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LoRa Alliance®
5177 Brandin Court
Fremont, CA 94538
United States

Enabling CSMA for LoRaWAN®
Technical Recommendation

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Authored by the CSMA Working Group of the LoRa Alliance Technical Committee

Technical Committee Chair and Vice-Chair:
A. YEGIN (Actility), O. Seller (Semtech)

Working Group Chair:
G. de Guillebon (Semtech)

Editor:
M. Li (WANDS, NTU)

Contributors:
A. Gamage (WANDS, NTU), G. de Guillebon (Semtech), M. Li (WANDS, NTU), M. Luis (Semtech), O. Seller (Semtech)

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1 Conventions

The keywords "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in IETF Best Current Practice 14 (BCP14 [RFC2119] [RFC8174]) when, and only when, they appear in all capitals, as shown here.

In this document:

- The octet order for all multi-octet fields SHALL be little endian.
- EUI are 8-octet fields and SHALL be transmitted as little endian.
- By default, `RFU` bits are Reserved for Future Use and SHALL be set to 0 by the transmitter of the packet and SHALL be silently ignored by the receiver.
- A range of integer values is noted as `min_value`…`max_value`, where minimum and maximum values are included.

2 Introduction

LoRaWAN specification [TS001] adopts ALOHA mode as the Media Access Control (MAC) mechanism for channel (CH) access. The ALOHA MAC mechanism implies that whenever an end-device is ready to transmit a frame, it is transmitted regardless of the condition of the channel. This mechanism results in a high probability of frame collisions under congested networks. Alternatively, Carrier Sense Multiple Access (CSMA) can allow LoRaWAN nodes to verify the absence of potential collisions before transmitting on a shared medium. However, enabling CSMA under LoRa modulation entails unique challenges. This document provides recommendations for LoRaWAN devices to minimize such collisions by enabling CSMA in conjunction with the LoRaWAN specification.

The proposed mechanism in this document is fully compatible with the LoRaWAN specification. As such, incorporating the recommended additions in this document does not require changes to other LoRaWAN subsystems, such as gateways, network servers, and application servers. At the same time, end-devices enabled with CSMA co-exist and contribute towards a positive impact on the entire network.

3 Enabling Carrier Sense in LoRa Radios

Accurate detection of the presence of a LoRa frame through the radio is key to enabling CSMA for LoRaWAN. This section introduces technical solutions to enable accurate detection of LoRa frames.

Because LoRa modulation is unique, its unique features need to be considered in order to accurately detect when a channel is in use. LoRa modulation allows the concurrent reception of frames with different Spreading Factors (SFs) within the same channel (SF orthogonality). At the same time, LoRa frames can be received under the noise floor. Therefore, considering such attributes is key to enabling reliable and efficient CSMA for LoRaWAN networks.

A commonly used metric for estimating an occupied channel is the Received Signal Strength Indicator (RSSI). RSSI, however, is not a suitable predictor to detect the presence of a LoRa frame for two reasons. First, relying on RSSI for carrier sense loses potential transmission opportunities offered by LoRa's orthogonality. For example, withholding an SF7 transmission due to high RSSI caused by an SF12 frame is an inefficient use of spectrum resources. Second, LoRa frames traversing underneath or near the noise floor would be missed by RSSI measurements. For example, the RSSI threshold of -80dBm translates to an outdoor detection range of approximately 100m at 14dBm transmission power [TOSN'22]. The range is further reduced indoors and is significantly smaller compared to the potential collision range of LoRaWAN. Therefore, relying on RSSI to detect the presence of a LoRa frame may lead to inaccurate channel sensing with numerous missing detections of LoRa transmissions.

Alternatively, all LoRa radios are equipped with a Channel Activity Detection (CAD) module that is specially designed for LoRa. It has the following important features as demonstrated in [TOSN'22]:

- CAD is SF-selective, i.e., it can detect transmissions in a specified SF while remaining insensitive to other transmissions of different SFs.
- CAD is an energy-efficient operation compared with the energy consumption of data transmissions.
- CAD works indoors and outdoors with a high detection accuracy. Therefore, instead of RSSI, the CAD module is better suited to be utilized as an effective and a reliable tool to estimate channel occupancy.

