata model. An overview over the general configuration values can be found in Table 3.8. Scheduled MAC and its number of slots limit the number of devices per protocol. A slot length of 4.704 s results in 765 possible slots per hour. The simulations use a network of 2250 devices, 750 Random Access devices, 750 LBT devices, and 750 Scheduled devices. The number of devices using each protocol is not changed during the different simulations as this would influence the results. Instead, the distribution across the channels is changed. A list of the different distributions can be found in Table 3.9. In S3.1, the devices with different protocols are equally spread out across the channels. In S3.2-S3.4, one protocol is assigned its own channel, and the other two protocols are equally spread across the remaining two channels. For S3.2, Random Access is assigned its own channel, in S3.3 LBT is assigned its own channel, and in S3.4 Scheduled is assigned its own channel. In S3.5, each protocol is assigned its very own channel.

3.5.4 LBT Backoff Procedure

Different single-channel and multi-channel strategies are feasible for LBT backoff. This scenario aims to investigate if a multi-channel backoff approach can improve the collision probability or energy efficiency of the network. For single-channel backoff the strategies Time Random (1), Time Constant (2), and Continuous Listening (3) are tested. For multi-channel backoff the strategies Channel Random (4) and Channel Set (5) are tested.

Table 3.8: General configurations

Channel count	3
Simulation time	24 hours
Payload minimum	1 B
Payload maximum	51 B
Maximum drift	50 ppm
Sensor distribution	uniformly around gateway

Table 3.9: Protocol distribution across different channels

name	Random Access	LBT	Scheduled
S3.1	250 / 250 / 250	250 / 250 / 250	250 / 250 / 250
S3.2	750 / 0 / 0	0 / 375 / 375	0 / 375 / 375
S3.3	0 / 375 / 375	750 / 0 / 0	0 / 375 / 375
S3.4	0 / 375 / 375	0 / 375 / 375	750 / 0 / 0
S3.5	750 / 0 / 0	0 / 750 / 0	0 / 0 / 750

All backoff strategies are evaluated for networks with 1 to 400 LBT devices. The payload size is kept random between 1 B to 51 B and the maximum drift is kept at 50 ppm. The devices are distributed uniformly by area around the gateway and are assigned their SF according to the Hata model. An overview of the general configuration values can be found in Table 3.10.

In S4.1.1 - S4.1.12 the single-channel methods are compared against each other. First the Time Random (1) strategy is simulated in S4.1.1 with a backoff time randomly chosen between 0.4 s and 1.75 s for each transmission. The Time Constant (2) strategy is simulated in S4.1.2 - S4.1.5 with backoff values of 0.5 s, 1 s, 1.5 s, and 2 s. In S1.6 the devices are simulated using Continuous Listening (3) which is similar to 1-persistent CSMA. The same setups are simulated a second time in S4.1.7-S4.1.12 with cross-traffic from 400 devices Random Access devices.

S4.2.1 - S4.2.9 simulate backoff methods in a four-channel network. First S4.2.1 - S4.2.3 simulate Random Time (1), Channel Random (4) and Channel Set (5) with 800 Random Access devices and 1-400 LBT devices equally spread across all channels. These configurations are used to compare time based backoff and channel based backoff. S4.2.4 - S4.2.6 repeat this comparison butt with all LBT devices assigned to the first channel to compare time based backoff and channel based backoff under a different channel distribution. Lastly S4.2.7 - S4.2.9 simulate different distributions of LBT and Random Access devices across the channels for Channel Set backoff to compare to S4.2.6. S4.2.6 models a network with LBT assigned to one channel and equal Random Access traffic across all channels. S4.2.7 models a network with LBT assigned to one channel, most Random Access traffic on two dedicated channels with some cross-traffic on the LBT channel, and one dedicated backoff channel. S4.2.8 models a network with one dedicated LBT channel, one dedicated backoff channel, and all Random Access traffic on the remaining two channels. S4.2.9 models a network with the LBT and Random Access devices spread equally across three channels and one channel dedicated to backoff messages.

