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TUNDRA Sensor

Technical Reference Manual

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Revision History

TRM Version	Date	Editor	HW Generation: FW Version	Comments
0.1	November 10, 2020	Carter Mudryk	Gen2: v0.3.0	Initial draft based on Smart Room Sensors TRM v1.1.
0.2	February 16, 2021	Carter Mudryk	Gen2: v1.0.0	• Updated to include Store & Forward system UL and DL format. • Updated to include accelerometer configuration registers.
1.0	August 13, 2021	Carter Mudryk	Gen2: v2.1.0	• Updated Store & Forward to match improvements (protocol v0.5). • Removed accelerometer support. • Added analog probe functional descriptions. • Minor formatting and grammatical changes.
1.1	August 17, 2021	Carter Mudryk	Gen2: v2.1.0	• Minor updates based on feedback. • Simplified and clarified the S&F RLE description.
1.2	September 22, 2021	Carter Mudryk	Gen2: v2.1.1	Corrected Store & Forward configuration register format.
1.3	June 7, 2022	Carter Mudryk	Gen2: v2.1.2	Corrected header (channel ID) for reporting external analog probe voltage.
1.4	June 10, 2022	Carter Mudryk	Gen2: v2.1.2	Corrected register address for *ticks per external analog voltage*
1.5	June 24, 2022	Carter Mudryk	Gen2: v2.1.2	• Corrected numbers in Figure 2-2. • Clarified parameter *N* in fragmented retransmission scheme in Section 0.

TRM Version	Date	Editor	HW Generation: FW Version	Comments
2.0	October 14, 2022	Carter Mudryk	Gen2: v2.1.2 Gen2.5: v3.0.0	• Moved FW versioning notes to Revision History table. • Changed document name from “TS” to “TUNDRA.” • Updated Gen2.5 T-codes. • Added anti-bricking strategy. • Updated battery management descriptions to reflect coulomb-counting implementation for battery gauging. • Added accelerometer functional description. • Added accelerometer registers. • Updated probe voltage-temperature conversion information for Gen2.5 devices. • Updated register 0x 2F. • Updated S&F description to reflect probe temperature support. • Added registers for supporting analog probe temperature threshold-based reporting. • Minor grammatical and formatting corrections.
2.1	November 23, 2022	Carter Mudryk	Gen2: v2.1.2 Gen2.5: v3.1.0	• Added warning for new battery passivation possibility in magnetic wakeup and LED pattern sections. • Minor grammatical and formatting corrections.

TRM Version	Date	Editor	HW Generation: FW Version	Comments
2.2	February 22, 2023	Carter Mudryk	Gen2: v2.1.2 Gen2.5: v3.1.0	• Added “Document Status” row in cover page. • Added new rows in Table 1-1 and order codes in Table 1-2 for probe variants equipped with a digital probe. • Rearranged subsections in §1. • Added new §1.3 to explain probe details and function. • Moved some probe information from §3.2.3.2 to §1.3. • Included thermistor probe operational temperature range. • Corrected digital probe external reed switch state UL report format. • Updated analog probe voltage-to-temperature conversion in Appendix 1: Analog Probe Voltage to Temperature Conversion. • Added Appendix 2: Default Configuration Register Values. • Minor grammatical and formatting corrections.

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ABP .... Activation By Personalization
ADR.... .... Adaptive Data Rate
AS....... .... Asia
AU...... .... AUstralia
CRC .... Cyclic Redundancy Check
DL....... .... DownLink
DR .... Data Rate
EIRP ... . Effective Isotropic Radiated Power
EU .... Europe
FW .... FirmWare
HW..... .... HardWare
ID .... IDentity/IDentifier
IN .... INdia
IoT...... .... Internet of Things
KR .... KoRea
LED..... .... Light-Emitting Diode
LoRa... .... Long Range
LoRaMAC....... LoRaWAN MAC
LoRaWAN ...... LoRa Wide Area Network
LSB .... Least Significant Byte
LSb .... Least Significant bit
LTC .... Lithium Thionyl Chloride
MAC... .... Media Access Control
MCU .. .. MicroController Unit
MSB... .... Most Significant Byte
MSb ... . Most Significant bit
NA .... North America
NS...... .... Network Server
NVM.. .... Non-Volatile Memory
OTA ... . Over-The-Air
OTAA. .... OTA Activation
PCB.... .... Printed Circuit Board
PCBA.. .... PCB Assembly
POST.. .... Power-On Self Test
R .... Read
RH...... .... Relative Humidity
RLE..... .... Run-Length Encoding
RO...... .... Read-Only
Rx .... Receive/Receiver
S&F.... .... Store & Forward
SW..... .... SoftWare
TRM... .... Technical Reference Manual
Tx....... .... Transmit/Transmitter
UL .... UpLink
US...... .... United States
v......... .... version
W....... .... Write

1 Overview

IMPORTANT: Not all features described in this manual may be applicable to devices programmed with older FW versions. Refer to the Revision History table to verify which FW versions included the addition of new features. To check which version of FW your device has, send a command to query your device as described in Section 3.2.4.2.

This document contains the technical information about the supported functionality of the TEKTELIC *TUNDRA Sensor* device variants, referred to as *Sensors* henceforth. In particular, the LoRa IoT uplink (UL) and downlink (DL) payload structures and user-configuration settings are described in detail. This document assumes an understanding of the NS and its command interfaces.

The TUNDRA Sensor is a multi-purpose LoRaWAN IoT sensor run on a single LTC C-cell battery and packed into a compact polycarbonate casing. The Sensor's primary purpose is to measure and report ambient temperature and relative humidity (RH) data. Additionally, the probe variants support either an external digital magnetic reed switch probe or an external analog voltage thermistor probe. In the case of the digital probe version, the state of the switch can be reported and counted. In the case of the analog probe version, the voltage and temperature can be measured and reported[1].

The ambient temperature, ambient RH, and probe readings can be saved on the device using the *Store & Forward* (S&F) system to ensure data is not lost if network connectivity is broken.

The Sensor is also equipped with an accelerometer, which, as a motion detector, can be used to detect and report acceleration events, or trigger an additional temperature report upon detecting motion. The accelerometer output vector can also be reported periodically if knowledge of the orientation is of interest.

Additional sensing features include on-board (MCU) temperature and remaining battery lifetime data. The battery lifetime of the Sensor has been estimated to be up to 8 years with the default configuration settings.

The Sensor is also equipped with an internal magnetic switch which is used to wake the device from the DEEP SLEEP state (used for shipping) and to force ULs when the device is active.

Table 1-1 presents the currently available TUNDRA Sensor HW variants. Note that both the digital and analog probe options for the probe HW variants share the same module-level T-code. Whether The factory-equipped probe type is distinguished by the order code, as shown in Table 1-2

[1]Analog probe voltage reporting is supported in all TUNDRA probe models and all FW versions, but probe temperature reporting is only supported by FW v3.0.0 and newer. To convert probe voltage to temperature for older FW versions, a conversion must be applied at the application level. See Appendix.

Table 1-1: TUNDRA Sensor HW Variants

PCBA-Level T-Code	Module-Level T-Code	Description	Battery / Enclosure Size
T0006907 (Gen2) T0008175 (Gen2.5)	T0006778	TUNDRA Sensor, Base	C-cell
	T0007334	TUNDRA Sensor, Base + Wall-Mounting	
	T0007380	TUNDRA Sensor, Analog Probe	
		TUNDRA Sensor, Digital Probe	
	T0006779	TUNDRA Sensor, Analog Probe + Wall-Mounting	
		TUNDRA Sensor, Digital Probe + Wall-Mounting	

The TUNDRA Sensor variants are available with FW that supports most of the regional channel frequency plans specified by the LoRaWAN Regional Parameters Specification [1]. Table 1-2 lists all the supported regions and the corresponding product order codes.

Table 1-2: TUNDRA Sensor Supported LoRaWAN Regions and Order Codes

LoRaWAN Region	T0006778	T0007334	T0007380 Analog Probe	T0007380 Digital Probe	T0006779 Analog Probe	T0006779 Digital Probe
Australia (AU915)	SENCNNAU915	SENCMNAU915	SENCNPAU915	SENDNPAU915	SENCMPAU915	SENDMPAU915
Europe (EU868)	SENCNNEU868	SENCMNEU868	SENCNPEU868	SENDNPEU868	SENCMPEU868	SENDMPEU868
India (IN865)	SENCNNIN865	SENCMNIN865	SENCNPIN865	SENDNPIN865	SENCMPIN865	SENDMPIN865
Japan (AS923)	SENCNNJP923	SENCMNJP923	SENCNPJP923	SENDNPJP923	SENCMPJP923	SENDMPJP923
Korea (KR920)	SENCNNKR920	SENCMNKR920	SENCNPKR920	SENDNPKR920	SENCMPKR920	SENDMPKR920
Singapore (AS923)	SENCNNSN923	SENCMNSN923	SENCNPSN923	SENDNPSN923	SENCMPSN923	SENDMPSN923
North America (US915)	SENCNNUS915	SENCMNUS915	SENCNPUS915	SENDNPUS915	SENCMPUS915	SENDMPUS915

The LoRaWAN information streams supported by the Sensor FW have been shown in Table 1-3. Sections 2 and 3 are split up into subsections corresponding to each of these streams.

Table 1-3: TUNDRA Sensor Information Streams

Stream Direction	Data Type	Sent on LoRaWAN Port [decimal]
UL (Sensor to NS)	Forced (empty) UL using the magnetic reed switch	**0**
	Sensor data from the MCU and battery gauge	**10**
	Sensor data for ambient temperature, relative humidity, and/or external analog voltage probe (when configured to not be stored in the **S&F system**)	
	S&F system error reports	**14**
	Sensor data for ambient temperature, relative humidity, and/or external analog voltage probe (when configured to be stored in the **S&F system**) when it is first measured and reported	**32**
	S&F system sensor data when it is retransmitted after a request DL	**33-34**
	Responses to Configuration and Control Commands	**100**
DL (NS to Sensor)	Putting the Sensor into DEEP SLEEP	**99**
	Configuration and Control Commands	**100**
	Requests to forward data from the **S&F system**	**112-122**

The default configuration on the Sensor for reporting transducer readings and storing data in the S&F system has been has been shown in Table 1-4.

In Sections 2 and 3, the UL and DL payload formats are explained, respectively. There is a webapp encoding/decoding tool available at https://www.atlas.tektelic.com/ that allows for easy DL command formation and UL reading [2]. This tool can be used to change Sensor configuration settings and decode ULs as desired.

Table 1-4: TUNDRA Sensor Default Reporting Behavior

Report	Report Type	Default Periodicity	Default S&F Behaviour
Battery voltage	Periodic	1 day	N/A
Ambient temperature	Periodic	1 hour	Stored
	Event based	Each time above-threshold motion is detected and each time motion stops	
Ambient relative humidity	Periodic	1 hour	Stored
	Event-based	Each time above-threshold motion is detected and each time motion stops	
External probe analog voltage[2]	Periodic	Disabled	Not-Stored
	Event-based	Disabled	
External probe temperature[1,2]	Periodic	1 hour	Stored
	Event-based	Each time above-threshold motion is detected and each time motion stops	
External probe digital state[3]	Event-based	Each time the probe reed switch is opened or closed	N/A
Acceleration vector	Periodic	Disabled	N/A
Accelerometer motion alarm	Event-based	Disabled	N/A
MCU temperature	Periodic	Disabled	N/A
Empty UL	Event-based	Each time the magnetic reed switch is triggered	N/A

[2] Only applicable to probe variants with an analog probe. See Table 1-1.

[3] Only applicable to probe variants with a digital probe. See Table 1-1.

1.1 LED Behavior

The Sensor is equipped with two on-board LEDs: **GREEN** and **RED**. Their behaviour patterns reflect the internal device state and are described in the following subsections. The LED behaviour is not user configurable.

1.1.1 Power-On and Network Join Operation

When the Sensor is powered-on or reset:

1. Both **GREEN** and **RED** are turned off when the Sensor is powered on (including after a soft reset).
2. Both **GREEN** and **RED** are turned on when the POST begins.
3. When the POST ends, depending on the POST result:
    a. If the POST passes, **GREEN** is toggled ON and OFF every 50 ms for 0.5 sec, as shown in Figure 1-1.
    b. If the POST fails, **RED** is toggled ON and OFF every 50 ms for 0.5 sec, as shown in Figure 1-1.

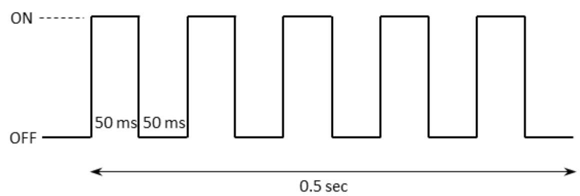

Figure 1-1: The GREEN or RED LED Pattern After the POST

4. Both **GREEN** and **RED** are turned off when the POST and the subsequent LED flashing specified in item 3 end.
5. While the Sensor is attempting to join:
    a. **GREEN** is toggled ON and OFF every 50 ms for the first hour. After that, it only flashes twice (ON time: 50 ms, OFF time: 50 ms) every 5 sec. This scheme has been shown in Figure 1-2.
    b. **RED** flashes just once:
        i. with a pulse duration of 25 ms right after transmitting a JOIN REQUEST.
        ii. with a pulse duration of 100 ms right after receiving a JOIN ACCEPT.