A request to the CAD module reports back either a busy or a free channel for the selected channel and SF combination for the duration of a set number of LoRa symbols [AN1200.48]. To this end, a CAD request that results in a busy channel is referred to as a *failed CAD.* Otherwise, a clear channel is assumed.

The CAD module requires configuration prior to use. The configuration is subject to the version of LoRa modem implementation integrated into the radio module. Therefore, for radio-specific details about CAD configuration, the reader is expected to refer to the radio's datasheets.

4 CSMA Protocol for LoRaWAN

This section details the CSMA mechanism for LoRaWAN. The aim of the CSMA protocol is to avoid collisions from neighboring end-devices, such that the best probability of reception at the gateway is achieved with minimal energy overhead. The proposed protocol inherits the rationale of LMAC-2, proposed by A. Gamage, et al., which first appeared in [MobiCom'20], and was thereafter improved in [TOSN'22]. This section introduces the reader to the rationale and the details of the proposed protocol with the help of state transition diagrams highlighting all possible states. The reader is then presented with an example, where two nodes contend for the same CH/SF combination. Finally, a table of recommended parameters is presented.

4.1 Rationale

A LoRaWAN collision occurs when two or more devices choose the same frequency channel and spreading factor, and transmit frames that overlap in time. Therefore, in a less-congested environment, an end-device can simply estimate which channel is clear and proceed to transmission. This clear channel estimation is referred to as the Distributed Coordination Function (DCF) Interframe Space (`DIFS)` phase. The purpose of the `DIFS` phase is to ensure a clear channel. Once the CH and SF are configured, the `DIFS` phase is comprised of performing two consecutive CADs. A successful `DIFS` phase occurs when both CADs report a clear channel. If either CADs fail, a failed `DIFS` window is recognized, indicating that the channel is not clear to send. In this case, the end-device should attempt the `DIFS` phase again after configuring the radio to a different CH, while maintaining the same SF.

If the channels are known to be heavily contended, simply relying on the `DIFS` phase alone may not be sufficient to ensure a good chance of collision avoidance. This is because, as the numbers of end-devices increase, the possibility that two or more devices starting CSMA process at the same time also increases, thereby increasing the possibility of collisions. The addition of a random Back-Off (`BO)` phase after the `DIFS` phase can aid in reducing such occurrences. Therefore, the CSMA protocol for the contended networks is comprised of two parts, a `DIFS` phase followed by an optional `BO` phase. The `BO` phase further reduces collisions by introducing a random number of few additional CADs. Doing so reduces the possibility of two or more frames colliding should the end-devices start the `DIFS` processes at approximately the same time.

If `BACKOFF_MAX` is set to 0, the `BO` phase is disabled and the variable `NumBackoff` is set to 0. If `BACKOFF_MAX > 0`, then the `BO` phase is enabled. When the `BO` phase is enabled, the end-device enters the `BO` phase immediately after completing a successful `DIFS` phase. It first generates a random number between `1` and `BACKOFF_MAX` and assigns it to the variable `NumBackoff`; this initial value of `NumBackoff` represents the number of `BO` slots the end-device should complete prior to transmission. For each `BO` slot during the `BO` phase, the end-device decrements `NumBackoff` by one for each CAD request reporting a clear channel. When `NumBackoff` reaches zero, the frame is immediately transmitted. Since the end-device continuously checks the availability of the channel during the `BO` phase, an occupied channel will reset the CSMA state of the end-device back to `DIFS` phase, in which case, the end-device needs to complete a successful `DIFS` phase again to resume decrementing the remaining `BO` slots (`NumBackoff`). Note that `NumBackoff` is not set to a new random value until the frame is transmitted. It should be noted that a busy channel during a CAD operation within the `DIFS` or `BO` phase will render a failed `DIFS` or a `BO` slot, respectively. In both cases, the end-device state is set back to `DIFS`, and should perform the next `DIFS` phase after configuring the radio to an unused channel pseudo-randomly, while maintaining the same SF.