All single-channel configurations are listed in Table 3.11 and all multi-channel configurations are listed in Table 3.12

Table 3.10: General configurations

Simulation time	24 hours
Payload minimum	1 B
Payload maximum	51 B
Sensor distribution	uniformly around gateway

List of backoff strategies

1. Random time: The device will remain idle a random duration before retrying to transmit
2. Constant time: The device will remain idle a constant duration before retrying to transmit
3. Continuous listening: The device will keep listening to the channel and start transmitting as soon as it is free
4. Random channel: The device will randomly choose a different channel and retransmit there.
5. Constant channel: The device will try to retransmit on a set channel. In case that fails, it will follow 1

Table 3.11: Overview of setups for single channel backoff scenarios

name	#chl	#LBT	LBT strategy	backoff time	#Random Access
S4.1.1	1	1-400	Time-Rdm (1)	0.4s-1.75s	0
S4.1.2	1	1-400	Time-Set (2)	0.5s	0
S4.1.3	1	1-400	Time-Set (2)	1s	0
S4.1.4	1	1-400	Time-Set (2)	1.5s	0
S4.1.5	1	1-400	Time-Set (2)	2s	0
S4.1.6	1	1-400	Continuous-Listen (3)		0
S4.1.7	1	1-400	Time-Rdm (1)	0.4s-1.75s	400
S4.1.8	1	1-400	Time-Set (2)	0.5s	400
S4.1.9	1	1-400	Time-Set (2)	1s	400
S4.1.10	1	1-400	Time-Set (2)	1.5s	400
S4.1.11	1	1-400	Time-Set (2)	2s	400
S4.1.12	1	1-400	Continuous-Listen (3)		400

Table 3.12: overview of setups for multi channel backoff senarios

name	#chl	#LBT	LBT strategy	#Random Access
S4.2.1	4	[1-100,1-100,1-100,1-100]	Time-Rdm (1)	[200,200,200,200]
S4.2.2	4	[1-100,1-100,1-100,1-100]	Channel-Rdm (4)	[200,200,200,200]
S4.2.3	4	[1-100,1-100,1-100,1-100]	Channel-Set (5) →4	[200,200,200,200]
S4.2.4	4	[1-400,0,0,0]	Time-Rdm (1)	[200,200,200,200]
S4.2.5	4	[1-400,0,0,0]	Channel-Rdm (4)	[200,200,200,200]
S4.2.6	4	[1-400,0,0,0]	Channel-Set (5) →4	[200,200,200,200]
S4.2.7	4	[1-400,0,0,0]	Channel-Set (5) →4	[200,300,300,0]
S4.2.8	4	[1-400,0,0,0]	Channel-Set (5) →4	[000,400,400,0]
S4.2.9	4	[1-133,1-133,1-134,0]	Channel-Set (5) →4	[267,267,266,0]

4 Evaluation

This section presents and evaluates the results of the simulations conducted for this thesis. First the results of the single-channel protocol comparison are evaluated. Afterwards the results investigating the influence of channel-selection and the results for the protocol dedicated channels are presented and evaluated. Lastly the evaluation of the LBT backoff results is conducted.

4.1 Single Channel Protocol Comparison

The simulations of this section compare the different MAC protocols in a single-channel environment.

Figure 4.1 shows the collision probability of a transmission in a LoRaWAN with all devices using one specific channel access protocol. The plot has the number of end devices in the network on the x-axis and the resulting collision probability on the y-axis. The different colored lines show the various protocols; the dashed line shows the theoretical collision probability for Random Access calculated using $1 - e^{-2\cdot\lambda\cdot b}$. $\lambda \cdot b$ is the offered load with λ being the transmission arrival rate at the gateway and b being the average ToA of a message. The simulated performance of Random Access follows its theoretical performance closely. There is a slight deviation as the simulation describes the probability that a transmission experiences a collision while the theoretical value describes the probability of an overlap at any one point during a transmission. The simulation could calculate the same probability using the total duration of all collisions and the total ToA of all transmissions but this would not be as fitting for this evaluation. LBT significantly improves on the collision probability compared to Random Access with $\frac{2}{3}$ the probability for a network with 800 devices. However, it must be noted that the performance of LBT is directly correlated with the number of devices "hearing" each other. In networks of smaller area the performance will increase while the performance in wider spread networks can deteriorate to that of Random Access in the worst case. The collision probability of Scheduled is constantly zero in the idealized simulation environment. With no cross-traffic blocking time synchronization messages, the clock drift can be well dealt with, and no messages drift far enough to interfere with other transmissions. However, it must also be noted that Scheduled could only be used to a network size of 765 devices, at which point all slots in one hour have been assigned to a device. This limitation can be extended using multiple channels, but it should be considered when deploying Scheduled LoRa devices.

