Generic Model to Quantify Energy Consumption for Different LoRaWAN Channel Access Methods

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***Abstract*—LoRaWAN is one of the most promising Internet of Things technologies with regard to low energy consumption. However, the currently used random channel access has much potential for improvement. Thus, current literature studies alternative channel access approaches, but the energy consumption is often not taken into consideration. For that reason, we present a generic model to quantify energy consumption in LoRaWAN for different channel access mechanisms based on a state machine. With our model, we can describe the energy consumption for specific access mechanisms or for the complete network. Our model shows that random access only performs best if no additional receive windows are opened. A simple improvement is Listen before Talk. For networks with high load, improvements are achieved by a more complex scheduled MAC. Our model serves as a basis for future energy consumption studies, conducted through measurements or simulations.**

***Index Terms*—LoRaWAN, channel access, energy consumption**

I. Introduction

The massive integration and adoption of the Internet of Things (IoT) in our everyday life enables many opportunities, but also comes with new challenges. The distribution of sensors in many rural and urban areas fosters automation and reduces cost by avoiding unnecessary manual maintenance. However, deploying numerous sensors induces costs for hardware and network operation. Luckily, complex network structures and sensor behavior is not expected, nor required for many applications, consumes unnecessary energy, and opposes the vision of more sustainable networks.

Therefore, LoRaWAN increased in popularity in recent years. According to IoT analytics, LoRaWAN already makes up 37 % of the global market share for Low Power Wide Area Network (LPWAN) connections [1]. Furthermore, it is expected that LoRaWAN and Narrowband-IoT will dominate the market in the coming five years [1]. Reasons for the fast growth are the simple network structure, low energy consumption, with a battery life of several years, and transmission possibilities across large distances. However, the drawback of LoRaWAN are small possible data rates.

Nevertheless, technologies like LoRaWAN can help to reduce cost and energy consumption in the access network. Furthermore, it can tailor the network better, based on application areas and needs. But the random channel access approach in LoRaWAN leads to message collisions and data loss, and thus a reduced reliability in data transmission. For that reason, several alternative channel access mechanisms are recently studied in literature [2], [3], [4], but energy consumption, and potential increases in energy requirements compared to the state-of-the-art random channel access in particular, is still neglected. Hence, we investigate the energy consumption for Listen before Talk (LBT), slotted ALOHA, and scheduled MAC as alternatives for a LoRaWAN channel access. The relevant states in a transmission cycle from sensor wake up until its return to sleep mode are examined and a transmission process diagram is presented for all channel access mechanisms. Afterwards, energy consumption equations are formulated for all approaches and different scenarios are studied to investigate energy performance. To this end, real energy consumption values from LoRaWAN sensors are used.

The contribution of this work is to answer the following three research questions: 1) how do alternative channel access approaches perform in comparison to random access from an energy consumption point of view and which one is the best alternative, 2) how do different settings of the channel access approaches, with regard to channel sensing time, receive windows, and additional waiting times influence the energy consumption of the approaches, and 3) what is the influence of message collisions, especially with random access, on the overall energy consumption, and which channel access approach is best suited for which situation?

The remainder is structured as follows. Section II presents background information on LoRa and LoRaWAN and Section II-B summarizes related work. The methodology with a process diagram for all access approaches, the energy model, and a scenario overview is presented in Section III. In Section IV, the scenarios are evaluated and Section V concludes.

II. Background and Related Work

This section summarizes background information for LoRa and LoRaWAN in general, explains details on the transmission procedure of a sensor, and discusses related work at the end.

A. LoRa and LoRaWAN

LoRa is an LPWAN modulation technique based on the chirp spread spectrum. Its major benefits are long transmission distances and little energy consumption leading to battery life times of up to 10 years [5]. However, its drawbacks are a low data rate and unreliable communication because of the random channel access for message transmission. This leads to frequent collisions and data loss. However, recent literature studies alternative channel access approaches to reduce the potential for collisions and thus, improve the general reliability and quality in LoRaWAN.

LoRaWAN Channel Access: The currently used random channel access is similar to pure ALOHA and achieves a theoretical utilization of only 18.4 % [6] that can be increased because of the very robust physical layer [7]. Nevertheless, channel access with slotted ALOHA [2], LBT [3], and scheduled MAC [4] show less collisions and better performance with regard to potential data loss. The drawback of these alternatives is additional complexity by among others, channel sensing or synchronization. Furthermore, the additional overhead can influence the energy consumption of the sensors.