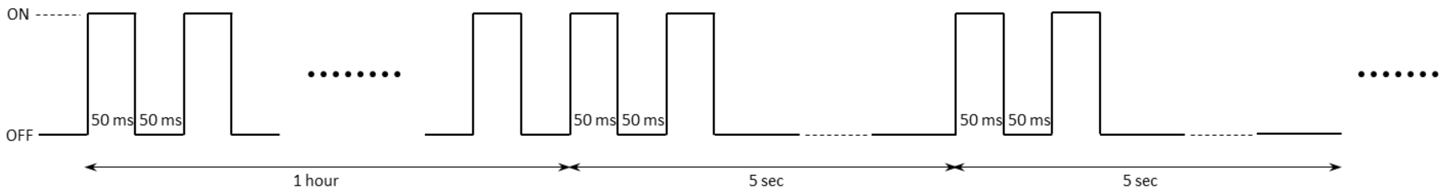

Figure 1-2: The GREEN LED Pattern During Join

6. NOTE: A slightly different pattern may occur if the Sensor is powered on for the first time with a new battery (e.g. a brand-new Sensor from factory or storage, replacing a dead battery, etc.).
   Due to the chemistry of the batteries (LTC), a passivation layer can build up internally over time and prevent high pulse current draws for a few minutes at the time of first-use [4]. The effect of this is a short ramp-up time of up to 5 minutes for successful network joining while this passivation layer naturally breaks down.
   If this occurs the LED pattern will be as follows:
   a. The LED pattern described in Steps 1-4 will occur.
   b. The **GREEN** flashing pattern in Step 5a will occur for 2 s, then all LED activity will stop for 5 s.
   c. Steps 6a-b repeat for up to 5 min until the passivation layer is broken down, after which the full patterns in Step 5a will continue as described until the Sensor has successfully joined the network.

1.1.2 Normal Operation

After the Sensor has joined the network:

a. **RED** flashes just once with a pulse duration of 25 ms right after transmitting an uplink.

b. **GREEN** flashes just once with a pulse duration of 25 ms right after receiving a downlink.

1.1.3 DEEP SLEEP

The Sensor displays an LED indication when it is brought out of DEEP SLEEP or reset by applying the magnetic pattern. The following LED pattern is displayed about 5 sec after the pattern is applied:

1. The POST LED pattern described in steps 1-3 in Section 1.4.1 above occurs after the device resets.

2. **GREEN** is toggled ON and OFF every 0.5 sec for 3 sec as shown in Figure 1-3.

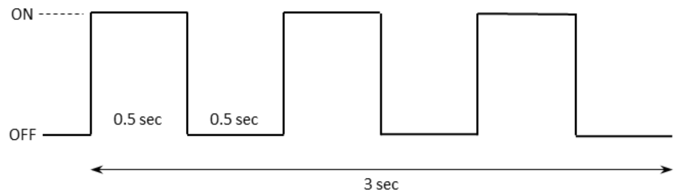

Figure 1-3: The GREEN LED Pattern After the Magnetic Wake-Up/Reset Pattern is Applied

There is another similar LED pattern for when the device is put back into DEEP SLEEP:

1. The POST LED pattern described in steps 1-3 in Section 1.4.1 above occurs after the device resets.
2. **RED** is toggled ON and OFF every 0.1 sec for 0.6 sec as shown in Figure 1-4.

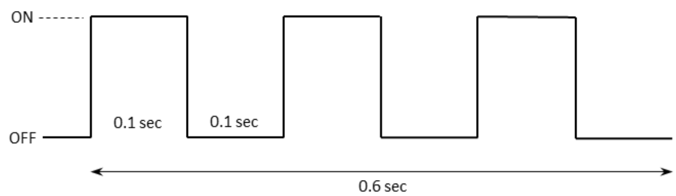

Figure 1-4: The RED LED Pattern Before Entering DEEP SLEEP

1.2 Internal Magnetic Switch Operation

The internal magnetic switch (not to be confused with the external probe digital magnetic switch) can be operated by the provided magnet, and is used for the following purposes:

1) **Sensor Reset:**

   This is mainly used to wake up the Sensor from DEEP SLEEP and have it begin trying to join the network. When the Sensor exits the factory, it is in the low-power DEEP SLEEP mode and can be activated using the specified magnetic pattern[4]. The same magnetic pattern can just be used to reset the Sensor during normal operation, causing it to try to rejoin the network.

   The magnetic pattern in this application is illustrated in Figure 1-5. A “magnet presence” is achieved by placing the magnet against the enclosure by the magnet symbol. A “magnet absence” is achieved by taking the magnet away from the enclosure. Figure 1-5 shows that the pattern involves sustaining a “magnet presence” continuously for at least 3 sec but less than 10 sec.

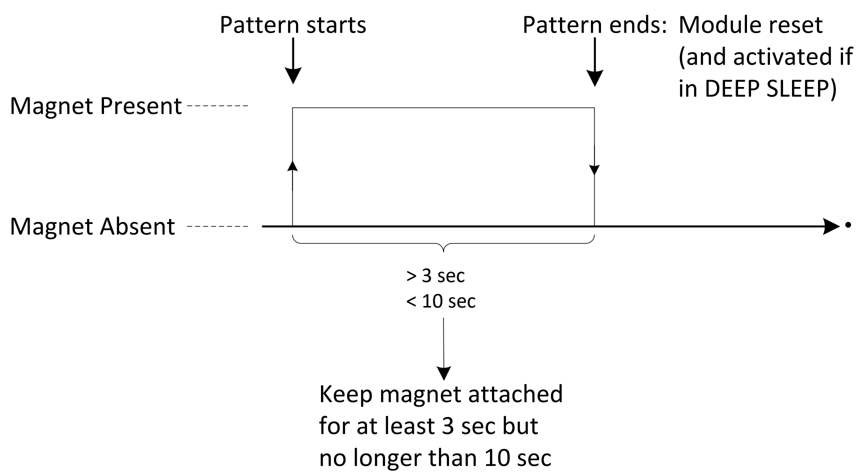

Figure 1-5: The Magnetic Reset/Wake-Up Pattern

[4] NOTE: The very first time a Sensor is woken up or powered on with a new battery, it is possible that there is some ramp-up time required before the Sensor is able to join the network. Due to the chemistry of the batteries (LTC), a *passivation layer* can build up internally over time and prevent high pulse current draws for a few minutes at the time of first-use [4]. This may occur for brand-new devices out of factory or storage, or when a user replaces the battery with a new one.

The effect of this is a short delay of a few minutes for successful network joining of the sensor while this passivation layer naturally breaks down.

See Section 0 for a description of the LED pattern to indicate this is occurring.

When the specified magnetic pattern is applied to the Sensor it displays an LED indication, described in Section 1.1.3, to show that it has accepted the magnetic pattern. In all cases, the magnet pattern causes the Sensor to reset. The state the Sensor was in at the time the magnetic pattern was applied will determine what occurs after resetting:

- If the Sensor was in DEEP SLEEP when the pattern was applied, after resetting it will wake up and begin trying to join the network.
- If the Sensor was in normal operation when the pattern was applied, after resetting it will try to rejoin the network. This is a standard *soft reset*.
- If the Sensor was in the middle of the process of trying to join the network when the pattern was applied (i.e. after it has sent the first JOIN REQUEST UL but before it has received the JOIN ACCEPT DL), after resetting it will enter DEEP SLEEP mode. Applying the magnet pattern again after this will cause the Sensor to wake up again as normal.

2) **Forced UL:**

This is used to get the LoRaWAN Class-A Sensor to open a receive window so it can receive DL commands from the NS, or simply to trigger the Sensor to uplink transducer data prior to its next scheduled periodic report.

The magnetic pattern for this case involves placing and taking away the magnet to and from the magnet sign at the bottom of the enclosure briefly for less than 2 seconds, as shown in Figure 1-6. *It is important to note here that mistakenly holding the magnet attached to the module for more than 3 sec may trigger a module reset, as explained in item 1 above.*

The magnetic-forced UL contains an empty payload on ***LoRaWAN port 0***. See Section 0 for more information.

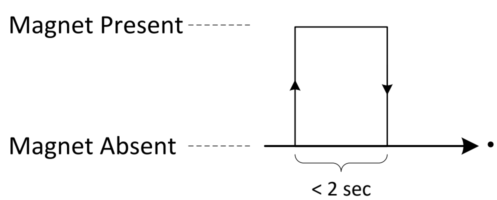

Figure 1-6: The Magnetic UL-Trigger Pattern

1.3 External Probe Operation

TUNDRA Probe variants can be ordered with the choice of either a digital reed switch or an analog thermistor. The default input mode, digital or analog, depends on whether a digital or analog Sensor variant was ordered; see Table 1-2. The input mode is a configurable parameter (determined by register 0x 2D; see Table 3-7), meaning that it can be toggled by the user at any time, regardless of the original probe at the time of manufacture.

1.3.1 Digital Probe Operation

In the digital input mode, the external reed switch probe has only two values or states:

- Open (magnet absent) with a value of 0x 01.
- Closed (magnet present) with a value of 0x 00.

This mode of operation supports periodic (§3.2.3.1) and event-based (edge-triggered) reporting.

The input is edge-triggered and can be set to be triggered by the rising edge (Low/Closed to High/Open), falling edge (High/Open to Closed/Low), or both (default setting). See §3.2.3.2.1 for configuration details.

Depending on the edge-trigger configuration, every time the input voltage changes such that the edge transition is detected, the *event counter* is increased. The *count threshold* is a configurable parameter that represents the value the event counter must reach before an event-based LoRa transmission is triggered. Whenever such an event-based transmission occurs, the event counter is automatically reset to 0 and starts incrementing as events continue to occur until the counter reaches the threshold again, thus triggering another event-based transmission. See §3.2.3.2.2 for configuration details.

Available telemetries for reporting over LoRa include the current switch state (open/closed), the count of edge-triggers since the last report, or both (default). See §3.2.3.2.3 for configuration details.

For example, if the count threshold is set to 1 and both rising/falling edges are triggered, then every time a magnet is either brought close to or removed away from the probe tip, a LoRa report will be triggered including a count of 1 and the state of the switch after the transition event.

Application Examples for Digital Input Mode:

- Door Open/Close detection would use both rising and falling triggers to detect when the door was opened and when it was closed.
- If a sensor is intended to monitor room utilization it may be configured to only transmit after 100 events logged in the room. This may be useful for alerting cleaning staff that room requires attention.

1.3.2 Analog Probe Operation

In the analog input mode, one probe pin is grounded, and the other pin is pulled up to VMCU (2.0 V) by a 68.1 kΩ resistor. The analog input has values in units of mV from 0 to VMCU (the precision is 1 mV[5]). The included probe is a custom 10 kΩ NTC thermistor. The supported probe operational temperature range is -40°C to 105°C[6].

For Gen2.5 devices (FW v3.x.x), the Sensor FW can convert the measured probe voltage to temperature and report either the raw voltage or converted temperature as determined by register 0x 2F; see Table 3-7. By default, the Sensor reports probe temperature.

For Gen2 devices (FW v2.x.x), the Sensor SW cannot convert the voltage to temperature. The measured voltage can be converted to temperature at the application-level by using the formula provided in Appendix 1: Analog Probe Voltage to Temperature Conversion. Analog operation supports periodic (§3.2.3.1) and threshold-based reporting (§3.2.3.3).

Available telemetries for reporting over LoRa include raw voltage or temperature (converted from voltage)[1].

NOTE: Analog input pulse frequency must be less than 3 Hz.

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[5] The actual ADC output has a resolution of 0.61 mV.

[6] NOTE: This is the range for the probe tip and not the range for the TUNDRA sensor base, which is -40°C to 85°C.

1.4 Accelerometer Operation

The accelerometer in the Sensor can be disabled or enabled and supports both periodic-based and event-based reporting. The accelerometer is enabled by default.

In the case of the periodic-based reporting, only the acceleration vector (X-axis, Y-axis, Z-axis) is reported.

In the case of event-based reporting, the accelerometer is used to generate a report when:

- Motion is detected that matches some configurable criteria. This is called an *acceleration event*.
- The motion has ended. This is called an *acceleration clear*.

The criteria that determine whether an acceleration event is registered are whenever the absolute value of any axis exceeds a certain threshold, for a certain number of times, within a certain period. These criteria are all configurable through the registers as described in Section 3.2.3.5. For example, with default configuration settings, as soon as the acceleration magnitude on any axis is measured to be greater than 2 *g* (register 0x 54, *Acceleration Event Threshold*) one time (register 0x 52, *Acceleration Event Threshold Count*) in less than 10 seconds (register 0x 53, *Acceleration Event Threshold Period*), an acceleration event is registered.

An acceleration clear is when the previous acceleration event is considered "cleared." This occurs as soon as no further above-threshold acceleration is registered for at least a configurable *grace period* (register 0x 55). No additional acceleration-event-based UL reports are sent before an acceleration clear is registered. For example, after an acceleration event has been registered, the Sensor must not sustain any above-threshold movement for the full 5-minute (default) grace period before an acceleration clear is registered. Until that time, no additional acceleration alarm ULs are sent. Every time an above-threshold acceleration is measured after a registered accelerometer event but before that event has been cleared, the grace period timer resets to 0.

Whenever an acceleration event is registered, it is configurable what type of data is reported. As an option, an acceleration alarm UL can be reported. In this case, an acceleration alarm clear UL will be reported as soon as an acceleration clear is registered, as explained in the previous paragraph. No additional acceleration alarms are reported before the first acceleration alarm clear is registered. An example sequence of detected motion and generated acceleration ULs is shown in Figure 1-7.