However, certain regulatory authorities, such as the [FCC], mandate equal use of all channels, i.e., a channel that was utilized for transmission once should not be utilized again until all other channels have been transmitted on. Therefore, when a CAD reports a busy channel during either the `DIFS` or `BO` phase, the available channels for the end-device are limited to the number of remaining unused channels (`NumAvailableCh`), where `AvailableCh` is the list of those channels. Suppose an end-device has eight available channels and only one of them has been used previously for a transmission. During the next transmission, the end-device should only attempt to transmit on one of the seven remaining channels.

The end-device may restrict the number of channel hops per frame by setting the `MaxChanges` parameter. Upon finding a busy channel, the end-device will channel-hop a maximum number of `MaxChanges` times before defaulting to ALOHA. The list `AvailableCh` is reset when all channels have been transmitted on. The variable `MaxChanges` is reset for each new frame. Usage of `MaxChanges` is further discussed in Section 4.2.1.

Another reason for adopting both the `BO` phase and the `DIFS` phase is when an application requires prioritization of some end-devices. In a network where all end-devices use both `BO` phase and `DIFS` phase, nodes that utilize lower `BACKOFF_MAX` values will receive an advantage in capturing the channel. The reason for the prioritization is as follows. After completing a successful DIFS phase, the random number of `BO` slots (`NumBackoff`) assigned to the prioritized end-device will be lower than that assigned to a non-prioritized end-device due to the lower `BACKOFF_MAX` value. Therefore, devices with lower `BACKOFF_MAX` values are more likely to capture the channel faster as opposed to others under the same CH/SF.

4.2 State Transitions

Figure 1 illustrates the state transitions when an end-device follows CSMA:

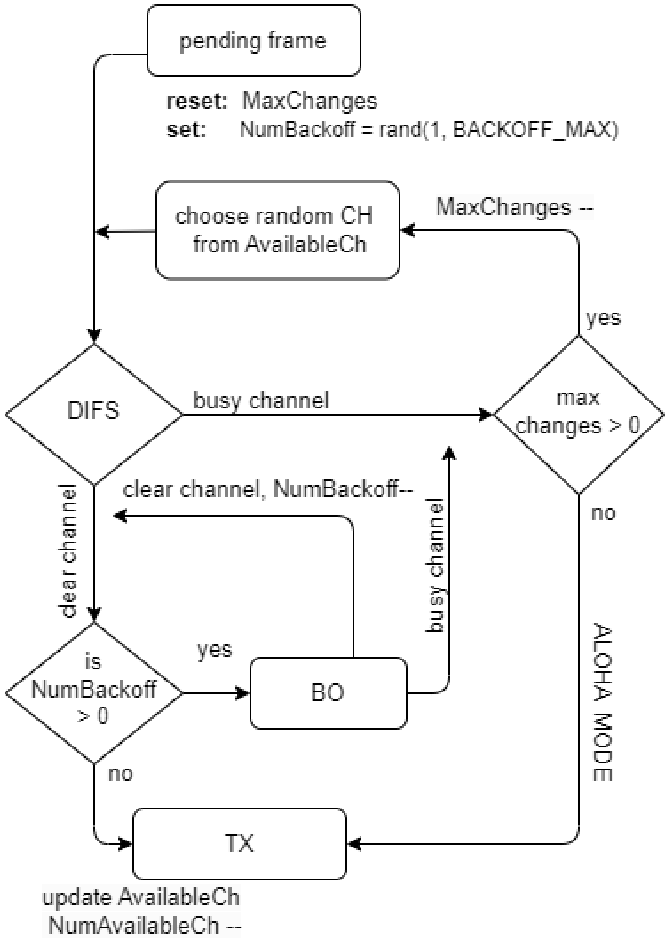

Figure 1: LoRaWAN CSMA state transition diagram

4.2.1 State Transitions of an End-Device Adopting DIFS without BO

This section explains state transitions for an end-device that follows `DIFS` phase only. Such a device does not have the `BO` phase enabled and can typically be deployed under low-contended environments. To disable `BO` phase, `BACKOFF_MAX` is set to 0.

