Improving LoRaWAN's Successful Information Transmission Rate with Redundancy

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***Abstract*—The adaptation of Internet of Things in our everyday life shows different new demands and challenges. One of the fastest growing technologies in this context are Low Power Wide Area Networks with LoRaWAN as one of their most prominent representatives. The promise of this technology is to transmit sensor data over large distances with very little energy consumption. But transmission behavior, and especially overhead and collision probability, must be studied in detail to improve transmission quality and energy consumption due to the random access nature of LoRaWAN. Because of that, this work investigates the LoRaWAN channel capacity by analyzing the transmission overhead, the collision probability, and the data loss. At the end, an energy consumption comparison is done. The contribution is a novel approach based on aggregation and retransmission that shows a decreased data loss of up to 20 % compared to the currently used random channel access.**

***Index Terms*—Collision probability, packet loss, IoT, LoRa**

I. Introduction

There is a large amount of heterogeneous devices that are connected in current Internet of Things (IoT) networks. In this broad range of application areas, often only a specific set of available features is required. Weather monitoring, street lighting, or smart parking are just some examples that do not generate large amounts of data or require low delay. The focus of these scenarios is low energy usage, cheap deployment, and transmission across long distances. There, a technology like Long Range Wide Area Network (LoRaWAN) is applicable.

The LoRa Alliance expects that 75 % of the IoT market will be fulfilled by Low-Power Wide-Area Network (LPWAN) solutions [1], with LoRaWAN and NB-IoT being the current market leaders [2]. Since LoRa operates on unlicensed frequency bands, the technology can be used by everyone and has many application areas, e.g., in smart cities. But since messages in LoRaWAN are transmitted with random channel access, the channel usage, robustness, and collision probabilities must be investigated in detail to plan and operate a complete network. And improving the channel quality is simple: increase the throughput by reducing the collisions, and especially the loss.

This work studies the data loss for a message transmitted across a single LoRaWAN channel by studying the collision probability, the message overhead, and the possibility to detect transmission errors [3]. Different forward error correction and retransmission approaches are studied and compared by means of collision probability, loss rate, and energy consumption. This investigation is the basis for a novel approach to transmit data with LoRa. Furthermore, it is also usable together with state of the art access mechanisms like slotted ALOHA or CSMA to avoid loss by interferences. At the end of this work, it is shown that the energy consumption for the different approaches is highly dependent on the payload length and the data loss rate as a result of channel utilization.

The main contribution of this work is a simple aggregation and retransmission-based approach to decrease the overall message loss rate in a LoRaWAN channel. The approach works with random transmission start times for all messages transmitted in the channel. For 10,000 messages transmitted each hour in a single channel, the loss rate can be reduced by up to 20 % compared to the currently used state of the art approach. Especially one approach with direct retransmission after error detection shows promising results, also from an energy consumption perspective.

The remainder of this work is structured as follows. Section II presents background information on LoRa followed by related works in Section III and the methodology with the transmission approaches in Section IV. Section V presents the model evaluation and Section VI concludes this work.

II. LoRa Transmission Background

LoRa is an LPWAN modulation technique used to transmit data in LoRaWAN. The most important parameter for LoRa transmissions is the time on air (ToA) which describes the required duration to transmit a single LoRa message. It is influenced by several adjustable parameters according to the Semtech datasheet [4].

A. Time on Air of LoRa Messages

The ToA of a LoRa message is dependent on three factors: the available bandwidth (BW), the spreading factor (SF), and the total LoRa message length. In this work, the 868 MHz frequency band (EU868) is used exemplary with 125 kHz channel width, as typically used in Europe.

Spreading Factor: The different SFs in LoRa determine the number of raw bits a symbol carries. For example, for SF 7, one symbol maps to 7 bit. The symbol duration T_s can be calculated according to

$$T_s = \frac{2^{SF}}{BW}. \tag{1}$$

Thus, by using a higher SF, the channel usage for the transmission of a single symbol is longer.