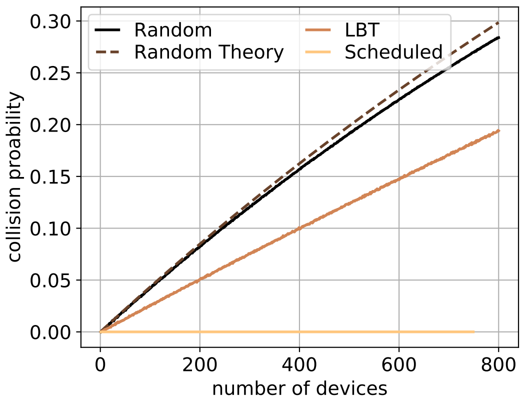

Figure 4.1: Collision probability, 1 - 800 devices, different MAC

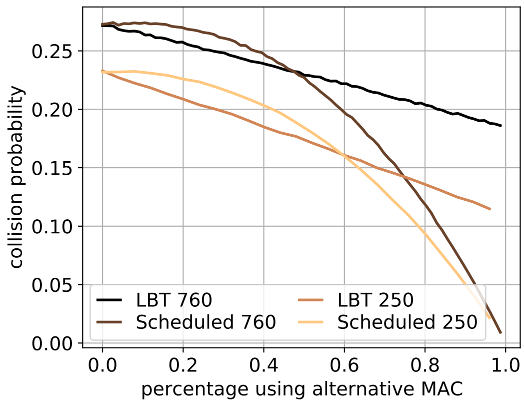

Figure 4.2: Collision probability, varying percentage of devices using alternative MAC, 760 devices and 250 devices

Figure 4.2 shows the collision probability of scenarios S1.4 to S.1.7 in relation to the percentage of devices using an alternative MAC. In the simulations, networks of 760 and 250 devices are gradually changed from using Random Access to LBT or Scheduled MAC. The x-axis shows the percentage of devices using an alternative MAC, and the y-axis shows the collision probability. The black and orange lines have LBT as alternative MAC, the brown and yellow lines have Scheduled. The collision probability in the networks with the LBT devices declines linearly with the percentage of devices using LBT. The network with 250 devices shows a more significant improvement than the one with 760. In contrast to LBT, the collision probability of Scheduled declines exponentially, very slowly at first and fast in the end until it reaches 0 % collision probability. The percentage at which Scheduled performs better than LBT is 48 % for 760 devices and 60 % for 250 devices. This indicates Scheduled MAC being superior to LBT is dependent on the percentage of devices using the alternative MAC. In small networks, only a small number of devices need not use the alternative MAC to make LBT a better option.

Figure 4.3 shows the average energy usage of a device's transceiver per hour in scenarios S1.1 - S1.3. The x-axis indicates the number of sensors, and the y-axis the energy used per hour per transceiver in mWh. Random Access and LBT use around 0.07 mWh which would allow the LoRa transceiver to run off an average AA battery with 2000 mWh for 1202 d while transmitting once per hour. If it were only transmitting once per day, the transceiver would last for around 10 920 d. Slotted ALOHA and Scheduled have a much higher energy usage than Random Access and LBT. After transmitting their data, they wait for the rest of their slot for a synchronization message from the gateway, which uses a lot of extra energy. LBT does not seem to use much more energy than