The simplest scenario is where the selected CH/SF combination by the end-device is not contended by another. In this case, the end-device entering the `DIFS` state will successfully complete two CADs, indicating a clear channel. This completes a successful `DIFS` phase. The end-device then transitions to transmission state. When the frame is transmitted, the end-device decrements `NumAvailableCh` by one. At the same time, the end-device marks the channel as used in `AvailableCh`.

In cases where the end-device identifies a busy channel during `DIFS` state, the end-device configures the radio to a different random channel from `AvailableCh` before starting a new `DIFS` phase. The key reason to hop to a different channel upon finding a busy channel is because repeatedly performing `DIFS` on a fixed channel that was reported as busy is less likely to result a clear channel. Therefore, the end-device would have a better chance of finding a clear channel by hopping to a different one.

A key concern, however, is how many times the end-device should hop across channels in the unlikely case where many consecutive channels are found to be busy. At such times of high network demand, the end-device would spend too much time hopping across too many channels. This overhead can be high, especially when the number of available channels is also high. Therefore, a stop condition is provided to control this behavior. The user-configurable parameter `MaxChanges` sets a limit on the number of times an end-device can hop to a different channel upon finding a busy channel. `MaxChanges` is reset to its initial value upon each transmission. Accordingly, prior to hopping to a random channel, the end-device checks if `MaxChanges>0`, i.e., to see if further channel changes are allowed. If so, the end-device can hop randomly to one of the `AvailableCh`, one that has not been transmitted on yet. Each hop decrements `MaxChanges` by one. When `MaxChanges=0`, or when all `AvailableCh` have been tried, no further channel changes are allowed. In that case, the end-device shall simply transmit the frame under ALOHA.

Recommended values for key CSMA parameters are provided in Section 4.3.

4.2.2 State Transitions of an End-Device Adopting DIFS with BO

This section describes state transitions when an end-device adopts both `DIFS` and `BO` phases. To enable `BO` phase, `BACKOFF_MAX` is set to a non-zero integer, e.g., 6 or as recommended in Section 4.3. When an end-device enters the CSMA process, it assigns a random value from {1,2,3,4,5,`BACKOFF_MAX` } to `NumBackoff`.

Again, the simplest scenario is when the selected CH/SF combination by the end-device is not contended by another. The end-device first enters the `DIFS` state and completes a successful `DIFS` phase. After the successful `DIFS` phase, the end-device checks if the existing `NumBackoff` value is greater than `0`. `NumBackoffs>0` implies the end-device has not completed its `BO` phase during this transmission effort and the end-device will start or resume the `BO` phase. As such, the end-device immediately moves to `BO` state and waits until `NumBackoff` is decremented to 0 per each CAD returning a clear channel. When `NumBackoff=0`, the end-device then transitions to transmission state. When the frame is transmitted, the end-device decrements `NumAvailableCh` by one. At the same time, the end-device marks the channel as used in `AvailableCh`.

In cases where the end-device identifies a busy channel during the `DIFS` state or the `BO` state, the end-device shall immediately transition to the `DIFS` state. Following the channel hopping criteria explained in Section 4.2.1, the end-device then configures the radio to a different random channel from the list of `AvailableCh` and transitions to the `DIFS` phase again. Note that `NumBackoff` for a frame is not set to a new random initial value until that frame is transmitted. The use of the `MaxChanges` and `NumAvailableCh` parameters apply, as described in Section 4.2.1.