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B. LoRa Message

A LoRa message consists of a preamble, 4.25 symbols for synchronization, an optional header, and the LoRa packet. The preamble length $n_{preamble}$ can be changed between 6 and 65535 symbols, while it is 8 symbols for the EU868 band. The number of symbols payload can be calculated by

$$n_{payload} = 8 + max(\lceil (n_{packet}) \rceil \cdot (CR + 4), 0) \quad (2)$$

with

$$n_{packet} = \frac{(8PL - 4SF + 28 + 16CRC - 20IH)}{4(SF - 2DE)}. \quad (3)$$

More details about the parameters are given by the Semtech datasheet [4]. The usage in the simulation and the abbreviations are presented in Table II. The total number of symbols for a single message is

$$n_{complete} = n_{preamble} + 4.25 + n_{payload} \quad (4)$$

Thus, with $ToA = T_s \cdot n_{complete}$ the ToA of a single LoRa message is received.

C. LoRaWAN Channel Quality

There are three ways to vary the utilization of a collision affected LoRaWAN channel: 1) increase the message sending rate, 2) decrease the overhead, or 3) decrease the collision probability, and thus the loss. According to [5], the message sending rate is limited by the maximal channel throughput of ALOHA. The transmitted data of one device is limited in LoRaWAN by the duty cycle [6]. Thus, the study in this work is focused on decreasing the overhead, the collision probability, and thus the data loss.

Message Overhead: The message overhead in LoRa is directly coupled with the payload length in relation to the preamble and header. Thus, a larger payload decreases the message overhead with little influence of the SF.

Redundancy: Redundancy can be added to a transmission in two ways: message redundancy and payload redundancy. Each message is sent several times to increase the probability of a correct transmission when message redundancy is used. This leads to a higher sending rate and increases the total collision probability. The same is achieved when the number of messages per transmission cycle is increased. Thus, this is not discussed in detail. For payload redundancy, or layer 2 forward error correction (FEC), in this work always n payloads are aggregated to one message and transmitted. Thus, the last $n - 1$ payloads of the previous messages must be stored at the sensor for the next transmission but the overhead from preamble and message header is decreased. Furthermore, if the receiver does not receive a message correctly, no negative acknowledgment must be sent and the receiver can wait for the next sending cycle. The drawback is, that lost messages are delayed by a complete transmission cycle and much overhead is created in total. Pre-studies show that especially FEC 2 shows promising results and is thus further studied in this work. Larger FEC approaches show large overhead and are only usable for very specific scenarios with high transmission guarantees and low time constraints.

Message Retransmission: The goal with message retransmissions is to detect error-prone transmissions and request the missing data again. According to [3], the collision position within a LoRa message is important. The authors state, that for the same SF and received signal strength, the sender can be extracted if the message is not colliding within the last six symbols of the message preamble. Then, a retransmission request can be sent to the sender.

D. Energy Consumption with LoRa

According to literature [7], [8], a typical LoRa measurement and transmission cycle for a sensor is as follows: wake up, measure, process data, transmit data, optional data reception, and return to sleep mode. In the following, relevant parameters and basic considerations about energy consumption for LoRa transmissions are presented.

Relevant Parameters: The main goal is to improve the successful transmission rate with redundancy within LoRaWAN. Thus, wake-up, sleep, and the measurement procedure is not influenced and thus, not further analyzed. The other relevant operations that consume energy for LoRa sensors are data write, data read, and the transmission and data reception itself. Since for all LoRa device classes, and especially for class A devices that are the most relevant ones, up to two receive windows are opened for each transmission anyway. It is assumed that the reception of a message acknowledgment uses the same amount of energy than a negative acknowledgment in case of a detected collision in the retransmission scenarios.

According to the model in [7], the required energy to transmit one bit E_{bit} in a LoRa message is dependent on the total message length, the SF, and the transmission power

$$E_{bit} = \frac{P_{cons}(P_{Tr}) \cdot n_{complete} \cdot T_S}{8 \cdot PL} \quad (5)$$

with the consumed energy $P_{cons}(P_{Tr})$ as a function of the required transmission power. For this investigation, a transmission power of 13 dBm is chosen that corresponds to 92.4 mW [7]. Note that in this work, the energy usage per correctly received, and thus useful byte is investigated to be consistent with the rest of this work. In contrast, the reference paper uses the energy per useful bit.

Regarding data handling operations, write and read are of interest for this calculation. According to [9], a Toshiba TC58DVG02A1FT00 128 MB NAND flash requires 0.0202 μJ per byte for write and 0.0322 μJ per byte for read operations for the device only, while it is 0.0962 μJ for write and 0.105 μJ for read operations per byte with an installed CPU. In the following the goal is to investigate the impact of aggregation that leads to additional memory write and read operations. Therefore, the measured values with CPU suggested in [9] are used. For different hardware, the model parameters needs to be adapted. However, the absolute values for energy per useful byte are of less interest while the different behavior for the presented scenarios is more important.