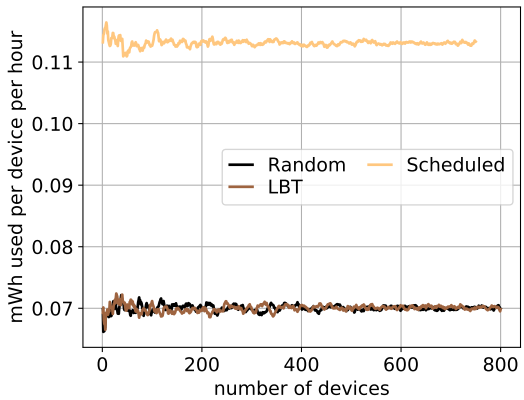

Figure 4.3: Energy usage per device per hour

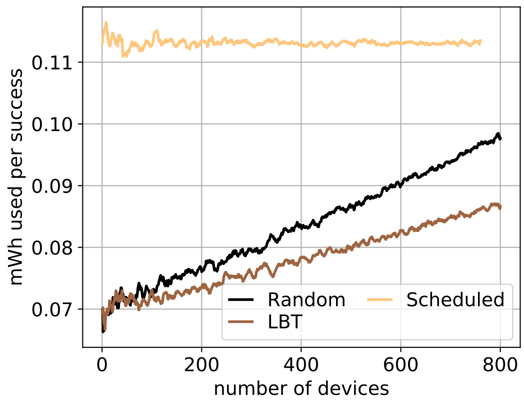

Figure 4.4: Energy usage per successful transmission

Random Access, even though the LBT devices use extra energy during their listening and backoff phases. The energy used during the sleep and transmission phases is significantly more than during the idle and listing phase. Transmitting uses considerably more energy, and the sleep phase is almost 100 % of the time, while the average listening phase is very short and idling uses a relatively small amount of energy. An example of the energy used during the phases for realistic times can be found in Table 4.1. These values are calculated using the LoPy transceiver energy values found in Table 3.3 and average time measurements taken from the simulations. Real LoRa devices have more circuity on board than just a LoRa transceiver leading to higher energy usage during the backoff phase. An investigation into the energy usage of different real-life sensors and simulations using their values would be an interesting addition for a future work.

To consider the different collision probabilities of the protocols, Figure 4.4 shows the energy usage per successful transmission. The x-axis shows the number of sensors, and the y-axis the energy used per successful transmission in mWh. Both Random Access and LBT have a linearly increasing energy usage per successful transmission with an

Table 4.1: Example for energy usage

state	time	energy used
sleep	3600 s	0.004 95 mW
listening	11 ms	0.000 12 mW
idle	3 s	0.0044 mW
transmitting	0.7 s	0.057 75 mW

increasing number of devices because of their decreasing success probability. LBT is slightly more energy efficient than Random Access. Scheduled MAC has a constant energy usage per successful transmission since all its transmissions are successful.

4.2 Sensor Channel Selection

This section presents the results of the simulations described in Section 3.5.2, investigating the impact of the channel selection mechanism on the collision probability in a multi-channel network.

Figure 4.5 shows the collision probability using a perfectly split-channel selection. The x-axis shows the number of devices per channel, the y-axis the collision probability. The lines represent the networks with one channel, two channels, and six channels. The collision probability of the two multi-channel setups is practically the same as in the single-channel setup. Each channel is assigned the same number of end devices, virtually making the multi-channel simulations two and six independent channels, each with the collision probability of a one-channel environment.

The random channel selection delivered similar results to the split channel selection. Between the one, two, and six channel simulations the collision potability stayed the same. This means a random channel selection can be used in practice to approximate a perfectly split selection and keep its performance advantage without the need of any extra complexity to assign channels.

In contrast, using SF based channel selection, the collision probability increases with the number of used channels. Figure 4.6 shows the collision probability using the SF based channel selection. The x-axis shows the number of devices per channel, the y-

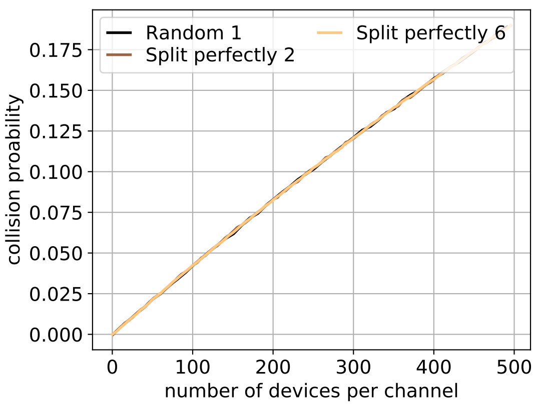

Figure 4.5: Collision probability; Split perfectly channel selection; 1,2, and 6 channels

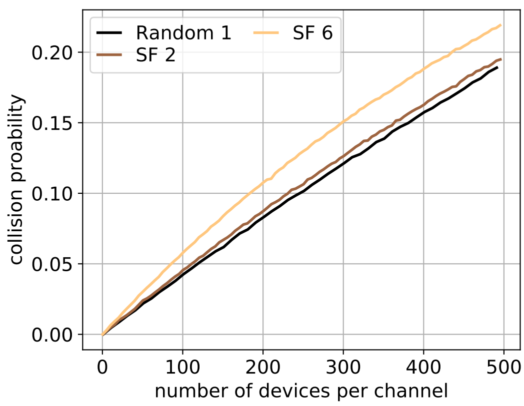

Figure 4.6: Collision probability; SF based channel selection; 1,2, and 6 channels

axis the collision probability. The lines represent the networks with one channel, two channels, and three channels. While the collision probability is only slightly higher than the single-channel baseline in the two-channel network, it is significantly higher in the six-channel network. At 500 devices per channel, the six channel network has a more than 20 % higher collision probability. The sensors are distributed uniformly over the area around the gateway and assigned their SF based on their distance. Circle area grows quadratic relative to the radius leading to more devices being placed further away from the gateway and getting assigned a higher SF. This unequal distribution of SFs leads to an unequal distribution of the devices across the channels, which in turn increases the average collision probability. An unequal distribution causes a higher collision probability because the higher probability on the fuller channels affects more devices than the lower probability on the emptier channels leading to a total increase in collisions.