The other options of what to report after an acceleration event is registered are ambient temperature, ambient RH, probe voltage, probe temperature, MCU temperature, or any combination of these telemetries. By default, these telemetries are not reported in the case of accelerometer events; only the acceleration alarm is reported. If any of these additional telemetries are configured to be sent based on accelerometer events, they will be reported in a separate, subsequent UL following the acceleration alarm. These are reported in the same format as a regular periodic report. When the accelerometer clear is registered, another additional report is sent in an UL. This function is particularly useful for use-cases in which the sensed telemetries are needed when the Sensor moves from one place to another; the telemetry would be updated when the device begins to move from location A and then again when it is left motionless to stay in position B.

Event-based reporting in the case of acceleration events can be disabled, in which case neither the acceleration alarm nor additional telemetries will be reported (see register 0x 56).

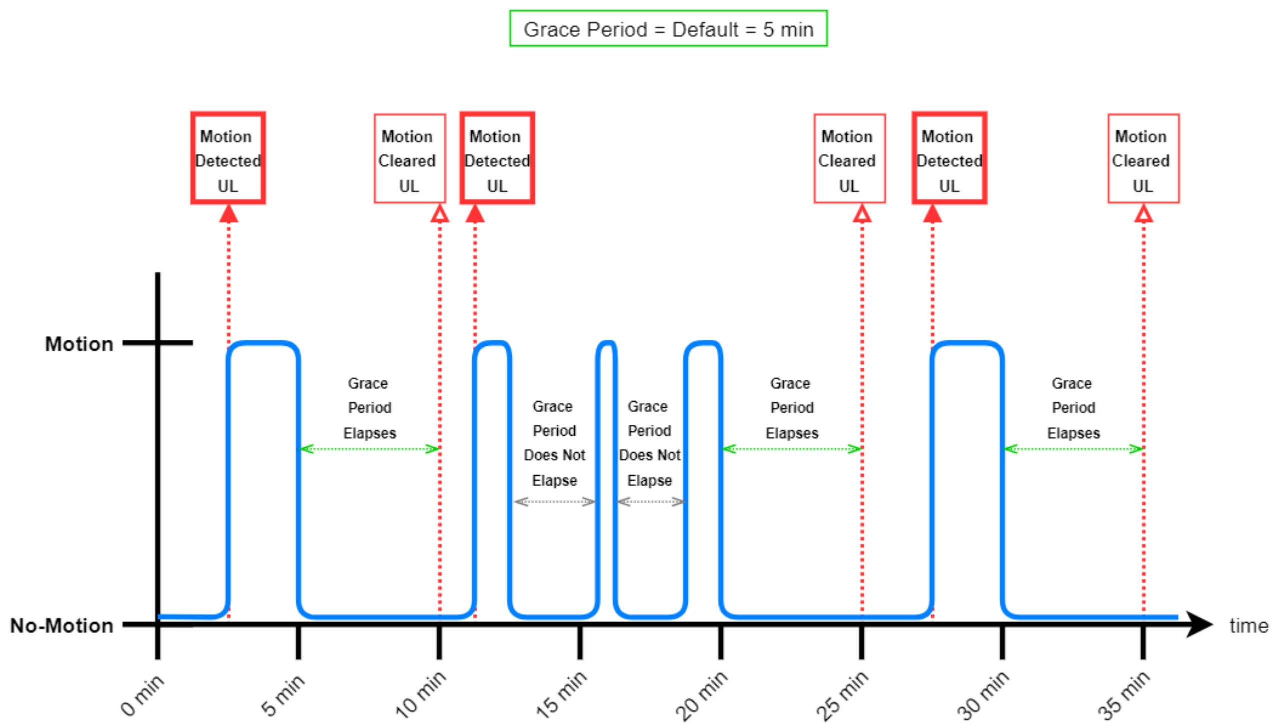


Figure 1-7: Example Sequence of Accelerometer Events and UL Reports

1.5 Store & Forward

Store & Forward (S&F) is a system design feature intended to support the storing of TUNDRA Sensor transducer data so that it can be accessed and forwarded to the Network Server and Application layer at a later time. This is to prevent data loss in the case of network connection interruption, dropped packets, dead battery, or otherwise.

The S&F system implemented for the TUNDRA Sensor is capable of storing 3 types of transducer data: the ambient temperature, ambient RH, analog probe data. All other transducer data is not stored and cannot be retrieved at a later time. By default, the Sensor stores all 3 types of data[7].

As explained in Section 3.2.3.2, the analog probe data is measured as a voltage which can then be optionally converted to temperature before reporting. All probe data is stored in voltage format, but whether it is reported as this raw voltage or converted temperature depends on the value of register 0x 2F.

The TUNDRA Sensor regularly samples transducers and uplinks this data to the NS at regular intervals as defined by the tick settings (see Section 3.2.3.1). The 3 data types mentioned above are also stored in the Sensor's memory at the time of UL by default. This is in contrast to other data types and data on other sensors that do not support S&F; in these cases, the data is discarded after the UL.

The stored data is stored and indexed through *tagging*.

1.5.1 Tagging

The Sensor tags all the data packets that are intended to be uplinked, and that can be retransmitted later if requested, with a 2-byte *tag header*. The tag header is the first 2 bytes in a tagged frame payload, and is a wraparound counter indexing the data packets that are uplinked and stored in the flash non-volatile memory (NVM), so they can be retrieved and retransmitted later if requested by the application. Figure 1-8 shows this scheme.

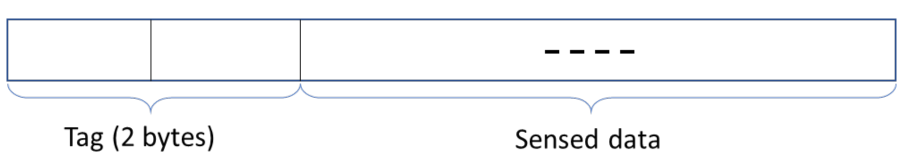


Figure 1-8: Tagged LoRaWAN Frame Payload

Note: Tags are incremented for all sensed data destined to go over the air, whether or not the sensor succeeds at sending them over the air. Also, all tagged sensed data are saved to NVM

[7] TUNDRA variants not equipped with a probe cannot and do not store analog probe data.

regardless of the sensor being successful at uplinking them. Failure at uplinking can be due to LoRaMAC rejecting the packet because of duty cycle limitations in some regions.

1.5.2 Storing

The Sensor stores every tagged frame payload in its NVM. This includes the tag header and corresponding data sample(s) in the payload.

The Sensor can store up to 3000 tagged entries. Each entry can include ambient temperature data, ambient RH data, analog probe voltage data, or any combination thereof. For example, if the Sensor is configured to sample and UL temperature twice as frequently as RH and not configured to store probe voltage or probe temperature, entry 0001 would contain both temperature and RH, entry 0002 would only contain temperature, entry 0003 would include both, and so on. Once tag 3000 has data written to it, the next entry will overwrite tag 0001. This way, the oldest entries are overwritten with the newest data once every tag is full.

Stored data persists through resets, loss of Sensor power, and loss of network coverage, and battery replacement.

By default, 3 types of storable data (ambient temperature, ambient RH, and probe temperature) are stored every time the transducers are sampled. If one or more one of these telemetry types is not of interest, then storage can be disabled through a DL command as explained in Section 3.2.1.

1.5.3 Forwarding

The Sensor can retrieve the data identified by their tag headers from its NVM. The requested tag headers are communicated to the Sensor via a DL. The Sensor responds with the retrieved data by forwarding it via a UL.

The Sensor does not have any knowledge on which data packets were not initially received by the NS, so it does not forward data automatically. The forwarding of data must be controlled by a user or application.

All probe data is stored in voltage format, but whether it is forwarded as this raw voltage or converted temperature depends on the value of register 0x 2F (see Section 3.2.3.2).

Please see Sections 0 and 0 for the UL and DL formats for forwarding and requesting stored data.

2 UL Payload Formats

The UL streams (from the Sensor to the NS) include the following:

- Empty, forced uplinks using the magnetic reed switch (***sent on LoRaWAN port 0***).
- The non-tagged readings obtained from on-board transducers (***sent on LoRaWAN port 10***).
- Reporting errors from the S&F system (***sent on LoRaWAN port 14***).
- The tagged readings obtained from on-board transducers (***sent on LoRaWAN port 32***).
- The forwarded tagged readings that were stored in memory (***sent on LoRaWAN ports 33-34***).
- Response to configuration and control commands from the NS (***sent on LoRaWAN port 100***)

These topics are explained in the following subsections.

All data contained in Sensor telemetry ULs (not responses to configuration and control commands) falls into one of the following reporting categories:

- **Periodic Reporting**: Scheduled reporting of telemetry at regular, configurable intervals. The reporting intervals are configured through the use of the tick registers as described in Section 3.2.3.1.
- **Event-Based Reporting**: Various external events can trigger unscheduled telemetry ULs outside of the periodic reporting schedule. These external events include function button presses, magnetic switch actuation, motion of the device above the accelerometer threshold, and temperature measurements outside of the threshold window. Each event elicits a different type of response from the Sensor. Not all event-based reporting is enabled by default.

This section describes the *format* of the report payloads. For details on what causes event-based reporting and how to configure the Sensor's event-based behaviour, see the relevant subsections for the particular transducer of interest in Section 0.

2.1 Forced Uplinks

Since DLs can only be received by the Sensor during the Rx window which is opened after sending an UL, it is sometimes desirable to force the Sensor to send an UL instead of waiting for the next one. This can be done by physically applying the magnet with the pattern specified in Figure 1-6 in Section 0.

The resulting UL will have an empty payload and is sent on ***LoRaWAN port 0***.

2.2 Frame Payload to Report Non-Tagged Transducer Data

Non-tagged data (meaning that it is not stored in the S&F system) includes the battery voltage, MCU temperature, and external probe reed switch data. The ambient temperature, ambient RH, and external probe analog voltage are tagged and stored by default but can optionally be un-tagged and not stored (see Section 3.2.1).

Each data field from the Sensor is encoded in a frame format shown in Figure 2-1. A big-endian format (MSB first) is always followed.

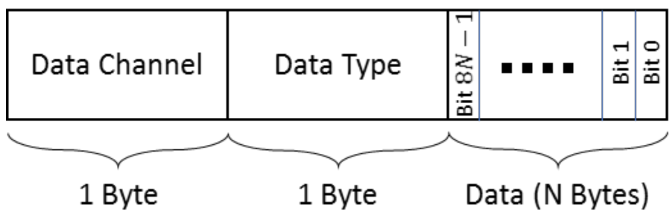


Figure 2-1: The UL Frame Payload Format for Non-Tagged Transducer Data

A Sensor message payload can include multiple transducer data frames. The ordering of frames can be in any order. A single payload may include data from any given transducer. The Sensor payload frame values are shown in Table 2-1. In this table, the bit indexing scheme is as shown in Figure 2-1.

Non-tagged transducer data in the UL are sent through ***LoRaWAN port 10 (0x 0A)***.

Table 2-1: UL Frame Payload Values for Non-Tagged Transducer Data

Information Type	Channel ID	Type ID	Size	Data Type	Data Format	JSON Variable (Type/Unit)
Battery Voltage[8]	0x 00	0x FF	2 B	Analog	• 10 mV / LSB (signed)	*battery_voltage: <value> (signed/volt)*
Remaining Battery Capacity[9]	0x 00	0x D3	1 B	Percentage	• 1% / LSB (unsigned)	*rem_batt_capacity: <value> (unsigned/%)*
Remaining Battery Lifetime[9]	0x 00	0x BD	2 B	Days	• 1 day / LSB	*rem_batt_days: <value> (unsigned/days)*
MCU Temperature	0x 0B	0x 67	2 B	Temperature	• 0.1°C / LSB (signed)	*mcu_temperature: <value> (signed/°C)*
Ambient Temperature	0x 03	0x 67	2 B	Temperature	• 0.1°C / LSB (signed)	*ambient_temperature: <value> (signed/°C)*

[8] Not available on FW v3.0.0 and newer.

[9] Only available on FW v3.0.0 and newer.

Information Type	Channel ID	Type ID	Size	Data Type	Data Format	JSON Variable (Type/Unit)
Ambient RH	0x 04	0x 68	1 B	RH	• 0.5% / LSB	*relative_humidity: <value> (unsigned/1%)*
External Probe: Digital Reed Switch State	0x 0E	0x 00	1 B	Digital	• 0x 00 = Low—Magnet present • 0x 01 = High—Magnet absent	*ext_reed_switch_state: <value> (unsigned/no unit)*
External Probe: Digital Reed Switch Count	0x 0F	0x 04	2 B	Counter	• Integer number	*ext_reed_switch_count: <value> (unsigned/no unit)*
External Probe: Thermistor Analog Voltage	0x 02	0x 02	2 B	Analog	• 1 mV/LSB (signed)	*ext_probe_voltage: <value> (signed/V)*
External Probe: Thermistor Analog Temperature[1]	0x 02	0x 67	2 B	Temperature	• 0.1°C / LSB (signed)	*ext_probe_temperature: <value> (signed/°C)*
Acceleration Alarm Status[10]	0x 00	0x 00	1 B	Digital Input	• 0x 00 = Alarm inactive (motion no longer detected) • 0x FF = Alarm active (motion detected)	*acceleration_alarm (unsigned/no unit)*
Acceleration Vector[10]	0x 00	0x 71	6 B	Acceleration	• 1 milli-*g*/LSb (signed) • Bits 32-47: X-axis acceleration • Bits 16-31: Y-axis acceleration • Bits 0-15: Z-axis acceleration	*acceleration_vector { xaxis: <value>, (signed/g) yaxis: <value>, (signed/g) zaxis: <value> (signed/g) }*

NOTE: As explained in Section 3.2.3.2, the analog probe data is measured as a voltage which can then be optionally converted to temperature before reporting. All probe data is stored in voltage

[10] Accelerometer function is only available in FW v3.0.0 and newer.

format, but whether it is reported as this raw voltage or converted temperature depends on the value of register 0x 2F.