III. Related Work

For successful transmissions in LoRaWAN, the available frequency channels must be utilized efficiently. For that reason, different related approaches to improve the channel access and decrease the collision probability in LoRaWAN are introduced. One of the first works dealing with the challenge of channel access in LoRaWAN is available from Bankov et. al. [10]. The limits of among others, modulation and channel access is discussed. Especially scheduling approaches like slotted ALOHA and CSMA are suggested as usable channel access methodologies by Beltramelli in [11]. Slotted ALOHA [12], [13] and CSMA [14], [15] is also studied by many other works and valuable results are received with several limitations. The main challenge of Slotted is the device synchronization. For CSMA, the hidden node problem must be taken into consideration. In contrast, all approaches presented in this work do not suffer from these problem, while in addition they are applicable together with Slotted or CSMA to reduce loss, for example from random interference in the channel.

Furthermore, several simulation are done for LoRaWAN channel access. For example CSMA is simulated with ns-3 simulator in [16]. Other authors use the FLoRa simulator [17], to study the adaptive data rate behavior. In addition, theoretical works are available for example [18]. There, the authors optimize a LoRaWAN and reduce collisions by the assignment of radio frequency parameters through a MILP formulation. A theoretical model to calculate packet loss with an uniform SF in relation to the time on air is available in [19]. Another possibility to study collisions in LoRa is an orthogonality study of different SF. This is done with a theoretical examination in [20]. The authors show that it is possible to transmit with two SF simultaneously if the receive power is comparable.

Low energy consumption is one important requirement for LPWAN. Thus, [21] studies the energy consumption for the LoRaWAN device classes from a theoretical and experimental perspective. Several additional energy consumption models are available in literature [8], [7]. Since one important goal in LPWAN is minimizing energy consumption, this is done by the authors of [22] for a LoRaWAN by controlling the transmission cycles of the sensors. The basis for this prediction is an Artificial Neural Network.

IV. Methodology

This section presents a novel channel access approach to increase the transmission quality in LoRaWAN in four steps. Afterwards, the studied scenarios are highlighted.

Step 1: Detection: First, the collision detection is based on the fact that the sender can be detected, if the sent message is not colliding within the last six symbols of the preamble according to [3]. When a message is colliding and the sender can be determined, an acknowledgment is sent.

Step 2: Redundancy: Redundancy is important to decrease the information loss rate. For that reason, when a device receives the acknowledgment that a sent message collided, an additional transmission is done according to two possible approaches: direct retransmission or retransmission in the next sending cycle. If the retransmission is done in the next sending cycle, the compromised data is backed up at the device.

Table I: Scenario Overview

Abbr	Explanation	Agg.	Red.	Ret.
FEC	Forward Error Correction	-	+	-
RET D	Retransmission Direct	-	-	+
RET A	Retransmission Aggregation	+	-	+
FEC RET	FEC with Retransmission	+	+	+

Step 3: Aggregation: The data stored from the previous sending cycle is aggregated to the next data for transmission. This has two benefits: collided data can be sent again to decrease the total data loss and benefit from aggregation by decreasing the preamble and message header overhead. The drawback of this approach is, that additional storage space must be available and more energy is used for write and read.

Step 4: Retransmission: In the next transmission cycle, data is transmitted. The sensor stays active until a specific time is passed. If no acknowledgment is received from the gateway, data has been transmitted correctly or data is lost without detecting the transmitter. In the following, different scenarios are described to study the behavior.

A. Scenario Overview

The scenarios show different target optimization goals (aggregation, redundancy, retransmission). An overview of all scenarios and the abbreviations is available in Table I.

Forward Error Correction (FEC): A good way to decrease the data loss rate in a LoRaWAN channel is FEC. FEC 2 shows a good trade-off between payload overhead and correct data transmission and is studied in this work.

Message Retransmission (RET): In the direct retransmission approach (RET-D), data is retransmitted directly after 1 s waiting time, when a typical class A LoRaWAN device opens its receive window [23]. When two messages collide, at least the preamble of the second message collides and is thus lost. The investigation of retransmissions after a random time interval is also studied with similar results. Thus, it is not presented in detail. In the retransmission approach with aggregation (RET-A), the collided data is stored for the next transmission cycle, aggregated, and transmitted with the next data. Here, two variations are studied: 1) new sending times for all messages are calculated for each run and 2) new sending times are calculated only for the collided and aggregated messages. For both scenarios, 50 runs with random initial transmission times are done.