The results of these scenarios show that the channel selection method can impact the collision probability, but the imbalance between channels needs to be significantly large. Only the unbalanced distribution of SFs was able to produce a significant diversion from the single-channel baseline. The results show no noticeable improvement when using a perfectly split selection compared to the random channel selection. A random channel selection should be sufficient for networks not utilizing channels for dedicated tasks.

4.3 Using Channels for Protocols

This section presents the results of the simulations described in Section 3.5.3, investigating whether assigning channels based on protocols can improve the collision probability. Figure 4.7 shows the collision probability in a network of 400 Random, 400 LBT, and 400 Scheduled devices distributed across three channels in different configurations. The x-axis is the maximum SF used in the simulation, while the y-axis is the collision probability. The lines represent the different distributions of the devices across the channels. All distributions have the same exponential growth based on their maximum SF. With a larger maximum SF, the simulations placed devices further away from the gateway, increasing the potential for hidden nodes and increasing the average ToA of a transmission, thus increasing the chance for collisions.

The highest collision probability is reached when the devices are equally distributed across the three channels. Random Access devices assigned to a dedicated channel with LBT and Scheduled devices equally distributed across the remaining two channels delivers the same collision probability as LBT assigned a dedicated channel and Random Access and Scheduled distributed. It is slightly lower than all protocols being spread out. The lowest collision probability is reached with Scheduled being assigned a dedicated channel and all protocols being assigned a dedicated channel. Based on the results, it can be concluded that only the separation of Scheduled improves the collision probability. A Scheduled device will never collide with another Scheduled device on the same channel

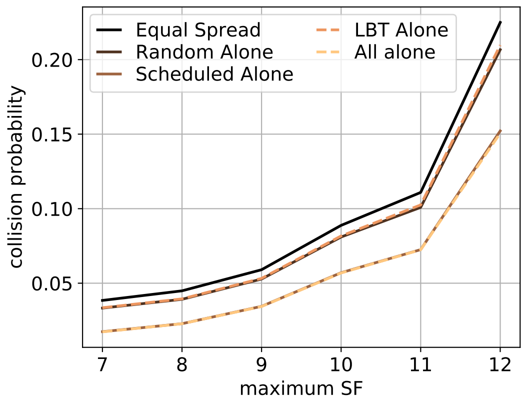

Figure 4.7: Collision probability for different channel distributions

thus assigning it a dedicated channel prevents all Scheduled transmission from colliding with Random and LBT transmissions. If all devices are distributed across three channels, the Scheduled devices can collide with any of the other 800 devices. If Random or LBT are assigned a dedicated channel, the Scheduled devices share two channels with only 400 devices of the other protocol, reducing the pool of transmissions to collide with by half.

The results clearly show that in a LoRaWAN with Scheduled devices, it is highly advisable to assign all Scheduled devices to a dedicated channel without cross traffic. Furthermore these results conform that lower SFs significantly improve on the collision probability.

4.4 LBT Backoff Procedure

This section presents the results of the simulations described in Section 3.5.4, comparing different single-channel and multi-channel backoff methods. The collision probability between the different methods in S4.1.1 - S4.1.6 and S4.1.7 - S4.1.12 is similar. The metrics of number of backoffs and total time of backoffs are used to compare their performance.

Figure 4.8 shows the average time a device is in a backoff state per hour, which includes sensing the medium and waiting. The x-axis shows the number of LBT devices in the network, while the y-axis shows the average time a device spends in the backoff state. The different colors represent the different single-channel backoff methods Random Time, Set Time 0.5 s, Set Time 1.0 s, Set Time 1.5 s, Set Time 2.0 s, and Continuous Listening. The average backoff time increases linearly with the device count. For the Set Time methods it is directly proportional to the time used with Set Time 2.0 s having the longest backoff time and Set Time 0.5 s having the lowest. Random Time is positioned