LoRa Message Transmission: The structure of LoRa messages with preamble, optional header, and payload is already well documented in literature, e.g. [8], [4]. However, significant influencing factors on the general transmission behavior, and in particular the airtime of LoRa messages, are the payload size and the Spreading Factor (SF). Other parameters like preamble length, header, and additional flags in the message also influence the time on air. However, this influence is small compared to the SF [4], the values are not adjustable, or set according to standardization. The time to transmit a single symbol T_s is directly influenced by the current bandwidth (BW) that is typically 125 kHz in Europe and the SF between 7 and 12. Thus, the time on air for a single symbol is achieved by $T_s = 2^{\mathrm{SF}}/\mathrm{BW}$. The time on air of one LoRa message is then achieved by multiplying the number of symbols of a single message with T_s. Since the BW value is not changing, the SF and the payload influences the duration an antenna must be powered in a LoRa sensor by the transmission duration. This, however, has the largest impact on the resulting energy consumption. To study the energy consumption of LoRa sensors, next the working sequence of sensors in LoRaWAN is introduced and important phases are outworked. An overview is visualized in Figure 1.

Working Sequence of Sensor Node: The typical working sequence of a LoRaWAN sensor is already discussed in literature [9], [10] and highlighted in the top part of Figure 1. After a sensor wakes up from sleep (1,2), it measures (3) and processes (4) its data. The actual transmission starts after the transceiver wakes up (5,6). Afterwards, optional data is received (7) and the sensor returns to sleep (1). The general data transmission process, that is dependent on the channel access approach, starts with *wake up transceiver* and ends with an optional *data reception*, shown by the bottom part of Figure 1. The remaining working sequence is independent from the access approach and thus, not considered in the energy study in this work. Different access approaches can add channel sensing (LBT) or a pre-defined waiting time (slotted ALOHA) after transceiver wake up or before transmission start. After a transmission, optional receive windows can be opened. If data is received in these windows, an additional process *data procedure* is required. Note, if additional wait, listen, or other procedures are added for different channel access approaches, the sleep duration is also influenced. This influence is small because of little energy consumption during sleep for LoRaWAN transceivers [10] and the little change in sleep duration compared to the total sleep time.

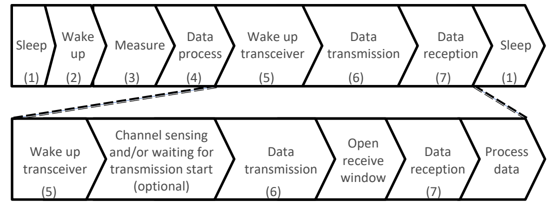

Figure 1: LoRaWAN transmission schedule workflow.

B. Related Work

LoRaWAN channel access was first studied in 2016 [8]. Since then, in particular studies with slotted ALOHA [2], LBT [3] or scheduled MAC [4] are promising. Different CSMA adaptations are investigated by simulations [11], but lack simple and efficient deployment. In addition, more detailed analyses of different channel access techniques extended for example slotted ALOHA [12]. Other ideas to reduce collisions in LoRaWAN are, among others, intelligent gateway planning [13], [14], adaptive data rate adjustments [15], or the use of redundancy [16]. In [17] the performance and energy efficiency of pure and slotted ALOHA, as well as non-persistent CSMA is modeled and perfect CSMA is modeled in [18]. In addition, different works study the energy consumption of a LoRaWAN sensor from wake up until its return to sleep mode [9], [10]. LoRaWAN device classes are compared in [19], power consumption studies for LoRaWAN in general are conducted in [20], and in [21], power optimization potential for LoRaWAN is examined. A simple energy model for channel access is already discussed in [22]. However, to the best of our knowledge, this is the first study that provides a model for a comprehensive energy comparison for several channel access approaches in LoRaWAN that includes a numerical evaluation.

III. Methodology

In this section, we model the energy consumption of one transmission for different channel access mechanisms and introduce an abstraction that allows the aggregation of different individual states with different behavior for energy modeling.

A. Channel Access as Process Diagram

The LoRaWAN channel access can be displayed as a process diagram, dependent on the channel access mechanism. Figure 2 shows this diagram of a transmission cycle for LBT, Random Access (RA), scheduled MAC as well as slotted ALOHA. The relevant part of a LoRaWAN transmission cycle with respect to energy consumption starts when the transceiver is powered and ends before the sensor returns to sleep. Table I summarizes the assumed states during a message transmission.