Hybrid Approach: The FEC-RET approach combines both strategies. In this scenario, for each message a FEC-2 mechanisms is used, while colliding messages are sent again with the RET-A approach in case of collision.

B. Transmission Simulation

The scenario study in this work is done with a lightweight and simple Python-based simulation. This has a large runtime benefit compared to more complex simulators like FLoRa [17]. The main goal is to increase the channel quality for LoRaWAN.

Table II: Simulation parameters

Parameter	Value	Parameter	Value
Number of messages per cycle	10,000	Spreading factor	7
Simulation time [hours]	1,000	Bandwidth [kHz]	125
Duration per sim cycle [s]	3600	Coding rate (CR)	4/8
Preamble length [symbols]	8	Payload CRC	enabled
Low datarate optimization (DE)	disabled	Header (IH)	enabled

Simulation Idea: The simulation idea used in this work is rather simple and based on four steps: 1) calculate the transmission start times of all sensors transmitting in the next simulation cycle; 2) based on the ToA of the LoRa messages, calculate the transmission end; 3) calculate collisions by overlapping sending intervals - check for possible retransmission by collisions in the payload only; 4) calculate potential retransmissions and check for additional collisions.

This approach has a large performance benefit compared to, for example, a discrete event simulation. Furthermore, no specific simulator is required. This strategy is possible because of two assumptions: there is no differentiation between single sensors or sensor types and thus sending rates of sensors. Only the total number of sending operations in one simulation cycle is relevant. Second, and resulting from the first point, the transmission start times are either dependent on the start times of the previous simulation cycle or randomly calculated and thus not influenced by any event in the same simulation cycle. In the retransmission case, the start and end time of the transmission is calculated immediately. This approach also works in case of collisions without massive overhead since the number of retransmissions per transmission and simulation cycle is limited to one. Otherwise the channel is blocked by a small number of sensors with retransmission messages only.

Simulation Parameters: The used simulation parameters are summarized in Table II. For comparability reasons, they are used according to [3] if not stated differently. A statement to the generalizability follows at the end of the evaluation. Especially to study larger payload sizes and message numbers in the channel without overload, SF 7 is used. The received signal strength is not varied.

One simulation cycle describes one hour of simulation. There, 10,000 LoRa messages are simulated. For each message, random transmission start times with uniform distribution between 0 s and 3,600 s with four decimal places are calculated each hour to avoid the collision of the same message each simulation hour. The total simulation duration is 1,000 h.

V. Evaluation

This section summarizes evaluation results for collision probability and loss percentage of the scenarios in Table I. At the end, the overall message overhead and the energy consumption is evaluated and a general discussion for usage and generalizability is given.

A. Collision Study

The collision probability evaluation based on the number of payload bytes of the introduced scenarios is visible in Figure 1.

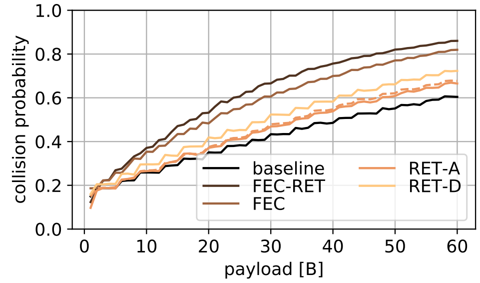

Figure 1: Collision probability comparison

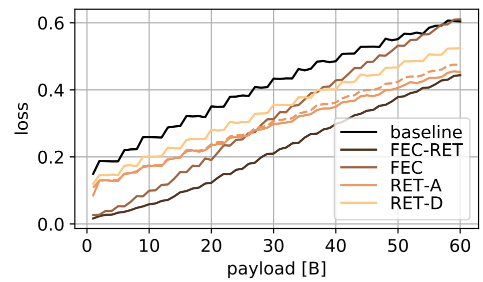

Figure 2: Overall data loss comparison

The baseline shows the currently used random channel access in LoRaWAN. It shows the least collision probability, with 42 % collisions for 30 B and 60 % for 60 B payload. Here, the least number of messages are transmitted without any data aggregation mechanism. The worst performance in case of collision probability is visible for both FEC approaches, while the FEC-RET approach shows a higher collision probability compared to the normal FEC approach. Both show more than 80 % collisions for a payload size of 60 B.