Examples:

In the following example payloads, the data channel ID and data type ID are boldfaced:

- 0x **0B 67** 00 0A
    - $0\text{x } \mathbf{0B\ 67}\ (\text{MCU Temperature}) = (0\text{x } 00\ 0\text{A}) \times 0.1°\text{C} = 1°\text{C}$
- 0x **00 FF** 01 2C
    - $0\text{x } \mathbf{00\ FF}\ (\text{Battery Voltage}) = (0\text{x } 01\ 2\text{C}) \times 0.01\ \text{V} = 3.00\ \text{V}$
- 0x **0E 00** FF **0F 04** 00 24
    - 0x **0E 00** (External Probe: Digital Reed Switch State) = FF = switch is open
    - 0x **0F 04** (External Probe: Digital Reed Switch Count) = 0x 00 24 = 36 switch state changes

2.3 Frame Payload to Report S&F System Errors

As described in Section 1.5, the S&F system stores data and indexes it by a 2-byte tag number. To retrieve data and forward it later, the user must send a DL requisition with the specific tag number(s) desired (see Section 0). If this DL includes any tag numbers that are empty (have not yet had any data stored under them) or cannot be retrieved, then the Sensor will respond with an UL containing those tag numbers. The payload size for *N* of these "bad" tags is 2*N*.

These error ULs are sent on ***LoRaWAN port 14 (0x 0E)***.

Example:

- 0x 02 67 02 68
  - Tagged entries 615 and 616 are empty; there is no data stored under those indices.

2.4 Frame Payload to Report Tagged Transducer Data

All tagged data are sent on ***LoRaWAN port 32 (0x20)*** when first sampled. The application can easily identify a tagged payload from the port number. After the UL is sent, the tagged data is stored in the S&F system for later retrieval.

Each tagged data field from the Sensor is encoded in a frame format shown in Figure 2-2 (default configuration). A big-endian format (MSB first) is always followed. The tagged data included in the UL can be the ambient temperature, ambient RH, probe analog voltage, probe temperature, or any combination thereof, depending on S&F configuration (ref. Section 3.2.1). By default, three data types are tagged as shown in Figure 2-2: ambient temperature, ambient RH, and probe temperature.

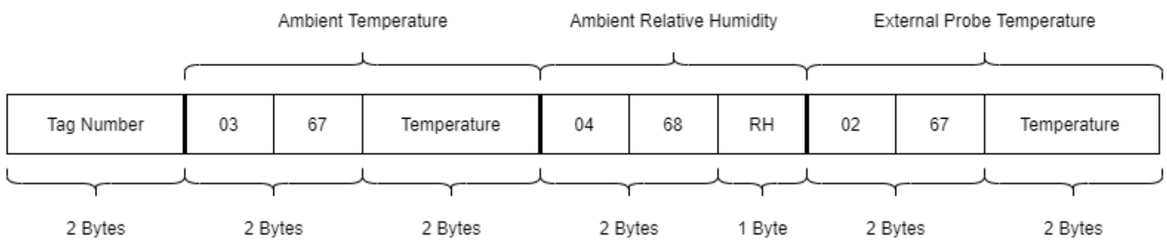


Figure 2-2: The Tagged UL Frame Payload Format

A Sensor message payload can include one or multiple transducer data frames. The frames may be arranged in any order. A single payload may include data from any given transducer. The Sensor tagged payload frame values are shown in Table 2-2. In this table, the bit indexing scheme is as shown in Figure 2-2. These telemetries have the same Channel and Type IDs compared to their un-tagged counterparts.

Table 2-2: UL Frame Payload Values for Tagged Transducer Data

Information Type	Channel ID	Type ID	Size	Data Type	Data Format	JSON Variable (Type/Unit)
Ambient Temperature	0x 03	0x 67	2 B	Temperature	• 0.1°C / LSB (signed)	*ambient_temperature: <value> (signed/°C)*
Ambient RH	0x 04	0x 68	1 B	RH	• 0.5% / LSB	*relative_humidity: <value> (unsigned/1%)*
External Probe: Thermistor Analog Voltage	0x 02	0x 02	2 B	Analog	• 1 mV/LSB (signed)	*ext_probe_voltage: <value> (signed/V)*
External Probe: Thermistor Analog Temperature[1]	0x 02	0x 67	2 B	Temperature	• 0.1°C / LSB (signed)	*ext_probe_temperature: <value> (signed/°C)*

NOTE: As explained in Section 3.2.3.2, the analog probe data is measured as a voltage which can then be optionally converted to temperature before reporting. All probe data is stored in voltage format, but whether it is reported as this raw voltage or converted temperature depends on the value of register 0x 2F.

Examples:

In the following example payloads, the data channel ID and data type ID are boldfaced:

- 0x 0A 46 **03 67** 00 0A
    - $0\text{x } 0\text{A } 46 = \text{Tag entry } \#2630$
    - $0\text{x } \mathbf{03\ 67}\ (\text{Ambient Temperature}) = (0\text{x } 00\ 0\text{A}) \times 0.1°\text{C} = 1°\text{C}$
- 0x 00 05 **04 68** 2A **03 67** FF FF
    - $0\text{x } 00\ 05 = \text{Tag entry } \#5$
    - $0\text{x } \mathbf{04\ 68}\ (\text{Ambient RH}) = (0\text{x } 2\text{A}) \times 0.5\% = 21\%$
    - $0\text{x } \mathbf{03\ 67}\ (\text{Ambient Temperature}) = (0\text{x FF FF}) \times 0.1°\text{C} = -0.1°\text{C}$
- 0x 06 1A **02 02** 0E 5E
    - $0\text{x } 06\ 1\text{A} = \text{Tag entry } \#1562$
    - $0\text{x } \mathbf{02\ 02}\ (\text{External Probe Analog Voltage}) = (0\text{x } 0\text{E } 5\text{E}) \times 0.1\text{ mV} = 3.678\text{ V}$

2.5 Frame Payload to Retransmit Stored Transducer Data

Upon receiving a DL requisition to forward (retransmit) some stored data, the Sensor will retrieve the data from flash and send it on ***LoRaWAN port 33 (0x21)***. The application layer can easily identify a retransmitted tagged payload from the port number.

Each tagged data field from the Sensor is encoded in a frame format shown in Figure 2-1. The Channel and Type IDs for the data types are the same regardless of whether the packet is a non-tagged initial UL, a tagged initial UL, or a forwarded tagged UL.

When the application or user requests retransmission of more than 1 missing packet, the requested tagged packets are retrieved and retransmitted in order (oldest to newest) with their original tags in one or more UL packets.

In general, the sensor will incorporate as many missing packets as possible into one UL packet. However, due to a possible DR decrease from when the packets were originally sent to when they are requested, the sensor may have to fragment a packet into several ULs. Therefore, there will be two cases of forwarding tagged data in general: *unfragmented* and *fragmented*.

a) Unfragmented Data Forwarding:

This is the case where the sensor retransmits one or more requested packets in a single UL.

As shown in Figure 2-3, the payload starts with tag m, which is the tag of the first packet in the set of the missing packets addressed in this payload. Forwarded data appear in the exact order as requested by the application, so their corresponding tags are not included in the payload shown in Figure 2-3; only the first tag is included.

The data of the ensuing requested packets are each separated by 1 byte which denotes the size (in units of bytes) of their respective lengths, so as to eliminate confusion as to what telemetry types are being included.

The data following each size byte N_q contains the channel ID and type ID bytes as well as the actual telemetry.

Example: if the 3rd tag that is requested has a temperature of 1°C, no RH data, and no external analog voltage data stored under it, then $N_3 = 0\mathrm{x}\,04$ and the following 4 bytes would be 0x 03 67 00 0A.

In Figure 2-3, missing tag m and its $q-1$ subsequent missing tags are being addressed. **LoRaWAN port 33 (0x21)** is used for unfragmented data forwarding.

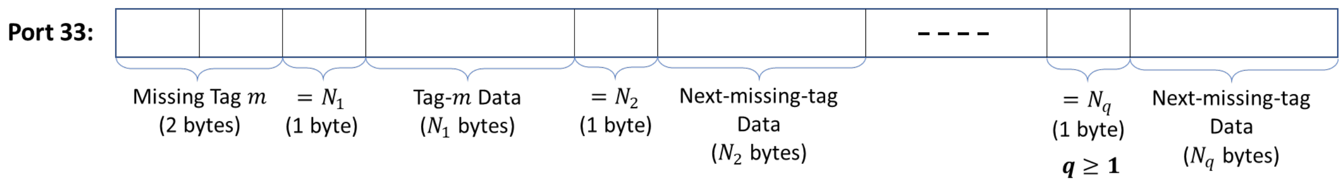


Figure 2-3: The Unfragmented Data Forwarding Payload Format

b) **Fragmented Data Forwarding:**

This is the case where the Sensor needs to retransmit one or more requested tag entries, but the data from a single tag entry cannot fit in a single UL due to the current DR payload size limitations. In this case, the Sensor needs to fragment the data of the packet and send the fragments in several ULs.

Note that if more than 1 tagged entries are requested in a single DL, a single UL will contain data only from a single tag entry. The other requested tag entry data will follow in subsequent ULs, each on ***LoRaWAN port 33***.

In the case where a single tag cannot fit into a single UL frame, the payload is fragmented into multiple ULs. All the fragments are sent with the same tag which is the tag number of the requested missing packet. This has been shown in Figure 2-4. Fragments include the first fragment, and one or more subsequent fragments. The first fragment is sent on ***LoRaWAN port 33 (0x21)*** in the exact same format as the unfragmented data retransmission. The subsequent fragment(s) is/are sent on ***LoRaWAN port 34 (0x22)***.

Individual fragments may not contain valid data; valid data is formed after appending all the parts at the application level.

The size byte included with the first fragment only (i.e., on port 33) indicates the length of all fragments combined (not including the 2-byte tag numbers *m*). This size is the key for understanding whether the data in each UL on the *"first-transmission port"* 33 is complete or just the first fragment. If the size byte matches the remaining contents of the payload, then it is an unfragmented UL and no further ULs are pending. If the size byte does not match the remaining contents of the payload, then it is the first fragment and there are pending ULs expected on the "*overflow port*" 34.

The user/application knows that it has received all the fragments correctly only when

i) it has received the first fragment on port 33,

ii) one or more fragments on port 34 are received that bring the total size of the payload to N, and

iii) there is no missing UL frame counter between the first fragment and what the user/application believes is the last fragment based on the payload size N.

If the above conditions are not satisfied, the user/application should assume that the packet has not been completely received and must be requested again.

This fragmented retransmission scheme allows for any number of fragments, but the Sensor minimizes the number of fragments based on the current DR.

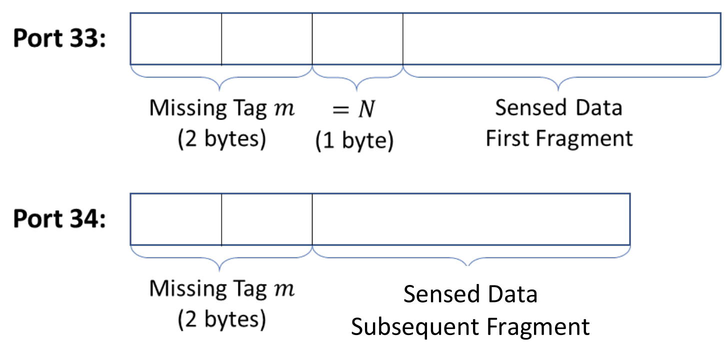


Figure 2-4: The Fragmented Data Forwarding Payload Format

Note: The Sensor responds to all retransmission requests received from the application in order. This response may not be immediate. If a request is received in the middle of the sensor sending fragments of the response to a previous request, the Sensor will finish responding to the previous request before switching to the new one.

Up to 100 tagged entries can be requested/sent at one time. If more than 100 entries are required, multiple DL requests are necessary. See Section 0 for information about how to request packet forwarding.

NOTE: As explained in Section 3.2.3.2, the analog probe data is measured as a voltage which can then be optionally converted to temperature before reporting. All probe data is stored in voltage format, but whether it is forwarded as this raw voltage or converted temperature depends on the value of register 0x 2F.

2.6 Response to Configuration and Control Commands

Sensor responses to DL configuration and control commands (which are sent on ***LoRaWAN port 100***; see Section 0) are sent in the UL on ***LoRaWAN port 100 (0x64)***. These responses include the following:

- Returning the value of a configuration register in response to an inquiry from the NS.
- Confirming that a configuration register has been overwritten.

In the former case, the Sensor responds by the address and value of each of the registers under inquiry (this can be in one or more consecutive UL packets depending on the maximum frame payload size allowed).

In the latter case, the Sensor responds with a CRC32 of the entire DL payload (which may be a combination of read and write commands) as the first 4 bytes of the UL frame. If the DL payload has also had read commands, the 4 CRC32 bytes are followed by the address and value of each of the registers under inquiry (similar to the Sensor response in the former case).