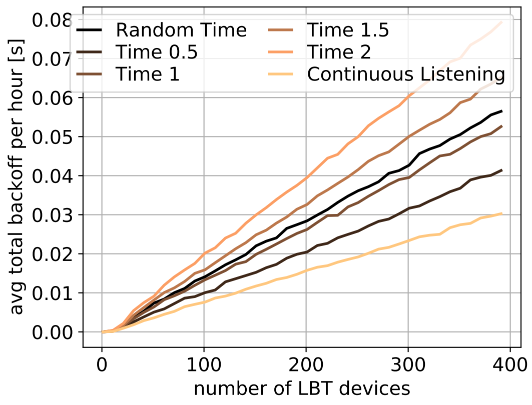

Figure 4.8: Average total backoff time each hour per device, no cross-traffic

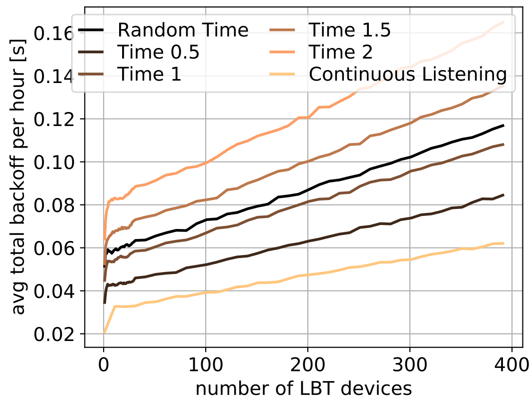

Figure 4.9: Average total backoff time each hour per device, 400 Random Access devices cross-traffic

between Set Time 1.0 s and Set Time 1.5 s based on its average backoff time of 1.08 s. Continuous Listening has the lowest backoff time of all methods with a 60 % lower backoff time than Set Time 2.0 s for 400 devices. The shorter backoff time allows the LBT devices to retransmit earlier than a longer backoff time, thus decreasing the total time spent backing off. However, this also means the devices spend more time sensing the channel, which might use more power depending on the specific end-device. The energy usage of the LoRa transceiver itself is not greatly influenced by the change in idle/listening time, as shown in Section 4.1. The same linear increase can be seen in Figure 4.9, which shows the average backoff time per hour, but with 400 Random Access cross-traffic devices. The x-axis indicates the number of devices, while the y-axis shows the total backoff time. The Set Time methods follow a similar linear growth with Set Time 2.0 s having the highest backoff and Set Time 0.5 s having the lowest backoff. The Random Time method places again between Set Time 1.0 s and Set Time 1.5 s and Continuous Listening still has the lowest backoff time. Based on this, it can be concluded that Continuous Listening will always result in the lowest possible backoff time as it retransmits as soon as the medium is sensed empty. However, sensing has a higher energy consumption than idling, making continuous listening potentially less energy efficient than time-based backoffs. Because of this, a time based backoff should be better for single-channel LoRaWANs. The optimal duration for a time based backoff depends on the ToA of the transmissions in the network.

Figure 4.10 compares the total backoff time of single-channel Random Time and multi-channel Random Channel and Set Channel backoff. The scenarios of the graph show a four-channel network with up to 400 LBT devices equally distributed across the channels and 800 Random Access devices distributed across the channels. The x-axis of the graph

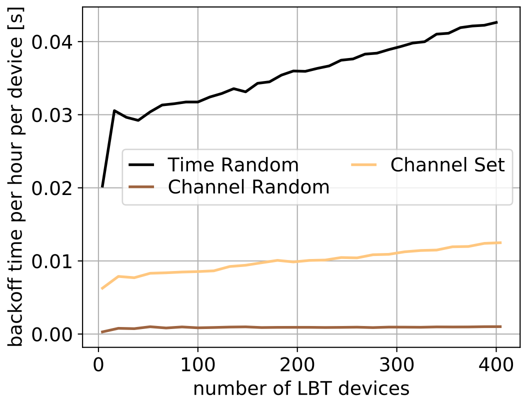

Figure 4.10: Backoff time per device per hour for different multi-channel backoff methods, LBT distributed across channels

is the number of LBT devices in the network, while the y-axis is the total backoff time per device per hour. The Random Time approach has the highest backoff time because it relies on waiting a random period until a re-transmission is tried. Channel Set has a significantly lower backoff time but is still higher than Channel Random. This is because in case the backoff channel of Channel Set is occupied, it falls back to the Random Time method, which increases its backoff time significantly. In contrast, the backoff time of Channel Random is closing in on zero, because the device will keep changing channels until an unoccupied channel is found, leading to its backoff time mainly consisting of the channel sensing action. The collision probability for the different methods is very similar.