The RET approaches in yellow and orange perform better than the FEC approaches but worse than the baseline. The RET-D approach performs worse with about 72 % collision probability for 60 B while the RET-A approaches show 68 % collisions. For the RET-A approach, the solid line shows random retransmission times of all collisions, while the dashed line shows complete random transmission times for all messages for each run. It is visible, that the complete random scenario performs slightly worse than calculating only the detected collisions new. This behavior occurs, since all messages that did not collide in the previous run are transmitted again in the same time window without collision. Only the messages that collided before can collide with them in the next transmission cycle.

B. Loss Study

The loss investigation dependent on the payload in bytes of all presented scenarios is shown in Figure 2. The baseline, without any aggregation or retransmission approaches shows the worst performance with a loss rate of 16 % for 1 B payload, up to 60 % for 60 B payload. In this scenario, the loss rate is equal to the collision probability. For the FEC approaches, it is visible that the used message redundancy decreases the

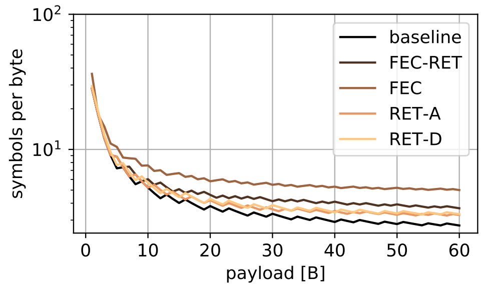

Figure 3: Transmitted symbols per byte comparison

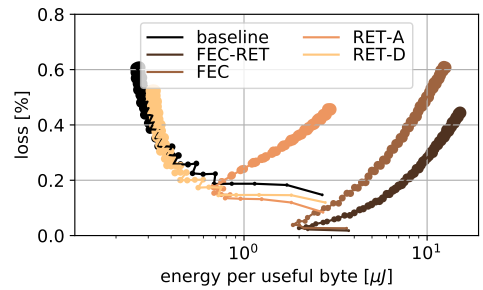

Figure 4: Energy consumption in relation to loss

loss rate, especially for small payload sizes below 5 %. For 60 B payload, however, the normal FEC approach performs similar to the baseline, while larger payloads perform worse. The best loss rate with 45 % for 60 B payload is achieved by the FEC-RET approach. It also shows the highest increase with increasing payload size and an increasing channel occupancy. The performance of the RET-approaches is between the baseline and the FEC-approaches, while here, again, RET-A performs better than RET-D. Furthermore, the randomness of the RET-A approach shown by the dashed line again increases the overall loss rate, especially for larger payload sizes.

C. Message Overhead

The overhead created by message retransmissions, FEC-mechanisms, message header, and the preamble is visualized in Figure 3 as the number of symbols required to transmit one byte. For small payloads, the additional overhead for all scenarios is small. The difference becomes visible for payload sizes above 5 B for the FEC approach and above 10 B for the other approaches.

The baseline approach performs best, since no additional transmission is required. Thus, for 60 B payload, only 2.74 symbols are used per byte. Only minor overhead is visible for the retransmission approaches, with 3.27 symbols per byte for the RET-A approach and 3.32 for RET-D. This also shows that aggregating the data is an additional improvement for message overhead compared to the direct retransmission. The worst performance is shown by the FEC-RET approach with 3.67 and FEC with 5 symbols per byte for 60 B payload.

D. Energy Consumption

One drawback of aggregation and FEC are increased energy requirements to write and read data before each sending operation. For that reason, in this section an energy consumption overview is given. Since special focus on the message retransmission and aggregation is set, the required energy per useful byte is compared with the loss rate for all scenarios.

Energy Consumption Comparison: The least energy is required by the random access baseline approach. For small payload sizes and few collisions in the channel, the RET approaches still perform comparable since a little number of retransmissions is required. For higher channel utilization and collision probability, like achieved with 60 B in this study, in the baseline scenario 0.26 μJ per useful byte is required and 0.32 μJ for the RET-D approach. In contrast, RET-A requires additional energy for data write and read operations. In contrast, both FEC approaches require much more energy.