3 DL Payload Formats

The DL message streams (from the NS to the Sensor) supported by the SW include the following:

- Putting the Tracker into DEEP SLEEP mode (***sent on LoRaWAN port 99***)
- Configuration and control commands used to change the Sensor's behavior or inquire the Sensor for the values of registers (***sent on LoRaWAN port 100***).
- Requests for retrieval of stored data (***sent in DL, LoRaWAN ports 112-122***).

3.1 Putting Tracker to Sleep OTA

For information about the alternative method for putting the Sensor into DEEP SLEEP (i.e. with a magnet), refer to Section 1.2.

The Sensors ship in a state of DEEP SLEEP to conserve power. Once activated by the magnetic wakeup pattern (see Section 0), a Sensor can be remotely put back into DEEP SLEEP by sending an OTA DL. This DL should be sent on ***LoRaWAN port 99 (0x 63)*** and the payload should be **0x 00**.

Upon receiving this DL, the Sensor will reset, then enter DEEP SLEEP.

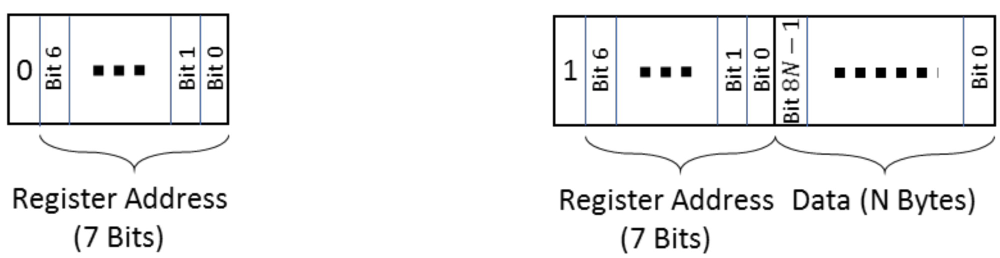
The magnetic wakeup pattern will then be required to bring this Sensor out of DEEP SLEEP, as usual.

3.2 Configuration and Control Commands

For Configuration and Control commands, the *register address* is used to access various configuration parameters. These addresses are bound between 0x00 and 0x7F, inclusive.

A single DL configuration and control message can contain multiple command blocks, with a possible mix of read and write commands. Each message block is formatted as shown in Figure 3-1. A big-endian format (MSB first) is always followed.

Bit 7 of the first byte determines whether a read or write action is being performed, as shown in Figure 3-1. All read commands are one-byte long. Data following a read access command will be interpreted as a new command block. Read commands are processed last. For example, in a single DL message, if there is a read command from a register and a write command to the same register, the write command is executed first.



(a) The read command (b) The write command

Figure 3-1: Format of a DL Configuration and Control Message Block

All DL configuration and control commands are sent on ***LoRaWAN port 100 (0x64)***.

When a write command is sent to the Sensor, the Sensor immediately responds with a CRC32 of the entire DL payload as the first 4 bytes of the UL frame on ***LoRaWAN port 100*** (also see Section 0).

DL configuration and control commands fall into one of the following four categories and are discussed in the following respective subsections.

- Store & Forward Configuration (Section 3.2.1)
- LoRaMAC Configuration (Section 3.2.2)
- Application Configuration (Section 3.2.3)
- Command and Control (Section 3.2.4)

3.2.1 Store & Forward Configuration

As mentioned in Sections 1.5.2 and 0, the ambient temperature, ambient RH, and external probe temperature values are all tagged and stored by default. However, it is possible for the user to decide which of these telemetry types is tagged and stored, and/or to optionally tag and store the external probe voltage instead of probe temperature. This feature is controlled by register 0x 0F as shown in Table 3-1.

Table 3-1: S&F Configuration Register

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 0F	Tagged Telemetry	2 B	• Bits 15-5: Ignored • Bit 4: 1/0 = RH tagged/not tagged • Bit 3: 1/0 = Ambient temperature tagged/not tagged • Bit 2: Ignored • Bit 1: 1/0 = External probe data tagged/not tagged • Bit 0: Ignored	Ambient temperature, ambient RH, and probe temperature stored. Probe voltage not stored. **0x 00 1A**	*tagged_telemetry: <value>* *(unsigned/no unit)*

Table 3-2 lists the commands for all the possible combinations of tagged and non-tagged telemetry configurations. These commands should be sent on ***LoRaWAN port 100***.

Table 3-2: S&F Configuration Commands for Selecting Which Telemetries are Stored

Ambient RH Stored	Ambient Temperature Stored	External Probe Data Stored	DL Command
✔			**0x 8F 00 10**
	✔		**0x 8F 00 08**
		✔	**0x 8F 00 02**
✔	✔		**0x 8F 00 18**
✔		✔	**0x 8F 00 12**
	✔	✔	**0x 8F 00 0A**
✔	✔	✔	**0x 8F 00 1A**
			0x 8F 00 00

NOTE: As discussed in Sections 1 and 3.2.3.2, all analog probe data is measured as a voltage which can then be optionally converted to temperature before reporting. All probe data is stored in voltage format, but whether it is forwarded as this raw voltage or converted temperature depends on the value of register 0x 2F.

3.2.2 LoRaMAC Configuration

LoRaMAC options can be configured using DL commands sent on port 100. These configuration options change the default MAC configuration that the Sensor loads on start-up. They can also change certain run-time parameters. Table 3-3 shows the MAC configuration registers. All the registers have R/W access, except for bit 1 on register 0x11, which is RO. In this table, the bit indexing scheme is as shown in Figure 3-1.

Table 3-3: LoRaMAC Configuration Registers

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 10	Join Mode	2 B	• Bit 15: 0/1 = ABP/OTAA mode • Bits 0-14: Ignored	OTAA mode **0x 80 00**	*loramac_join_mode:* *<value>* *(unsigned/no unit)*
0x 11	Options	2 B	• Bit 0: 0/1 = Unconfirmed/Confirmed UL • Bit 1 = 1 (RO): 0/1 = Private/Public Sync Word • Bit 2: 0/1 = Disable/Enable Duty Cycle • Bit 3: 0/1 = Disable/Enable ADR • Bits 4-15: Ignored	• Unconfirmed UL • Public Sync Word • Duty cycle enabled[11] • ADR enabled **0x 00 0E**	*loramac_opts {* *confirm_mode:* *<value>,* *(unsigned/no unit)* *sync_word: <value>,* *(unsigned/no unit)* *duty_cycle: <value>,* *(unsigned/no unit)* *adr: <value>* *(unsigned/no unit)* *}*
0x 12	DR and Tx Power[12]	2 B	• Bits 8-11: Default DR number • Bits 0-3: Default Tx power number • Bits 4-7, 12-15: Ignored	• DR0 • Tx Power 0 (max power; see Table 3-5 **0x 00 00**	*loramac_dr_tx {* *dr_number: <value>,* *(unsigned/no unit)* *tx_power_number:* *<value>,* *(unsigned/no unit)* *}*

[11] In the LoRaMAC RF regions where there is no duty cycle limitation, such as US915, the "enabled duty cycle" configuration of the Sensor is ignored.

[12] Tx power number m translates to the maximum Tx power, which is a function of the LoRaWAN RF region, minus $2 \times m$ dB. For a list of all values for each region, refer to the corresponding section in the LoRaWAN Regional Parameters specification document [1].

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 13	Rx2 Window	5 B	• Bits 8-39: Channel frequency in Hz for Rx2 • Bits 0-7: DR for Rx2	As per Table 3-5	*loramac_rx2 {* *frequency: <value>, (unsigned/Hz)* *dr_number: <value> (unsigned/no unit)* *}*

Note: Modifying these values only changes them in the Sensor. Options for the Sensor in the NS also need to be changed in order to not strand a Sensor and ensure desired operation. Modifying configuration parameters in the NS is outside the scope of this document.

Table 3-4: Default Maximum Tx Power in Different Regions

RF Region	Max Tx EIRP [dBm]
EU868	16
US915	30
AS923	16
AU915	30
IN865	30
KR920	14
RU864	16

Table 3-5: Default Values of Rx2 Channel Frequency and DR Number in Different Regions

RF Region	Channel Frequency [Hz]	DR Number
EU868	869525000	0
US915	923300000	8
AS923	923200000	2
AU915	923300000	8
IN865	866550000	2
KR920	921900000	0
RU864	869100000	0

LoRaMAC Configuration DL Examples:

- Switch Sensor to ABP Mode:
  - DL payload: { 0x **90** 00 00 }
- Set ADR enabled, no duty cycle, and confirmed UL payloads:
  - DL payload: { 0x **91** 00 0B }

- Set default DR number to 1 and default Tx power number to 2:
  - DL payload: { 0x **92** 01 02 }

3.2.3 Application Configuration

This section lists all possible application configurations (as part of DL configuration and control commands), including periodic Tx configuration and configurations of the different transducers.

3.2.3.1 Periodic Tx Configuration

All periodic reporting is synchronized around ticks. The *core tick* is simply a user-configurable time base unit that is used to schedule Sensor measurements. For each transducer in the Sensor, the number of elapsed ticks before transmitting can be defined. Table 3-6 shows a list of registers used to configure the Sensor periodic transmissions. All the registers have R/W access. Note that these registers only control *periodic reporting* and do not affect *event-based reporting* of the same type of telemetry (see Section 2).

The reporting period for each transducer is obtained as per the following:

<Transducer> *Reporting Period* $=$ ***Seconds per Core Tick*** $\times$ ***Ticks per <Transducer>***

where <Transducer> can be “Battery”, “Ambient Temperature”, “Ambient RH”, “Accelerometer”, “MCU Temperature”, or “External Probe” as shown in Table 3-6. If <Transducer> Reporting Period equals 0, it means that the <Transducer> periodic reporting is disabled. This happens when either the *Seconds per Core Tick* or *Ticks per <Transducer>* is equal to 0. The above relationship also shows that setting *Seconds per Core Tick* to 0 disables all periodic reporting. However, to disable the periodic reporting of a specific transducer, it is enough to set its *Ticks per <Transducer>* to 0.

Table 3-6: Periodic Tx Configuration Registers

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 20	Seconds per Core *Tick*	4 B	• *Tick* value for periodic events • Acceptable values: 0, 60, 61, …, 86400 • 0 disables all periodic transmissions • Other values: Invalid and ignored	3600 seconds = 1 hour/tick **0x 00 00 0E 10**	*seconds_per_core_tick: <value> (unsigned/sec)*
0x 21	*Ticks* per Battery	2 B	• *Ticks* between battery reports • 0 disables periodic battery reports	1 tick = 1-day period **0x 00 18**	*tick_per_battery: <value> (unsigned/no unit)*

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 22	*Ticks* per Ambient Temperature	2 B	• *Ticks* between ambient temperature reports • 0 disables periodic ambient temperature reports	1 tick = 1-hour period **0x 00 01**	*tick_per_ambient_temperature: <value> (unsigned/no unit)*
0x 23	*Ticks* per Ambient RH	2 B	• *Ticks* between ambient RH reports • 0 disabled periodic ambient RH reports	1 tick = 1-hour period **0x 00 01**	*tick_per_relative_humidity: <value> (unsigned/no unit)*
0x 24	Ticks per Accelerometer	2 B	• Ticks between accelerometer reports • Acceptable values: 0, 1, 2, …, 65535 • 0 disables periodic accelerometer reports	Periodic reporting disabled **0x 00 00**	*ticks_per_accelerometer: <value> (unsigned/no unit)*
0x 27	*Ticks* per MCU Temperature	2 B	• *Ticks* between MCU temperature reports • 0 disables periodic MCU temperature reports	Periodic reporting disabled **0x 00 00**	*tick_per_mcu_temperature: <value> (unsigned/no unit)*
0x 28	*Ticks* per External Probe (Digital/Analog Input)	2 B	• *Ticks* between external probe (digital/analog input) reports • A value of 0 disables periodic external connector (digital/analog input) reports	1 tick = 1-hour period **0x 00 01**	*tick_per_external_probe: <value> (unsigned/no unit)*

3.2.3.1.1 Anti-Bricking Strategy:

As a class-A LoRaWAN end-device, the Sensor can only be receptable to a DL in the short period after sending an UL. Therefore, if the Sensor is configured to send ULs very infrequently or not at all, it could become impossible to send a DL command. As the magnetic switch operation (see Section 0) cannot be disabled, it is impossible to completely brick the Sensor with a bad configuration; it is always possible to trigger the Sensor to UL something so it can receive DL commands for a desired configuration change.

However, there are use cases in which using the magnetic switch to trigger the Sensor may not be a convenient option, e.g. due to special mounting orientation, remote location, or in the case of reconfiguring a large number of devices. In these use cases, strategies to avoid bricking the Sensor are beneficial and included in the FW as follows.

The undesirable combinations that make the Sensor almost or completely irresponsive are:

> *All periodic reports are disabled OR have a minimum period of larger than a week, AND the accelerometer is disabled.*

If, after a configuration update request from the NS, the Sensor SW detects that the above situation occurs, the SW automatically sets the *core tick* value to 86400 seconds (i.e. one day) and the *ticks per battery* to 1.

3.2.3.1.2 Periodic Tx Configuration DL Examples:

- Disable all periodic events:
  - DL payload: { 0x **A0** 00 00 00 00 }
    - Register 0x20 with the write bit set to true
    - Seconds per *Tick* set to 0 (zero)—i.e. disable periodic transmissions
- Read current value of Seconds per *Tick*:
  - DL payload: { 0x **20** }
    - Register 0x20 with the write bit set to false
- Report Temperature every *tick* and RH every two *ticks*:
  - DL payload: { 0x **A2** 00 01 **A3** 00 02 }
    - Registers 0x22 and 0x23 with their write bits set to true
    - Temperature *Ticks* set to 1 (one)
    - RH *Ticks* set to 2 (two)

3.2.3.2 External Probe Configuration

Only the Probe variants of the TUNDRA Sensor are equipped with an external probe. See §1 for product codes. For a detailed description of how the probes function, see §1.3.