Figure 4.11 and Figure 4.12 show the collision probability and total backoff time per device per hour for networks using Set Channel backoff and different LBT and Random Access channel distributions. The x-axis of Figure 4.11 shows the number of LBT devices, while the y-axis shows the collision probability. The lowest collision probability is achieved when all LBT devices are assigned to one channel and the Random Access devices are spread out. In all other configurations, the increased collisions of Random Access outweigh the gains through an improved LBT performance. The Random Access devices distributed across three channels, all LBT devices on one channel and one channel reserved for backoff has a similar collision probability as the Random Access devices and LBT devices equally distributed across three channels with one channel reserved for backoff. Both have a significantly higher collision probability than the first distribution. For two channels Random Access devices, one channel LBT, and one channel LBT backoff the collision probability actually decreases with more LBT devices. The added LBT devices do not increase the collisions with Random Access messages while

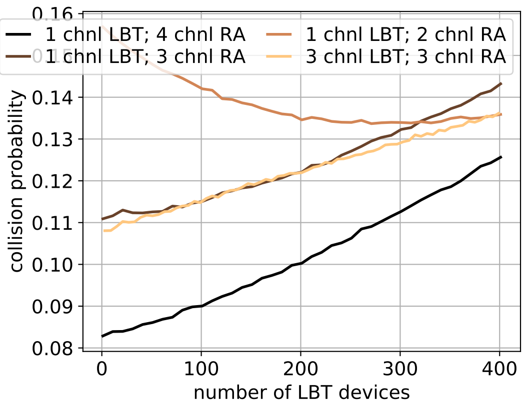

Figure 4.11: Collision probability using Set Channel and different channel layouts

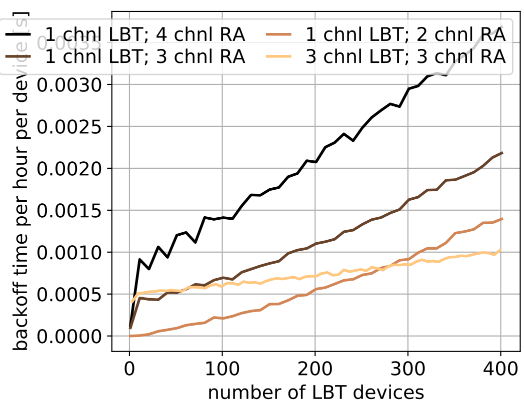

Figure 4.12: Backoff time per device per hour using Set Channel and different channel layouts

themselves having a lower collision probability. This causes the average probability in the network to decrease.

Figure 4.12 shows the backoff time per hour per device for these distributions. The longest backoff time is reached by one channel LBT and Random Access equally distributed across all channels. The extra Random Access devices on the LBT channel cause more collisions and thus more backoffs. Furthermore, the Random Access transmissions on the backoff channel cause the backoffs to collide and thus trigger Random Time backoffs on top. The second highest backoff time is reached by the Random Access devices distributed across three channels, with the LBT devices on one and the last channel dedicated to backoff. The backoff count is again increased because of the Random Access transmissions on the LBT channel. Because of the dedicated backoff channel, the chance for Random Time backoffs is minuscule. And even lower backoff time is achieved by the two dedicated Random Access channels, one LBT channel and one backoff channel. For LBT device counts below 250, this distribution results in the lowest backoff time. In the case of device counts larger than 250, the lowest backoff time is achieved using the three channels for Random Access and LBT devices and one dedicated backoff channel distribution. The difference between the backoff times for channel hop methods is minuscule. The little saved idle time is not a worthy trade-off for the decrease in collision probability. If the network has Random Access devices, they should be distributed as evenly as possible across the channels to reduce the collision probability as much as possible.

To investigate which backoff method is most suitable in this case, Figure 4.13 and Figure 4.14 compare the collision probability and the backoff time per hour per device in a network with equally distributed Random Access, the LBT devices assigned to one

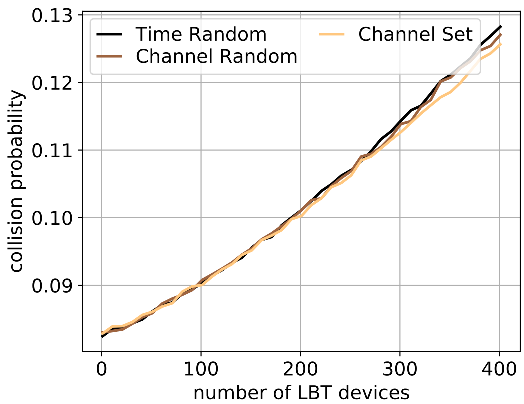

Figure 4.13: Collision probability for different multi-channel backoff methods, LBT on one channel