For further clarity, Figure 2 illustrates the importance of Back-Off under a typical use case, where two end-devices, device A and device B, follow CSMA with both `DIFS` and `BO` phases. The behavior of device A is described first. Device A initially generates a random value of 2 and assigns it to `NumBackoff` and enters the CSMA process. First device A follows `DIFS` phase where it completes a successful `DIFS` slot and enters the `BO` phase immediately. During the `BO` phase, device A decrements `NumBackoff` per each CAD reporting a clear channel. When `NumBackoff` reaches zero, the frame is transmitted.

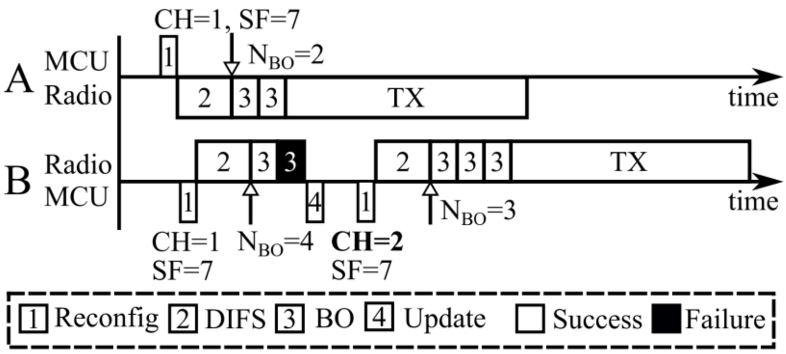

Figure 2: Two nodes contending for the same CH/SF combination

Figure 2 also illustrates the process where two end-devices, device A and device B, contend for the same CH/SF. Note that, device A and device B start the CSMA process at approximately the same time, and both complete a successful `DIFS` phase. When device B performs `DIFS`, it detects a clear channel. Accordingly, device B then enters the `BO` phase, but with `NumBackoff=4`. It starts decrementing `NumBackoff` with each successful CAD and reports a failed CAD in its second BO window. This is because during device B's second BO window, device A starts transmitting, which device B detects as a potential collision. As per the state transition diagram, device B decrements `MaxChanges` by one, changes channel randomly to one of the `AvailableCh` and transitions again to the `DIFS` state. After completing a successful `DIFS` phase in the new channel, device B immediately transitions to `BO` phase and resumes decrementing `NumBackoff` from three. When `NumBackoff` reaches zero, device B transmits the frame. Upon transmission, the end-device updates `AvailableCh` and `NumAvailableCh`.

4.3 Recommended Parameters

Parameter	Recommended Value	Short Description
DIFS	2 CADs	Integer number of CADs to assess a clear channel
BACKOFF_MAX	6	Integer limit of maximum possible number of backoff slots per frame. Use 0 to disable back-off or n to limit back-offs to n
NumBackoff	rand(1, BACKOFF_MAX)	Integer number of back-off slots per frame. NumBackoff ∈ {1,2,3,4,5,BACKOFF_MAX} CADs
MaxChanges	application specific, e.g., 6.	Integer limit of channel changes per frame
AvailableCh	N/A	List of available channels that have not yet been transmitted on
NumAvailableCh	N/A	Integer number of channels available in AvailableCh

Table 1: Summary of parameters

Table 1 provides a summary of recommended values for the key parameters involved. It should also be noted that the MaxChanges and BACKOFF_MAX parameters are application-specific. Once the channels have changed MaxChanges number of times, the end-device will lock into the already-set channel and transmit the frame using ALOHA. Also, the application can utilize different BACKOFF_MAX values for prioritization (lower BACKOFF_MAX means higher priority and vice versa).