The factory-equipped probe for a TUNDRA Sensor can be either a digital reed switch or an analog thermistor. The input mode (digital or analog) is determined by register 0x 2D. The default input mode depends on whether a digital or analog Sensor variant was ordered, although can be changed at any time.

Table 3-7 lists the external probe configuration registers. All registers have R/W access. In this table, the bit indexing scheme is as shown in Figure 3-1.

Table 3-7: External Probe Configuration Registers

Address	Name	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 2D	Mode	1 B	• Bit 0: 0/1 = Rising edge disabled/enabled • Bit 1: 0/1 = Falling edge disabled/enabled • Both bits 0 and 1 set to 0: Invalid and ignored • Bits 2-6: Ignored. • Bit 7: 0/1 = Digital/Analog (Reed Switch/Thermistor) Input mode	• Both rising and falling edges enabled • Input mode corresponds to which probe HW Reed switch probe: **0x 03** Thermistor probe: **0x 83**	*ext_probe {* *rising_edge_enabled: <value>, (unsigned/no unit)* *falling_edge_enabled: <value>, (unsigned/no unit)* *mode: <value> (unsigned/no unit)* *}*
0x 2E	Count Threshold	2 B	• Number of triggers for event transmission • 0 disables event transmission	1 trigger **0x 00 01**	*ext_reed_switch_count_threshold: <value>* *(unsigned/no unit)*
0x 2F	Value to Tx	1 B	For Digital Probe: • Bit 0: 0/1 = Digital Input state not reported/reported • Bit 1: 0 = Digital Input count not reported/reported • Both bits 0 and 1 set to 0: Invalid and ignored • Bits 2-3: Ignored For Analog Probe: • Bit 4: 0/1 = Probe analog voltage/temperature reported • Bits 5-7: Ignored	• Digital probe: State and count reported • Analog probe: Temperature reported **0x 13**	*ext_reed_switch_tx {* *report_state_enabled: <value>, (unsigned/no unit)* *report_count_enabled: <value> (unsigned/no unit)* *report_voltage_enabled: <value> (unsigned/no unit)* *report_temperature_enabled: <value> (unsigned/no unit)* *}*

3.2.3.2.1 Mode

In *digital input mode* (bit 7 = 0), the input is edge-triggered and can be set to be triggered by the rising edge (Low/Closed to High/Open), falling edge (High/Open to Closed/Low), or both. An attempt to set the Mode to 0x 00 (i.e. to disable both rising and falling edges) is ignored by the Sensor.

In *analog input mode* (bit 7 = 1), bits 0-6 of register 0x 2D, and the entire registers 0x 2E and 0x 2F are irrelevant and ignored.

3.2.3.2.2 Count Threshold

The *Count Threshold* is only applicable in the digital input (reed switch) mode, and determines when the Sensor transmits after seeing an *event* upon digital probe input. A digital event is defined as a single rising or falling edge transition, depending on the current configuration (see §3.2.3.2.1).

Depending on the edge-trigger configuration, every time the input voltage changes such that the edge transition is detected, the *event counter* is increased. The *count threshold* is a configurable parameter that represents the value the event counter must reach before an event-based LoRa transmission is triggered. Whenever such an event-based transmission occurs, the event counter is automatically reset to 0 and starts incrementing as events continue to occur until the counter reaches the threshold again, thus triggering another event-based transmission.

3.2.3.2.3 Value to Tx

The *Value to Tx* is applicable in both the digital input (reed switch) mode and analog input (thermistor) mode and determines what information is transmitted whenever a probe event-based or periodic transmission is required.

For digital probes (either or both can be enabled):

- If the value to Tx is digital input state, the transmission contains the current digital input state of the switch (i.e., 0x 01 for open or 0x 00 for closed).
- If the value to Tx is the digital input count, the transmission contains the number of times that the digital input was triggered since the last transmission.

For analog probes (either can be enabled but not both)[1]:

- If the value to Tx is analog voltage, the transmission contains the current measured probe voltage.
- If the value to Tx is probe temperature, the transmission contains the current measured probe temperature (converted by formula from probe voltage).

External Probe Configuration DL Examples:

- Have digital input be triggered only on falling edges:
  - DL payload: { 0x **AD** 02 }
    - Register 0x2D with write bit set to true
    - Rising edge disabled, falling edge enabled
- Read current value of *Count Threshold*:
  - DL payload: { 0x **2E** }

      - Register 0x2E with write bit set to false
- Transmit the digital input state as soon as the digital input is tripped 20 times:
  - DL payload: { 0x **AE** 00 14 **AF** 01 }
    - Registers 0x2E and 0x2F with their write bits set to true
    - Count threshold set to 20
    - Value to Tx set to input state
- Disable reed switch event-driven transmission, but report the number of times the reed switch has been triggered whenever a report is inquired (i.e. in the case of periodic reporting):
  - DL payload: { 0x **AE** 00 00 **AF** 02 }
    - Count Threshold set to 0 (zero)
    - Value to Tx set to digital input count

3.2.3.3 Transducer Thresholds Configuration

The Sensor supports threshold-based transmission of five different transducer telemetries:

- Ambient temperature: Measured by the temperature/RH transducer.
- Ambient RH: Measured by the temperature/RH transducer.
- MCU temperature: Measured by the MCU (with lower accuracy compared to the ambient temperature).
- External probe analog voltage.
- External probe temperature.

When a threshold window on a transducer is enabled, the Sensor reports the transducer value when it leaves the configured window, and once again when the transducer value re-enters the window[13].

Threshold-based reporting is compatible with periodic reporting. Table 3-8 shows a list of configuration registers for the temperature/RH/external probe threshold settings. All the registers have R/W access. In this table, the bit indexing scheme is as shown in Figure 3-1.

[13] Note that the threshold window here is defined as the open interval "(Low Threshold, High Threshold)", not e.g. the closed interval "[Low Threshold, High Threshold]"; i.e. even if the transducer value is equal to Low Threshold or High Threshold, the Sensor is considered to have left the threshold window.

Table 3-8: Transducer Thresholds Configuration Registers

Address	Name	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 39	Ambient Temperature/ RH Sample Period: Idle	4 B	• Sample period of Ambient Temperature/RH transducer: Idle state (sec) • Acceptable values: 30, 31, …, 86400 • Other values: Invalid and ignored	60 s **0x 00 00 00 3C**	*temperature_relative_humidity_sample_period_idle: <value> (unsigned/sec)*
0x 3A	Ambient Temperature/ RH Sample Period: Active	4 B	• Sample period of Ambient Temperature/RH transducer: Active state (sec) • Acceptable values: 30, 31, …, 86400 • Other values: Invalid and ignored	30 s **0x 00 00 00 1E**	*temperature_relative_humidity_sample_period_active: <value> (unsigned/sec)*
0x 3B	Low/High Ambient Temperature Thresholds	2 B	• Bits 8-15: High temperature threshold (signed, 1°C / LSB) • Bits 0-7: Low temperature threshold (signed, 1°C / LSB) • High threshold ≤ Low threshold: Invalid and ignored	• High threshold = 30°C • Low threshold = 15 °C **0x 1E 0F**	*ambient_temperature_threshold {* *high: <value>* *(signed/°C)* *low: <value>* *(signed/°C)* *}*
0x 3C	Ambient Temperature Thresholds Enabled	1 B	• Bit 0: 0/1 = Thresholds disabled/enabled • Bits 1-7: Ignored	Disabled **0x 00**	*ambient_temperature_threshold_enabled: <value>* *(unsigned/no unit)*
0x 3D	Low/High Ambient RH Thresholds	2 B	• Bits 8-15: High RH threshold (unsigned, 1% RH / LSB) • Bits 0-7: Low RH threshold (unsigned, 1% RH / LSB) • High threshold ≤ Low threshold: Invalid and ignored	• High threshold = 80% • Low Threshold = 15% **0x 50 0F**	*relative_humidity_threshold {* *high: <value>,* *(unsigned/%)* *low: <value>* *(unsigned/%)* *}*
0x 3E	Ambient RH Thresholds Enabled	1 B	• Bit 0: 0/1 = Thresholds disabled/enabled • Bits 1-7: Ignored	Disabled **0x 00**	*relative_humidity_threshold_enabled: <value>* *(unsigned/no unit)*

Address	Name	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 40	MCU Temperature Sample Period: Idle	4 B	• Sample period of MCU temperature transducer: Idle state (sec) • Acceptable values: 30, 31, …, 86400 • Other values: Invalid and ignored	300 s **0x 00 00 01 2C**	*mcu_temperature_sample_period_idle: <value> (unsigned/sec)*
0x 41	MCU Temperature Sample Period: Active	4 B	• Sample period of MCU temperature transducer: Active state (sec) • Acceptable values: 30, 31, …, 86400 • Other values: Invalid and ignored	60 s **0x 00 00 00 3C**	*mcu_temperature_sample_period_active: <value> (unsigned/sec)*
0x 42	Low/High MCU Temperature Thresholds	2 B	• Bits 8-15: High MCU temperature threshold (signed, 1°C / LSB) • Bits 0-7: Low MCU temperature threshold (signed, 1°C / LSB) • High threshold ≤ Low threshold: Invalid and ignored	• High threshold = 30°C • Low threshold = 15 °C **0x 1E 0F**	*mcu_temperature_threshold { high: <value>, (signed/°C) low: <value> (signed/°C) }*
0x 43	MCU Temperature Thresholds Enabled	1 B	• Bit 0: 0/1 = Thresholds disabled/enabled • Bits 1-7: Ignored	Disabled **0x 00**	*mcu_temperature_threshold_enabled: <value> (unsigned/no unit)*
0x 44	External Probe (Voltage or Temperature) Sample Period: Idle	4 B	• Sample period of analog input: Idle state (sec) • Acceptable values: 30, 31, …, 86400 • Other values: Invalid and ignored	60 s **0x 00 00 00 3C**	*probe_sample_period_idle: <value> (unsigned/sec)*
0x 45	External Probe (Voltage or Temperature) Sample Period: Active	4 B	• Sample period of analog input: Active state (sec) • Acceptable values: 30, 31, …, 86400 • Other values: Invalid and ignored	30 s **0x 00 00 00 1E**	*probe_sample_period_active: <value> (unsigned/sec)*

Address	Name	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 46	Low/High External Probe Voltage Thresholds	4 B	• Bits 16-31: High analog input threshold (unsigned, 1 mV/LSB) • Bits 0-15: Low analog input threshold (unsigned, 1 mV/LSB) • High threshold ≤ Low threshold: Invalid and ignored	• High threshold = 1200 mV • Low threshold = 600 mV **0x 04 B0 02 58**	*probe_voltage_threshold {* *high: <value>,* *(unsigned/V)* *low: <value>* *(unsigned/V)* *}*
0x 47	Low/High External Probe Temperature Thresholds	2 B	• Bits 8-15: High MCU temperature threshold (signed, 1°C / LSB) • Bits 0-7: Low MCU temperature threshold (signed, 1°C / LSB) • High threshold ≤ Low threshold: Invalid and ignored	• High threshold = 30°C • Low threshold = 15 °C **0x 1E 0F**	*probe_temp_threshold {* *high: <value>,* *(unsigned/V)* *low: <value>* *(unsigned/V)* *}*
0x 48	External Probe (Voltage or Temperature) Thresholds Enabled	1 B	• Bit 0: 0/1 = Thresholds disabled/enabled • Bits 1-7: Ignored	Disabled **0x 00**	*probe_voltage_threshold_enabled: <value>* *(unsigned/no unit)*

3.2.3.3.1 Transducer Sample Period: Idle

The *idle sample period* determines how often the transducer is checked when the reported value is within the threshold window. When first enabled, the transducer starts in the Idle state.

The minimum sample period in the idle state is 30 sec, and the maximum is 86,400 sec (one day). Values smaller than 30 for this register are invalid and ignored.

3.2.3.3.2 Transducer Sample Period: Active

The *active sample period* determines how often the transducer is checked when the reported value is outside the threshold window.

The minimum sample period in the active state is 30 sec, and the maximum is 86,400 sec (one day). Values smaller than 30 for this register are invalid and ignored.

3.2.3.3.3 Transducer Thresholds

The *Thresholds* for each transducer are stored in a 2-byte or 4-byte register, with the MSB(s) storing the upper threshold, and the LSB(s) storing the lower threshold. Temperature thresholds have a precision of 1°C per bit, and are stored/transmitted as 2's complement numbers. The RH thresholds have a precision of 1% per bit, and are stored/transmitted as unsigned numbers. The external thermistor voltage thresholds are also unsigned numbers, and have a precision of 1 mV per bit.

In all cases, the upper threshold must be greater than the lower threshold. Otherwise, the configuration is considered invalid and ignored.

For cases when probe threshold-based reporting is desired, the value of register 0x 2F will determine whether the *voltage* thresholds (register 0x 46) or *temperature* thresholds (reg 0x47) are used as the thresholds. This is because, as explained in Section 3.2.3.2, the analog probe data is measured as a voltage which can then be optionally converted to temperature before reporting. All probe data is stored in voltage format, but whether it is reported as this raw voltage or converted temperature depends on the value of register 0x 2F.