Process Diagram: A LoRaWAN channel access process diagram can be established with the following states, as shown in Figure 2. After the transceiver is powered on in state (S1), the channel access approach is selected. Note, sensors do not

Table I: Transmission states.

State	Name	Description
S1	wake up	Activation of transceiver module
S2	transmit	Transmission of payload data
S3	waiting	Waiting before next state transition
S4	listen	Channel sensing for ongoing transmission
S5	open receive window	Preparation for listening to incoming messages
S6	receive	Active receiving of a message
S7	processing	Processing of data before next transition

perform this distinction in general but we aggregate multiple channel access mechanisms in the same diagram to save space.

Random Access and Scheduled MAC: After the transceiver wakes up (S1), random access and scheduled MAC start immediately with data transmission (S2). Afterwards, optional receive windows may be opened (S5), data is received (S6), and further processing is performed (S7). When data is received or processed, another transmission cycle is possible, shown by the arrows back to (S2) after (S6) and (S7). The difference between random access and scheduled MAC is the state possibilities. Random access can be used without any receive window or data reception but for scheduled MAC, both (S5) and (S6) are required after each transmission to receive potential re-synchronizations. This also leads to a higher probability for state (S7) where received data is processed.

Slotted ALOHA: In contrast, the sensor waits (S3) for the next sending slot before it starts its transmission in slotted ALOHA. Afterwards, the state transition is according to random access or scheduled MAC. However, if another transmission cycle is started after (S6) or (S7), potentially another waiting state (S3) is required (this is not added to the diagram since its only optional for slotted ALOHA). This depends on the length of the slots and the time on air of the already transmitted messages in this slot.

Listen before Talk: First, it is determined whether the channel is occupied (S4) when LBT is used. If this is the case, the sensor waits (S3) until the next channel sensing is performed. If the channel is free, the sensor starts a transmission similar to the random access procedure. Furthermore, receiving data in state (S6) can be seen as channel sensing and the next transmission can immediately start. Thus, a transition between (S6) and (S2) is possible. Note that this transition is only possible if data receive is similar to channel sensing. If this is not possible, a transition to state (S4) is required. A transition from (S7) to (S4) is possible if additional data is processed. Here, we assume that additional channel sensing is required after a specific time of data processing.

B. *Channel Access Energy Model*

Based on the process diagram shown in Figure 2 and the time a sensor remains in a specific state, the energy consumption of different channel access approaches can be described. If t_x is the time a sensor is in state x, the complete time for one transmission T_{RA} for random access can be expressed by

$$T_{RA} = t_1 \cdot s_1 + t_2 \cdot s_2 + k(t_5 \cdot s_5) + t_6 \cdot s_6 + t_7 \cdot s_7, \quad k \in \mathbb{N}_0, \quad (1)$$

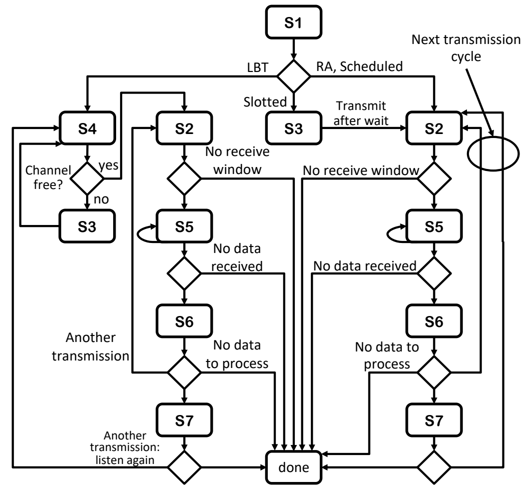

Figure 2: LoRaWAN channel access process diagram.

with s_x as the specific state and k as the number of receive windows. The required time T_S for a complete scheduled MAC transmission process can be computed analogously. The difference is only expressed by different t_x values and different probabilities for specific states. For slotted ALOHA, the time T_{Sl} can be computed via

$$T_{Sl} = t_3 \cdot s_3 + T_{RA}, \quad (2)$$

where a waiting time t_3 is added to the time required for a random access transmission T_{RA} with different state times and probabilities. Finally, the required time for a LBT transmission T_{LBT} can be expressed with

$$T_{LBT} = l(t_4 \cdot s_4) + (l-1)(t_3 \cdot s_3) + T_{RA}, \quad l \in \mathbb{N}, \quad (3)$$

with l channel sensing operations and thus, $(l-1)$ waiting states and again, different state times and probabilities compared to random access. Note that all computations follow the same principle as T_{RA}. However, the specific times a sensor remains in the states differs between the access technologies.