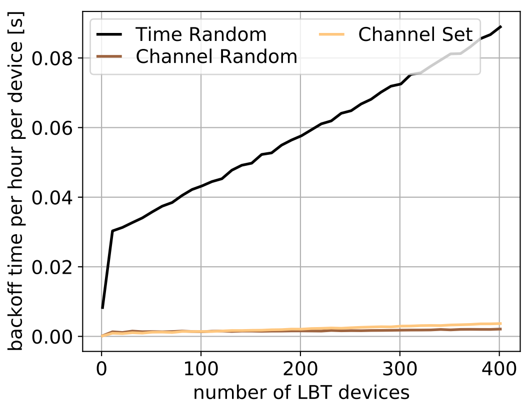

Figure 4.14: Backoff time per device per hour for different multi-channel backoff methods, LBT on one channel

channel, and different LBT backoff methods. The x-axis in Figure 4.13 is the number of LBT devices, while the y-axis is the collision probability. Time Random, Channel Random, and Channel Set all have similar collision probabilities, only slightly deviating from each other at a high device count. Time Random has a marginally higher collision probability than Channel Random, while Channel Set has a slightly lower one. The difference between backoff methods is much more significant with the backoff time, as seen in Figure 4.14. The x-axis is the number of LBT devices, while the y-axis is the backoff time per device per hour. Channel Set and Channel Random have almost zero backoff time, with Channel Set having slightly more. In contrast, Time Random has significantly more backoff time than the channel hop methods. In a multi-channel network, a channel hop backoff method seems superior to a time-based one, decreasing the backoff time and the collision probability. The network setup and device distribution decide if a Set Channel backoff is superior to a Random Channel backoff.

5 Conclusion and Outlook

LoRaWAN is one of the most prominent technologies in the rapidly growing IoT market. However, it has one fundamental drawback: Data transmission based on random channel access, and thus message collision and loss. For that reason, the exploration of alternative channel access methods is essential to future proof LoRaWAN. Channel access methods like LBT, Slotted ALOHA, and Scheduled can increase the channel throughput, and in particular the channel goodput by reducing the collision probability and the number of lost messages. This enables larger LoRaWAN deployments and more reliable communication.

This thesis presents a simulation study for multi-channel LoRaWANs using Slotted ALOHA, LBT, and Scheduled as alternative channel access methodologies. The results of the simulations confirm that alternative access methods can reduce the collision probability by 30 % when using purely LBT. However, the performance of LBT depends on the devices being able to sense each other's messages. Thus, in denser networks, the performance gain is larger than in widely spread out networks. Using Scheduled, collisions can be avoided completely. The energy consumption of the LoRa transceiver module is found to be 65 % higher for Scheduled than for Random Access and LBT. However, this does not take into account the energy consumption of the rest of the LoRa device. The results for the channel selection show that the lowest collision probability is achieved with a uniform distribution of Random Access devices across the channels, which can be approximated using a random channel selection. The performance of a Random Access or a LBT device is shown to be not affected by the protocol choice of the other devices on the same channel. In contrast, Scheduled is highly affected by the other devices and shows significant improvements if the rest of the channel's devices use the same protocol. The results of a simulation with an equal number of devices using Random Access, LBT, and Scheduled show a 45 % decrease in collisions when Scheduled devices use a dedicated channel.

This work shows the advantages alternative channel access mechanisms can have for LoRaWAN. Furthermore, it gives insight into possibilities to improve the collision probability and energy efficiency in multi-channel networks by utilizing an optimal channel selection and LBT backoff procedure. Analysis of different protocol distributions gives advice on improved Random Access, LBT, and Scheduled device distributions across channels to increase the channel throughput.

In particular, the energy usage of the protocols and the different LBT backoff methods should be tackled in future studies. The values used in the thesis are based on a LoRa transceiver module which is only part of a complete LoRa device. A more in-depth energy efficiency study using energy consumption values of multiple real-world sensors would provide additional valuable insights. Another possible expansion of this work is the inclusion of the capture effect in the simulation. In real-world LoRaWANs the transmission strength influences the decoding potential of messages at the gateway, and thus, the collision probability.

Figures

Tables

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Erklärung

Ich versichere, die vorliegende Bachelorarbeit selbstständig und unter ausschließlicher Verwendung der angegebenen Literatur verfasst zu haben. Darüber hinaus versichere ich, die Arbeit bisher oder gleichzeitig keiner anderen Prüfungsbehörde zur Erlangung eines akademischen Grades vorgelegt zu haben.

Würzburg, den 09.02.2022

(Vanessa Pfeiffer)