3.2.3.3.4 Transducer Thresholds Enabled

The *Thresholds Enabled* registers enable and disable the threshold reporting on the specified transducer. Thresholds and sample periods can be configured but are not activated unless the thresholds enabled bit is set.

Threshold Configuration DL Examples:

- Set ambient temperature thresholds:
    - DL payload: { 0x **BB** 19 0A }
        - Register 0x3B with write bit set to true
        - High threshold set to 25°C
        - Low threshold set to 10°C
- Read *Ambient Temperature/RH Sample Periods*:
    - DL payload: { 0x **39 3A** }
        - Registers 0x39 and 0x3A with their write bits set to false
- Set and enable Ambient RH thresholds:
    - DL payload: { 0x **BD** 3C 14 **BE** 01 }
        - Registers 0x3D and 0x3E with their write bits set to true
        - High RH thresholds set to 60% RH
        - Low RH threshold set to 20% RH
        - RH thresholds enabled

3.2.3.4 Battery Management Configuration

The sensor is equipped with a battery-gauging system that allows the ability to report battery data in units of remaining battery capacity [%], or remaining battery lifetime [days], or both. These battery gauging values are based on the nominal capacity of a new battery as well as usage from the time the device is first powered-on.

Table 3-9 shows the battery configuration register options. The value of this register determines what data is sent in a port 10 UL when a battery report is due (periodic or event-based).

Table 3-9: Battery Management Configuration Register

Address	Name	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 4A	Battery Report Options	1 B	• Bit 0: Ignored Deprecated; was used for voltage reporting, which is no longer supported in Gen2.5 devices • Bit 1: 0/1 = Remaining battery capacity [%] not reported/reported • Bit 2: Remaining battery lifetime [days] not reported/reported • Bits 0-2 all set to 0: Invalid and ignored • Bits 3-7: Ignored	Remaining battery capacity [%] and remaining battery lifetime [days] reported **0x 06**	*battery_tx {* *report_voltage_enabled: <value>, (unsigned/no unit)* *report_capacity_enabled: <value> (unsigned/no unit)* *report_lifetime_enabled: <value>, (unsigned/no unit)* *}*
0x 4B	Average Energy Trend Window	1 B	• Bits 0-7: Number of core ticks, ***w*** [1 update/LSB] Acceptable values: 1, 2, …, 255 0: Invalid and ignored	10 core ticks **0x 0A**	*avg_energy_trend_window: <value>* *(unsigned/no unit)*

3.2.3.4.1 Battery Report Options

This register determines what type of data is reported at the time a battery report is due (according to the periodicity defined by the values of registers 0x20 and 0x21). By default, the remaining battery capacity and remaining battery lifetime are reported. Gen2 devices only support battery voltage reporting.

3.2.3.4.2 Average Energy Trend Window

While the remaining battery capacity gradually drops throughout during normal operation of the Sensor, the remaining battery lifetime may go up or down, depending on the energy consumption of the device. For example, a Sensor configured to send a UL report every 15 minutes will consume more energy than one that is configured to send a UL report every 60 minutes. And since the Sensors can be reconfigured at any time during normal operation and change their energy consumption rate, the remaining lifetime will in-turn change as well.

The Sensor handles this by monitoring the average energy consumption trend over a certain time; the *Average Energy Trend Window.* The Sensor updates how much energy it has consumed at each core tick (register 0x20). The average energy trend window specifies the number of preceding core ticks over which the energy consumption trend is calculated. This average energy consumption trend is then used to estimate the remaining battery lifetime.

Note that the JOIN procedure consumes energy at a higher rate than normal default operation, so the remaining lifetime value reported will take some time to stabilize after the Sensor joins the network. It will take *w* core ticks over which "steady-state" energy consumption occurs before the remaining battery lifetime value will stabilize.

It is recommended that the core tick settings and average energy trend window be configured in relation to each other. For example, a large core tick setting and large window will result in a long time for the remaining battery lifetime to be calculated accurately and will take a long time to respond to changes in energy consumption. A small core tick setting and small window will result in more fluctuations in consecutive battery reports.

3.2.3.4.3 Note on End-of-Service Gauging

The algorithm is based on the average nominal battery capacity of a new battery, so when the battery is replaced, the remaining capacity is automatically reset. However, the remaining battery capacity will not be reset when the device is soft-reset for any reason, including an OTA reboot.

3.2.3.5 Accelerometer Configuration

The accelerometer in the Sensor can be disabled or enabled and supports both periodic-based and event-based reporting. The accelerometer is enabled by default.

For a description of how the accelerometer function works, refer to §1.4.

Table 3-10 shows a list of accelerometer configuration registers. All the registers have R/W access. In this table, the bit indexing scheme is as shown in Figure 3-1.

Table 3-10: Accelerometer Configuration Registers

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 50	Mode	1 B	• Bit 0: 0/1 = X-axis disabled/enabled • Bit 1: 0/1 = Y-axis disabled/enabled • Bit 2: 0/1 = Z-axis disabled/enabled • Bits 3-6: Ignored • Bit 7: 0/1 = Accelerometer off/on	• X-axis enabled • Y-axis enabled • Z-axis enabled • Accelerometer off **0x 07**	*accelerometer_mode {* *xaxis_enabled: <value>, (unsigned/no unit)* *yaxis_enabled: <value>, (unsigned/no unit)* *zaxis_enabled: <value>, (unsigned/no unit)* *poweron: <value> (unsigned/no unit)* *}*
0x 51	Sensitivity	1 B	• Bits 0-2 (Sample Rate): 0: Invalid and ignored 1/2/3/4/5/6/7 = 1/10/25/50/100/200/400 Hz • Bits 4-5 (Measurement Range[14]): 0/1/2/3 = ±2/±4/±8/±16 *g* • Bits 3, 6, 7: Ignored	• Sample Rate 10 Hz • Measurement Range ±8 *g* **0x 22**	*accelerometer_sensitivity {* *sample_rate: <value>, (unsigned/Hz)* *measurement_range: <value> (unsigned/g)* *}*
0x 52	Acceleration Event Threshold Count	2 B	• Number of acceleration events before an acceleration alarm is registered • Acceptable values: ≥ 1 • 0: Invalid and ignored	1 event **0x 00 01**	*acceleration_event_threshold_count: <value> (unsigned/no unit)*
0x 53	Acceleration Event Threshold Period	2 B	• Period in sec over which acceleration events are counted for threshold detection • Acceptable values: ≥ 5 • 0-4: Invalid and ignored	10 seconds **0x 00 0A**	*acceleration_event_threshold_period: <value> (unsigned/sec)*
0x 54	Acceleration Event Threshold	2 B	• Unsigned, 1 milli-*g*/LSb	2 *g* **0x 07 D0**	*acceleration_event_threshold: <value> (unsigned/g)*

[14] Measurement ranges ±2 *g*, ±4 *g*, ±8 *g*, ±16 *g* correspond to typical transducer output precisions of 16 m*g*, 32 m*g*, 64 m*g*, 192 m*g*, respectively. Note that if a threshold configured in register 0x44 is equal to or greater than the configured measurement full scale (2 *g*, 4 *g*, 8 *g*, 16 *g*), then the acceleration alarm will never be triggered.

Address	Value	Size	Description	Default Value	JSON Variable (Type/Unit)
0x 55	Acceleration Event Grace Period	2 B	• Time to pass, in sec, after the last acceleration alarm before the alarm can be cleared) • Acceptable values: ≥ 15 • 0-14: Invalid and ignored	5 min **0x 01 2C**	*acceleration_event_grace_period: <value>* *(unsigned/sec)*
0x 56	Acceleration Event Value to Tx	1 B	• Bit 0: 0/1 = Acceleration alarm UL report disabled/enabled • Bit 1: 0/1 = Ambient temperature report disabled/enabled • Bit 2: 0/1 = Ambient RH report disabled/enabled • Bit 3: 0/1 = Analog probe report disabled/enabled • Bit 4: 0/1 = MCU temperature report disabled/enabled • Bits 5-7: Ignored	Acceleration alarm report UL enabled **0x 01**	*acceleration_event_tx {* *acceleration_alarm: <value>,* *(unsigned/no unit)* *ambient_temp: <value>* *(unsigned/no unit)* *ambient_rh: <value>* *(unsigned/no unit)* *analog_probe: <value>* *(unsigned/no unit)* *mcu_temp: <value>* *(unsigned/no unit)* *}*

3.2.3.5.1 Mode

The accelerometer can be enabled or put in a power-down mode to save battery life. Additionally, it is possible to enable/disable X, Y, Z axes independently. When an axis is disabled, it is not considered in monitoring acceleration events. Also, its corresponding value in the output acceleration vector is 0.

3.2.3.5.2 Sensitivity

When enabled (powered on), the accelerometer always samples the transducer element at a fixed rate, called the sample rate. To capture an acceleration event, the physical event needs to last longer than the sample period. Larger sample rates have a shorter period and can therefore resolve shorter acceleration events. However, sampling the transducer at a larger rate increases the power usage, and impacts the battery life. Table 3-11 shows typical current draw deltas (with respect to the MCU background current at sleep) for the different sample rates when the accelerometer is enabled.

Table 3-11: Typical Current Draw Deltas at 3.6 V for Different Accelerometer Sample Rates

Sample Rate [Hz]	1	10	25	50	100	200	400
Current Draw [µA]	1.0	1.5	2.3	3.7	6.1	11.4	22.0

Furthermore, the Sensitivity register sets the measurement range or full-scale, which shows the dynamic range of accelerations that can be monitored on any enabled axis. Note that when enabled, the accelerometer is always put in a low-power mode, which means the output acceleration values on any given axis (X, Y, or Z), is an 8-bit signed number. Therefore, a measurement range of ±2 *g* implies a precision of 4/256 *g*/LSb.

3.2.3.5.3 Acceleration Event Threshold Count

By default, the accelerometer registers an acceleration event each time it detects movement. Depending on the use case, it may be desirable to increase the threshold count to reduce sensitivity. This feature is to allow for filtering out short acceleration events, while still allowing longer acceleration events to be reported.

3.2.3.5.4 Acceleration Event Threshold Period

The *Acceleration Event Threshold Period* is the amount of time that acceleration events are accumulated for threshold detection. For example, an *Acceleration Event Threshold Period* of 10 sec accumulates acceleration events over a 10-sec period from the time of first detection. An acceleration event is registered only if the number of acceleration events reaches the *Acceleration Event Threshold Count* before the *Acceleration Event Threshold Period* expires.

3.2.3.5.5 Acceleration Event Threshold

This parameter is the g-threshold for an acceleration event. Acceleration events are registered only if the *Acceleration Event Threshold* is exceeded on at least one of the enabled axes (X, Y, Z) within the *Acceleration Event Threshold Period* for at least the *Acceleration Event Threshold Count* number of times.

3.2.3.5.6 Acceleration Event Grace Period

The *Acceleration Event Grace Period* determines how long the Sensor waits before the previously registered acceleration event is cleared. For example, an *Acceleration Event Grace Period* of 5 min means that the Sensor clears a previously registered acceleration event only 5 min after the registered event, then starts monitoring to register a new acceleration event.

3.2.3.5.7 Acceleration Event Value to Tx

This register determines what is reported when an acceleration event is registered. The options are the acceleration alarm, ambient temperature, ambient RH, analog probe data (either voltage or temperature or both, depending on the value of register 0x 2F), and MCU temperature.

3.2.3.5.8 Accelerometer Configuration DL Examples

- Power on accelerometer and enable all axes:
  - DL payload: 0xC0 87

- Change threshold value to 800 m*g*:
    - DL payload: 0xC4 03 20
- Read *Accelerometer Value to Tx*:
    - DL payload: 0x46

3.2.4 Command and Control

Configuration changes are not retained after a power cycle unless they are saved in the Flash memory. Table 3-12 shows the structure of the Command & Control Register. In this table, the bit indexing scheme is as shown in Figure 3-1.

Table 3-12: Sensor Command & Control Register

Address	Access	Name	Size	Description	JSON Variable (Type/Unit)
0x70	W	Flash Write Command	2 B	• Bit 14: • 0/1 = Do not write/Write LoRaMAC Config • Bit 13: • 0/1 = Do not write/Write App Config and S&F config • Bit 0: • 0/1 = Do not restart/Restart Sensor • Bits 1-12, 15: Ignored	*write_to_flash {* *lora_configuration: <value>, (unsigned/no unit)* *app_configuration: <value>, (unsigned/no unit)* *restart_sensor: <value> (unsigned/no unit)* *}*

Address	Access	Name	Size	Description	JSON Variable (Type/Unit)
0x71	R	Metadata	7 B	• Bits 48-55: App version major • Bits 40-47: App version minor • Bits 32-39: App version revision • Bits 24-31: LoRaMAC version major • Bits 16-23: LoRaMAC version minor • Bits 8-15: LoRaMAC version revision • Bits 0-7: LoRaMAC region number (see Section 3.2.2)	*metadata {* *app_major_version: <value>, (unsigned/no unit)* *app_minor_version: <value>, (unsigned/no unit)* *app_revision: <value>, (unsigned/no unit)* *loramac_major_version: <value>, (unsigned/no unit)* *loramac_minor_version: <value>, (unsigned/no unit)* *loramac_revision: <value>, (unsigned/no unit)* *region: <value> (unsigned/no unit)* *}*
0x72	W	Reset Config Registers to Factory Defaults[15]	1 B	• 0x 0A = Reset App Config • 0x B0 = Reset LoRa Config • 0x BA = Reset both App and LoRa Configs • Any other value: Invalid and ignored	*configuration_factory_reset: <value> (unsigned/no unit)*

Note: The Command & Control Registers are always executed after the full DL configuration message has been decoded. The reset command should always be sent as an unconfirmed DL message. Failure to do so may cause a poorly designed NS to continually reboot the Sensor.