Energy State Reduction: While all states in the process diagram are required for a comprehensive description of a LoRa transmission, several states can be aggregated from an energy consumption perspective. First, each *open receive window* is practically spoken a *wait* and a *listen* operation if no data is received, and a *receive* operation if data is received. Furthermore, each *listen* operation is similar to *receive*. In addition, the *wake up transceiver* state (S1) is required for all channel access mechanisms, and thus independent of them. For that reason, it is not further investigated in this observation. If the energy consumption in state x is denoted as E_x for $x \in 2,3,6,7$, the energy consumption for random access can be denoted as

$$E_{RA} = t_2 \cdot E_2 + (k \cdot t_{5'} + t_6) \cdot E_6 + t_{3'} \cdot E_3 + t_7 \cdot S_7, \quad k \in \mathbb{N}_0 \quad (4)$$

with $t_{5'}$ as listening duration and $t'_{3'}$ as waiting time when a receive window is opened, and $t_{5'} + t_{3'} = t_5$. The energy consumption E_S for scheduled MAC can, again, be computed analogously.

For slotted ALOHA, the same changes are performed as for random access which lead to $E_{Sl} = t_3 \cdot E_3 + E_{RA}$. For LBT, the equation is updated to

$$E_{LBT} = l(t_4 \cdot E_6) + (l-1)(t_3 \cdot E_3) + E_{RA}, \quad l \in \mathbb{N}. \quad (5)$$

Note that the time spent in each state may differ between mechanisms again.

Complete Network Description: While a detailed view on all channel access approaches is given above, a general view on the complete network is required to describe the performance and energy efficiency of a LoRaWAN deployment. For that reason, we assume n sensors in the network while p_{RA} percent use random access, p_S percent use scheduled MAC, p_{Sl} percent use slotted ALOHA and p_{LBT} percent use LBT. Thus, the expected energy consumption for a single transmission in a deployment can be denoted as

$$E_{all} = p_{RA} \cdot E_{RA} + p_S \cdot E_S + p_{Sl} \cdot E_{Sl} + p_{LBT} \cdot E_{LBT}. \quad (6)$$

In combination with information on the transmission rate, e.g. once an hour per sensor, the expected energy consumption for all sensors in a network can be computed.

C. Numerical Results and Scenarios

To study the influence of the channel access approach on the energy consumption, different scenarios are outlined and discussed in the following parameter study. Therefore, all variable parameters are introduced first.

Variable Parameters: In the process of data transmission in LoRaWAN, several adjustable parameters influence the energy consumption in each state, either dependent or independent on the channel access approach. The energy consumption values are from the official Semtech datasheet for the SX1272 transceiver [1] for 3.3 V supply voltage, like typically used in literature [9], [10]. Since all values are dependent on the individual time a sensor is in the specific states, the energy consumption values are noted for 1 s duration.

Transmission S2: The transmission duration and the energy required to power the antenna and thus, the sending strength, influence the energy consumption of a sensor during a transmission most. Since the transmission duration in LoRa is determined by the number of symbols to transmit and the SF, both parameters influence the energy consumption. However, in general, all factors are independent on the channel access approach. The energy consumption from the SX1272 transceiver used for transmissions in this work are 0.059 J for +7 dBm, 0.092 J for +13 dBm, 0.297 J for +17 dBm, and 0.413 J for +20 dBm.

Wait/Idle S3: An idle or wait status is required for all channel access mechanisms before a receive window is opened. In addition, an idle period is added after transceiver wake up until the start of the upcoming slot in slotted ALOHA. Thus, this period is dependent on the wake up time and the slot length. When LBT is used, the idle period is dependent on the channel activity detection and the back-off duration. If the channel sensing in state S4 detects another message, an idle period of time t_3 is added. The value of t_3 is an implementation specific parameter while the energy consumption during idle is 4.95 μJ.

Receive S6: The main reason for a receive state for all approaches is to open receive windows and get acknowledgments for transmitted data. The energy consumption for these windows is dependent on the number of receive windows, the duration, and the power required for the sensor's antenna. Additional optional receive windows are implementation specific and can be opened for among others, negative acknowledgments, data rate adjustments, or clock synchronization. In particular, the clock synchronization reception is only required for slotted ALOHA and scheduled MAC transmissions. The energy consumption to receive data is 0.035 J - 0.037 J for Semtechs SX1272 transceiver.