5 Global Regulatory Compliance

5.1 Region with Listen Before Talk

Certain regions mandate the use of Listen Before Talk (LBT) explicitly using RSSI prior to transmission. Although [TOSN'22] shows that LBT with RSSI thresholding may impair LoRa orthogonality and will not improve low-power WAN (LPWAN) multiple access efficiency due to low Signal-to-Noise Ratio (SNR) capabilities of LoRa, in the case where LBT is mandated, a decision based on the RSSI value should be made, in accordance with LoRaWAN Regional Parameter documentation [RP002], prior to proceeding with CSMA procedures described in Section 4. LoRaWAN Regional Parameter documentation can be used to identify such regions. Regional regulations are not listed in this section, but the reader is requested to refer to the corresponding specification so that recent regulatory changes are reflected in the most recent version of LoRaWAN regional parameter documentation. In any case, the reader is expected to be up-to-date on all applicable local regulations and should adhere to them.

5.2 Regions with Mandatory Equal Channel Utilization

Some regions require that an end-device use all enabled channels once before being used again. In the unlikely case where all remaining channels are found to be busy, the end-device may use any unused channel under ALOHA.

6 Glossary

BO	Back-Off
CAD	Channel Activity Detection
CH	Channel
CSMA	Carrier Sense Multiple Access
DCF	Distributed Coordination Function
DIFS	DCF Interframe Space
LBT	Listen Before Talk
LPWAN	Low-Power WAN
MAC	Media Access Control
NumBackoff	Number of Back-Off Slots
RSSI	Received Signal Strength Indicator
SF	Spreading Factor
SNR	Signal-to-Noise Ratio
WAN	Wide-Area Network

7 Bibliography

7.1 References

[RP002] LoRaWAN® Regional Parameters

[TS001] LoRaWAN® L2 1.0.4 Specification

[AN1200.48] Application Note: SX126x CAD Performance Evaluation

[SX1261/2] SX1262 Long Range, Low Power, sub-GHz RF Transceiver

[TOSN'22] LMAC: Efficient Carrier-Sense Multiple Access for LoRa, Amalinda Gamage[+], Jansen Liando[+], Chaojie Gu[+], Rui Tan[+], Mo Li[+] and Olivier Seller[++], Nanyang Technological University[+], Singapore, Semtech[++], France. ACM Transactions on Sensor Networks (TOSN). 2022

[MobiCom'20] LMAC: Efficient Carrier-Sense Multiple Access for LoRa, Amalinda Gamage[+], Jansen Liando[+], Chaojie Gu[+], Rui Tan[+], Mo Li[+], Nanyang Technological University[+], Singapore. Proceedings of the 26th Annual International Conference on Mobile Computing and Networking, MobiCom '20. Article No. 43, Pages 1–13

[FCC] Federal Communications Commission 47 CFR Part 15, 2022

APPENDIX 1: CAD CONFIGURATION

Appropriate configuration of the CAD module is key to enabling accurate detection of potential collisions and improved energy efficiency during LoRaWAN CSMA. A single CAD operation is comprised of two parts. First, the radio switches to receive mode, gathering samples for a duration of a set number of symbols. Second, the radio briefly processes the received samples to check the presence of LoRa symbols and informs the MCU whether a symbol is found. Recent versions of LoRa radios allow the configuration of parameters such as the number of symbols per CAD and various thresholds that influence detection. However, CAD modules belonging to previous radio generations come preconfigured and further configuration is not allowed. Therefore, CAD modules of those generations can be used with the default configuration.

The rationale of configuring the CAD module is to achieve the highest energy efficiency per CAD while maintaining sufficient detection accuracy. For radios that allow CAD configuration, several parameters can be optimized. However, listing optimized configurations for each radio is not plausible due to the large number of LoRa radios. As such, an example of optimal configuration for the SX1262 is summarized in Table 2. As CAD parameters for other radios that allow configuration is similar, the reader is requested to refer to their respective datasheets to find radio-specific values that offer optimal detection, e.g., `cadSymbolMin`, `cadDetPeak`, and `cadSymbolNum`.