The percentage of data loss is studied in more detail in Figure 4 on the y-axis with the energy per useful byte on the x-axis. The size of dots shows the payload size from 1 B to 60 B, while smaller dots show smaller payload sizes. This is added, since in this work increasing payload is equal to higher channel utilization and thus, loss rate. For the baseline and the RET-D approach the energy per useful byte decreases, although the loss rate increases. For a loss rate of less than 30 %, the RET-D approach shows a better performance from an energy consumption perspective, for 40 % loss and more, the baseline performs better. This is equal to a payload size of more than 30 B and thus, according to Figure 1, a collision probability of about 40 % for the baseline and 50 % for the RET-D approach. In contrast, the RET-A approach shows a better performance up to 16 % loss percentage. Then, through additional write and read operations the energy per useful byte is increasing again. In contrast, both FEC approaches show a higher energy consumption per useful byte for all payload sizes as a result of data aggregation after each transmission. For the FEC approaches, the energy consumption is not only influenced by the loss but also by larger payload and the number of bytes that must be aggregated. This is visible for higher payloads where both FEC approaches perform much worse, while the simple FEC approach is better than the FEC-RET approach.

E. Discussion and Generalizability

The results of the study show, that the loss rate in a random access channel can be reduced by the studied scenarios. A typical random access LoRaWAN channel does not contain regular deterministic traffic only, but also messages generated by random events. This makes prediction of all arriving messages and planned retransmission of missing messages impossible. Furthermore, often very important or critical - event based messages have random arrival times. There, the RET-approaches show the benefit that at least the detected error-prone messages can be requested again. Similar behavior for random traffic with the RET-A scenario is visible in Figure 2. Thus, an efficient channel planning and collision avoidance mechanisms for regular traffic can be combined with decreasing the loss of random event messages.

From an energy consumption perspective, all scenarios perform worse than the baseline due to the additional operations. Especially the FEC-approaches have the largest drawbacks. But it is shown that lower collision probabilities and loss rates also decrease the energy consumption. However, for a more in-depth analysis, a detailed study of the energy consumption for different scenarios is required. When the transmit power is changed according to [7] or the flash of [9] without a CPU is used, the required energy per byte changes drastically. But still, more collisions and especially loss requires retransmissions and consumes energy. Thus, in general, the RET-D approach shows the best results of all presented scenarios from an energy consumption perspective.

In addition, the presented approaches are also usable with state of the art channel access methodologies like slotted ALOHA or CSMA. Since random interference is often a challenge in the open LoRaWAN in general, and the hidden node problem in particular for CSMA, aggregation techniques show one additional level of security against data loss or collisions. From a generalization perspective, there are three main assumptions made in the scenario definition: 1) only SF 7 is used. Literature shows that the transmission with different SFs is quasi orthogonal and data sent with higher SF or received with higher transmission power are more likely not lost. For this situation, the presented approach can be seen as upper bound where all messages are corrupt; 2) Different ToAs for different SFs and payload lengths are covered here by different payload length only. But the increased ToA for higher SFs can be used accordingly; 3) the number of messages in one transmission cycle is fixed. No approach is directly coupled with the number of messages sent in one cycle but rather the loss received by collisions. Further studies show, like expected, that less collisions are received for less messages and more collisions for more messages per hour. Nevertheless, this does not change the general results about the performance of the presented approaches.

VI. Conclusion

Environmental monitoring and the monitoring of technical components are rapidly developing applications of IoT. One of the most promising technologies is LPWAN, with LoRaWAN being one of its most prominent representatives. In the context of this development, this work presents a novel aggregation and retransmission based approach to reduce the loss rate in a LoRa channel by up to 20 %. Dependent on the scenario, the retransmission approach without FEC only slightly increase the collision rate, but benefit from a decreasing data loss rate, especially for larger payload sizes and thus for higher load in the channel. In contrast, for little load, currently used random channel access has 5-times higher loss than the presented FEC approach with only slightly lower collision rate. Compared to state of the art literature, no synthetic conditions are required and the usage with random traffic without any known transmission times is possible. From an energy consumption perspective, the RET-D approach shows only little overhead compared to random access. For all FEC approaches, the drawback are required write and read operations in every transmission cycle. Additional improvements can be possible with the investigation of state of the art flash memories. Furthermore, it is shown that especially the avoidance of collisions and loss is the best strategy to safe energy.

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