Process S7: Last, the energy consumption to process data is dependent on the processing task. For random access or LBT, for example, only an acknowledgments or general transmission specific updates must be processed. In contrast, time re-synchronizations need to be processed for slotted ALOHA and scheduled MAC. Thus, energy consumption to process data can vary a lot. For example, 1.8 μJ is measured in [9].

IV. Evaluation

This section presents scenarios to answer the research questions and discusses and analyzes each scenario in detail.

A. Scenario Description

The scenarios are established to analyze the influence of the channel access approach on the energy consumption. Therefore, the energy consumption for all approaches is studied dependent on the time on air for the transmission, sending strengths, and based on channel access approach specific differences in scenario *Sc 1*. It is designed to answer the first research question, how alternative channel access approaches perform. Afterwards, the influence of adaptation in access approaches and thus, different duration in specific states is discussed to answer the second research question in scenario *Sc 2*. Therefore, the influence of variable number of receive windows, number and duration of back-off delays for LBT, and re-transmission is studied. Please note, the first receive window is opened 1 s after transmission according to standardization [9]. We model the receive duration with 1 s to be able to receive also small messages transmitted with SF 12 (0.93 s for 1 B - 5 B payload) and open the next receive window 1 s after the first one is closed. Last, we assume message collision in the network. Thus, we answer the third research question on how message collision influences the energy consumption for the channel access approaches by studying the energy consumption per correctly received message in scenario *Sc 3*.

B. Energy Consumption for Channel Access Approaches

Initially, the energy consumption for the different channel access approaches, random access, slotted ALOHA, LBT, and scheduled MAC is compared. However, since slotted ALOHA consists of a short idle period before a random access-like

[1] https://www.semtech.com/products/wireless-rf/lora-core/sx1272

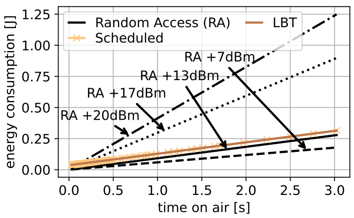

Figure 3: Energy consumption for channel access approaches (Sc 1).

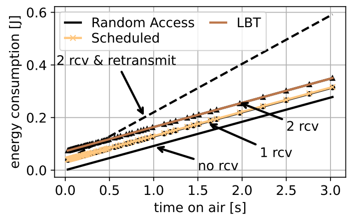

Figure 4: Energy consumption for variation in approaches (Sc 2).

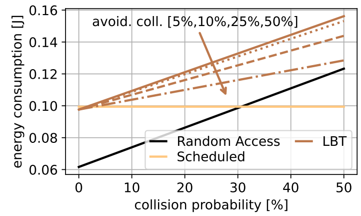

Figure 5: Energy consumption for variable collision probabilities (Sc 3).

Table II: Scenario overview.

Scen.	Research goal	Variables for energy consumption
Sc 1	General energy consumption study for all access approaches	Transmission time on air, sending strength
Sc 2	Study influence of access approach adaptation	Number receive windows, number and duration of backoff delays, processing consumption
Sc 3	Study influence of message collision	Message collision percentage

transmission, and only 4.95 μJ are required for idle, this mechanisms is not studied in detail since it behaves similar to random access. Slotted ALOHA is also only practical in deployments with a fixed time on air for all transmissions [4]. The energy consumption for the remaining approaches is compared in Figure 3. The y-axis shows the energy consumption in Joule, the x-axis the time on air. The colors show the different channel access approaches and the solid lines present a sending strength of +13 dBm for all approaches as reference. For random access, the result for a sending strength of +7 dBm, +17 dBm, and +20 dBm is highlighted by the different line types as annotated in the figure. LBT and scheduled MAC perform similar since the receive window opened after each transmission requires the same energy. However, by decreasing the duration of listen or receive times, the energy consumption decreases, with the lower limit equal to the random access approach displayed by the solid black line. In addition, higher energy consumption for a processing task increases the energy consumption for scheduled MAC linearly. Thus, it must be avoided that the processing task dominates other consumption factors. Furthermore, the sending strength dominates the usage of alternative channel access methodologies by far. Only very small messages with a time on air of less than 0.1 s show better results with higher sending strength. For larger messages, it is advisable from an energy consumption perspective to use alternative channel access methods or also accept a message loss and start a re-transmission.