A noteworthy parameter for consideration is `cadSymbolNum`, which configures the duration that the radio tunes to receive mode to sample the channel. A `cadSymbolNum=2` implies that each CAD requests the radio module to sample the channel for two symbol durations, which varies based on the set SF. Accurate detection of the presence of an on-going transmission requires maintaining false positives to a minimum across a wide range of RSSI. In the case of the SX1262, the application note [AN1200.48] highlights CAD configuration parameters, which are highlighted in Table 2. The registers, `cadDetMin`, `cadDetPeak`, and `cadSymbolNum` allow configuring the sensitivity of a single CAD operation.

SF	CAD Settings		
	`cadDetMin`	`cadDetPeak`	`cadSymbolNum`
SF7	10	22	2 symbols
SF8	10	22	2 symbols
SF9	10	24	2 symbols
SF10	10	25	2 symbols
SF11	10	26	2 symbols
SF12	10	30	2 symbols

Table 2: Optimal CAD settings for the SX1262 for two symbols

For radios that allow configurable CADs, consecutive CADs may be combined to form a single CAD to realize a slight energy gain. For example, a DIFS phase consists of two CADs that together consume four symbols. These two consecutive CAD operations can be merged into a single CAD operation of four symbols. Optimized parameters for a four symbol CAD are different to those described in Table 2 and can be found in [AN1200.48].

APPENDIX 2: CAD ENERGY OVERHEAD

CSMA introduces additional energy overhead for each transmission effort. In this section, a comparison between the CSMA energy footprint against that required for average transmission is made for three different SFs under three different transmission power levels. The results indicate that the addition of CSMA adds energy overhead of less than 1.5% for a 30-byte frame.

The CSMA energy footprint originates from two key phases, the DIFS phase and the BO phase. For the sake of simplicity, the overhead computation assumes that the end-device performs six CADs during both phases per frame, which is approximate and may vary based on network contention and the type of CSMA used. In order to compute the energy overhead, key choices related to radio type, transmission power, SF, and CAD configuration need to be made. These choices are summarized below and in Table 3.

Frame size: 30 bytes (payload + LoRaWAN headers)
LoRa Radio: SX1262
Band: 868/915 MHz

SX1262 CAD Configuration:

SF	CAD Setting			Energy(nAh)
	`cadDetMin`	`cadDetPeak`	`cadSymbolNum`	
SF7	10	22	2 symbols	2.84
SF9	10	23	2 symbols	11.7
SF12	10	28	2 symbols	64.59

Table 3: SX1262 CAD energy consumption

Table 4 presents the transmission characteristics of the SX1262 radio under three different power levels where Table 5 summarizes the CAD energy overhead for those power levels for SF7, SF9, and SF12 from [SX1261/2].

SX1262 Setting	Tx Current (mA)
Tx Current @14 dBm	45 mA
Tx Current @17 dBm	58 mA
Tx Current @22 dBm	84 mA

Table 4: Transmission characteristics of SX1262 under (868/915 MHz) band

SF	SF7	SF9	SF12
Airtime for 30 bytes	87.3ms	287.7ms	2138.1ms
Tx energy @14dBm	1091.25 nAh	3596.25 nAh	26726.25 nAh
Tx energy @17dBm	1406.50 nAh	4635.16 nAh	34447.16 nAh
Tx energy @22dBm	2037.00 nAh	6713.00 nAh	49889.00 nAh
CSMA overhead @14dBm	1.56%	1.95%	1.45%
CSMA overhead @17dBm	1.21%	1.51%	1.13%
CSMA overhead @22dBm	0.84%	1.04%	0.78%

Table 5: CSMA overhead for three different transmission power levels

Roughly speaking, performing CSMA for a 30-byte payload may impose an approximate overhead ranging from 0.8% - 2% of transmission energy. However, it should be noted that due to a large number of different configurations, values here are presented for illustration purposes only. Nonetheless, smaller values of overhead motivates the use of CSMA for LoRaWAN, which encourages the efficient use of spectrum and eventually optimizes spectrum and battery life through collision avoidance.