Thus, the answer to our first research question is *LBT and scheduled MAC as alternatives to random access increase the energy consumption at a first glance. However, the increase can be limited by reducing the sensing duration with LBT or the processing overhead with scheduled MAC. Furthermore, the additional energy consumption for a larger sending strength dominates the overhead for alternative MAC protocols and should thus be avoided.*

C. Variation in Channel Access Approaches

When random access is used, typically not only data is transmitted. Usually, receive windows are opened to get updates or acknowledgments from the gateway. Consequently, the energy consumption for pure transmission is only the minimal requirement. Therefore, Figure 4 shows the energy consumption for specific variations of all channel access protocols. The axes are kept like above, the black solid line shows the energy consumption for random access with a sending strength of +12 dBm and no receive window as reference (no rcv). By increasing the processing energy consumption for scheduled MAC (orange line) with a factor of 1000, only a minor increase in the energy consumption is detected. Thus, this result serves as a worst case observation for scheduled MAC where a receive window is opened and data is received and processed after each transmission. If only one receive window is opened for random access (1 rcv), similar energy is required as for scheduled MAC (dotted black line below orange line). For LBT, another message transmission is detected during the first sensing operation. During the second channel sensing, the channel is assumed to be free. The energy consumption for this behavior, shown by the brown line, increases by the same factor as opening two receive windows (2 rcv: black line highlighted with triangles). Hence, if always two receive windows are opened for random access, two channel sensing operations can be performed for LBT with the same energy requirements. In addition, if a transmission fails and data need to be re-transmitted after two receive windows were opened with random access (2 rcv & retransmit), a lot more energy is required, as shown by the dashed black line.

Consequentially, we answer our second research question with *channel sensing operations are similar to receive windows from an energy consumption perspective. However, channel sensing can avoid collisions in contrast to only detect them. Thus, it is better to use the additional energy for channel sensing and not to detect collisions. The best solution, besides random access without receive windows, is scheduled MAC. However, this approach is the most complex one and creates processing and synchronization overhead. Thus, it can not be used by all sensors, especially if clock drifts are large [4].*

D. Influence of Collisions on Energy Consumption

Depending on network load, collisions need to be resolved when using random access. Although collisions do not influence the energy consumption directly, in particular the energy consumption per successfully transmitted message is of interest. This study is presented in Figure 5 for the different approaches. The energy consumption in Joule is at the y-axis and the collision probability for the reference random channel access approach in percent is at the x-axis. The colors indicate channel access approaches. Since the hidden node problem must be taken into consideration in LBT, additional scenarios are considered. The solid brown line shows an LBT scenario where only 5 % of the collisions can be avoided, for the dotted line it is 10 %, for the dashed line it is 25 %, and for the dashed and dotted line it is 50 % respectively. In this scenario, we assume that one back-off is sufficient for a correct sensing and transmission procedure afterwards. Please note that in real networks, too many messages can block the complete behavior and a recursive study for channel sensing and back-offs is required. Furthermore, the collision probability is affected by the access approach. However, this study is left as future work. The results show the best performance for random access until 30 % collision probability. However, the collision probability is zero for scheduled MAC, and thus the energy consumption is constant. In contrast, LBT never performs better than random access from an energy consumption perspective, not even with 50 % collision probability reduction. Furthermore, a collision probability of 20 % and more is not practical in reality.

Thus, the answer on our last research question is: *from a sole energy consumption perspective, no alternative channel access mechanisms can compare with random access, even when the energy consumption per successfully transmitted message is studied. However, additional receive windows, re-transmission, and updates from the gateway also increase the energy consumption for random access. If this is taken into consideration, the alternative approaches are a viable solution, with and without large collision probabilities.*

V. Conclusion

Currently, LoRaWANs are set up in many cities. For that reason, it is now essential to study the energy requirements for channel access to develop future sustainable networks. Therefore, we present a generic model to quantify the energy consumption for different channel access approaches for single LoRa sensors, or for a complete LoRaWAN. Furthermore, we investigate channel access approaches based on their energy consumption, study different settings for each approach and analyze the influence of collisions on the energy consumption. Our study shows that random channel access has the least energy requirements if the sensors only transmit data. However, if additional receive windows must be opened and collided data must be re-transmitted, alternatives like LBT perform better by collision avoidance instead of collision resolution. Furthermore, a Scheduled MAC approach performs best with larger load in the network, more required receive windows, or channel sensing periods. However, this improvement comes with additional complexity and management overhead. This work serves as a basis for future channel access studies with focus on energy consumption. In particular, a broad parameter study, the influence of the complete LoRaWAN sensor instead of the transceiver only, and a detailed collision study must be conducted in the future. Therefore, our model can be applied by adjusting only energy and time values for the states.

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