3.2.4.1 Flash Write Command

Configuration changes are not retained after a power cycle unless they are saved in the flash memory. The *Flash Write Command* register should be written to in order to save changes that have been written to other registers. This can be done in a separate DL at any time, or be included in the same payload as the other write commands.

[15] After sending the reset-to-factory-defaults command, the Sensor is automatically reset with corresponding default configuration values.

Changes made to the LoRaMAC registers (0x 10 to 0x 15) must have bit 14 in the command set to 1 in order to be saved. Changes made to the application registers (0x 20 to 0x 63) must have bit 13 set to 1 in order to be saved. Both bits can be set to any combination of 1s and 0s.

The *Flash Write Command* register can also be used to reset the device and cause it to rejoin the network. This is done by setting bit 0 to 1. Immediately after receiving this command in a DL, the Sensor will reset. This means that if the command was sent in a confirmed DL, the confirmation reply UL will not be sent. The Sensor will rejoin the network but then get the command sent again, causing a loop of continual rebooting. It is important to not send the reset command as a confirmed DL.

3.2.4.2 Metadata

Bits 32 to 55 of the *Metadata* register contain the application revision numbers which define the FW version. The FW version is reported in the format as shown in Figure 3-2, which is shown using the example FW v1.0.15.

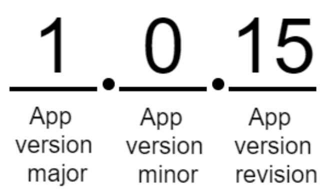


Figure 3-2: Example FW Version Format

Bits 8-31 in the *Metadata* register contain the LoRaMAC version numbers. The format is the same as shown in Figure 3-2. This number is not to be confused with the LoRaWAN specification version according to the LoRa Alliance standards. The LoRaMAC version number is the version of the LoRaMAC layer of the FW developed by TEKTELIC.

The LoRaMAC region number is the last byte of the *Metadata* register. Current LoRaMAC regions and corresponding region numbers for the Tracker are listed in Table 3-13.

Table 3-13: LoRaMAC Regions and Region Numbers

LoRaMAC Region	Region Number
EU868	0
US915	1
AS923	2
AU915	3
IN865	4
KR920	6
RU864	7

3.2.4.3 *Reset Configuration to Factory Defaults*

The *Reset Configuration to Factory Defaults* register is written to in order to reset all of the other register values (0x 10 to 0x 63).

Command and Control DL Examples:

- Write Application Configuration to flash
  - DL payload: 0x F0 20 00
- Write Application and LoRaMAC Configurations to flash
  - DL payload: 0x F0 60 00
- Reboot Device
  - DL payload: 0x F0 00 01
- Get FW version, and reset App Configuration to factory defaults
  - DL payload: 0x 71 F2 0A

3.3 Requests to Forward Stored Data

To retrieve and retransmit temperature or RH data that has been stored in the Sensor's memory, a DL request must be sent from the user or application. This DL request tells the sensor which tag entries to retransmit. The format and port of the request DL depends on whether one tagged entry is required or many tag entries are required.

3.3.1 Requesting a Single Tagged Entry

To request a single stored data entry, the 2-Byte tag number is sent on ***LoRaWAN port 112 (0x70)***.

For example, to request tag entry #1725, **0x 06 BD** is sent on port 112. The Sensor will respond with the data stored under that tag entry in the format described in Section 0.

3.3.2 Requesting Multiple Tagged Entries with Simple Bitmapping

To request more than a single stored tag entry, there are two methods: bitmapping (this section) and RLE (Section 3.3.3).

The simplest way for a user to manually encode a DL request to forward tagged data is through bitmapping. The packet format is as shown in Figure 3-3.

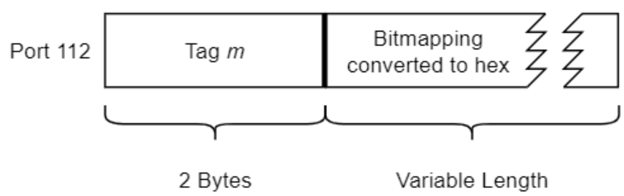


Figure 3-3: Bitmapping DL Format to Request Multiple Tagged Entries

As shown, the packet is sent on ***LoRaWAN port 112 (0x70)*** and the first 2 bytes in the payload is the tag number m, which is the first tag that is being requested (i.e. the smallest tag number). The latter part of the payload is the bitmapping (converted to hexadecimal) which tells the Sensor which other subsequent tags are being requested.

In this bitmapping scheme, each bit (from left to right) after tag m represents the next consecutive tag index number. If a bit is set to 1, then that means that tagged data needs to be forwarded. If a bit is set to 0, then that means that tagged data is not to be forwarded. Note: zeroes must be added at the end of the bitmapping to complete a full byte.

Bitmapping Request DL Examples

- Tags 2337-2353 are requested:
  - Tag m = 2337 = 0x 09 21
  - Bitmapping = 0b 1111 1111 1111 1111 = 0x FF FF
  - Payload = 0x 09 21 FF FF

- Tags 1, 3, 5, 6, and 9 are requested:
  - Tag m = 1 = 0x 00 01
  - Bitmapping = 0b 0101 1001 = 0x 59
  - Payload = 0x 00 01 59
- Tags 478, 483, and 484 are requested
  - Tag m = 478 = 0x 01 DE
  - Bitmapping = 0b 0000 11 = 0b 0000 1100 = 0x 0C
  - Payload = 0x 01 DE 0C

3.3.3 Requesting Multiple Tagged Entries with RLE

Formulating a DL payload request to forward stored data on a regular basis can be time-consuming. Therefore, if the use-case involves regular and repeated forwarding, it is recommended that an application is developed to monitor and formulate DL requests automatically. In this case, the RLE encoding scheme for requesting multiple tagged entries is the preferred method regarding an optimized payload size, time-on-air, number of ULs, and battery life.

To request more than a single stored data entry, a *Run-Length-Encoding* (RLE) compression scheme is used. Up to 100 tag entries can be requested at once using this scheme. The following are definitions of the variables used in this section:

- $w = \text{word size}$: The number of bits in a repeating RLE block.
- $m = \text{1st tag \#}$: The first missing tag entry that is requested.
- $b_n = 1/0 =$ MSb of the n^{th} word: defines whether the word denotes a run of missing/requested tags (1) or non-missing/non-requested tags (0).
- $L_n = \text{run length}$: The $w - 1$ LSbs in each word that define the run length of missing or non-missing tags (as specified by the value of b_n).
- $q = \text{number of words.}$
- $p = \text{number of placeholder 0s at the end of the payload.}$

LoRaWAN ports 112 (0x70) to 122 (0x7A) are used to request data forwarding, where the different ports indicate the word size in bits, w, of the scheme:

Port 112 (0x70): RLE with $\boldsymbol{w = 0}$ (sending only a 2-byte tag header)

Port 112 (0x70): RLE with $\boldsymbol{w = 1}$ (equivalent to bitmap encoding, see Section 3.3.2)

Port 113 (0x71): RLE with $\boldsymbol{w = 3}$

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Port 122 (0x7A): RLE with $\boldsymbol{w = 12}$

The cases of $w = 0$ and $w = 1$ use the same port and are distinguished at the sensor simply by the number of bytes in the payload. The case of $w = 2$ has been eliminated as it is always inferior to the case of $w = 1$ in terms of compression.

The general RLE scheme payload has been illustrated in Figure 3-4. The Sensor is able to understand and decode the RLE requests to derive the requested tag numbers. If the payload has only 2 bytes ($w = 0$), it is decoded as pointing to only one missing tag, Tag m. However, for payloads longer than 2 bytes, the **w-bit RLE words** successively determine run lengths of 0's and 1's after Tag m, where a 1 indicates a missing/requested tag.

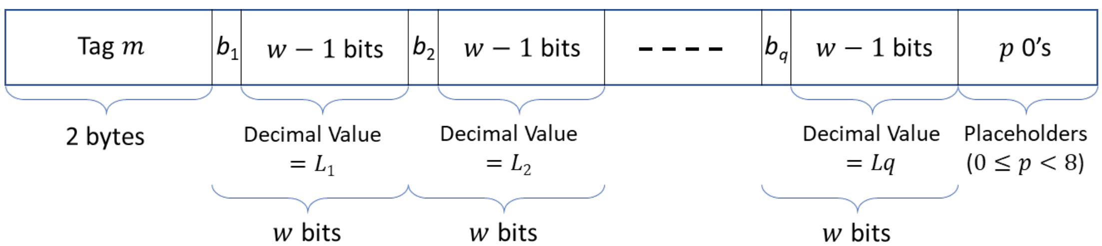

Figure 3-4: RLE Packet format for Requesting Multiple Tag Entries

The MSb in each word is the first bit of a run. The $w - 1$ LSbs define the length of the run after the MSb (from 0 to $2^{w-1} - 1$). For example, with a word length of 4 bits ($w = 4$), a run of 1111111 is encoded as 1110, a run of only one 1 is encoded as 1000, a run of only one 0 is encoded as 0000, etc. Therefore, the payload in Figure 3-4 is decoded as follows:

Tag m: labeled 1 (i.e. missing)

Tags $m + 1$ to $m + 1 + L_1$: labeled b_1 (if $b_1 = 0$, none is missing, if $b_1 = 1$, all are missing)

Tags $m + 2 + L_1$ to $m + 2 + L_1 + L_2$: labeled b_2

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Tags $m + q + L_1 + \cdots + L_{q-1}$ to $m + q + L_1 + \cdots + L_{q-1} + L_q$: labeled b_q

Note that in Figure 3-4, p is such that $q\,w + p$ is an integer multiple of 8 bits, so the length of the whole payload becomes $2 + \frac{q\,w+p}{8}$ bytes.

Also, note that the RLE scheme with $w = 1$ (and thus, $L_1 = L_2 = \cdots = L_q = p = 0$) degrades to a bitmap encoding scheme where successive tags after Tag m are simply encoded as 0 or 1 depending on being received or lost:

Tag m: labeled 1

Tag $m+1$: labeled b_1

Tag $m+2$: labeled b_2

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Tag $m+q$: labeled b_q

Appendix 1: Analog Probe Voltage to Temperature Conversion

External Probe Thermistor Voltage/Temperature Conversion for Gen2 Devices (FW v2.x.x+)

This is applicable only to probe Sensor variants equipped with the thermistor (analog voltage probe HW).

The 2-byte frame payload in a Sensor UL containing a probe voltage value V is reported in units of mV. To convert to temperature T in units of °C, the following approximate formula can be applied.

$$T = (6.4308 \times 10^{-17})V^6 - (4.6080 \times 10^{-13})V^5 + (1.2941 \times 10^{-9})V^4 - (1.8114 \times 10^{-6})V^3 + (1.3363 \times 10^{-3})V^2 - (0.53853)V + 109.29$$

This polynomial is empirical and based on the best fit to temperature test calibration data. It is not based on a theoretical model nor uses values specified by the thermistor probe data sheet.

Appendix 2: Default Configuration Register Values

Configuration Parameter Name	Category	Register Address [Hex]	Default Value [Hex]
Tagged Telemetry	Store & Forward	0F	00 1A
Join Mode	LoRaMAC	10	80 00
LoRaMAC Options		11	00 0E
LoRaMAC DR and Tx Power		12	00 00
LoRaMAC Rx2 Window		13	As per Table 3-5
Seconds per Core Tick	Periodic Transmission	20	00 00 0E 10
Ticks per Battery		21	00 18
Ticks per Ambient Temperature		22	00 01
Ticks per Ambient RH		23	00 01
Ticks per Accelerometer		24	00 00
Ticks per MCU Temperature		27	00 00
Ticks per External Probe Input		28	00 01
Mode	External Probe	2D	03 (digital probe) 83 (analog probe)
Count Threshold		2E	00 01
Value to Tx		2F	13
Ambient Temperature/RH Sample Period: Idle	Transducer Thresholds	39	00 00 00 3C
Ambient Temperature/RH Sample Period: Active		3A	00 00 00 1E
Low/High Ambient Temperature Thresholds		3B	1E 0F
Ambient Temperature Thresholds Enabled		3C	00
Low/High Ambient RH Thresholds		3D	50 0F
Ambient RH Thresholds Enabled		3E	00
MCU Temperature Sample Period: Idle		40	00 00 01 2C
MCU Temperature Sample Period: Active		41	00 00 00 3C

Configuration Parameter Name	Category	Register Address [Hex]	Default Value [Hex]
Low/High MCU Temperature Thresholds		42	1E 0F
MCU Temperature Thresholds Enabled		43	00
External Probe (Voltage or Temperature) Sample Period: Idle		44	00 00 00 3C
External Probe (Voltage or Temperature) Sample Period: Active		45	00 00 00 1E
Low/High External Probe Voltage Thresholds		46	04 B0 02 58
Low/High External Probe Temperature Thresholds		47	1E 0F
External Probe (Voltage or Temperature) Thresholds Enabled		48	00
Battery Report Options	Battery Management	4A	06
Average Energy Trend Window		4B	0A
Mode	Accelerometer	50	07
Sensitivity		51	22
Acceleration Event Threshold Count		52	00 01
Acceleration Event Threshold Period		53	00 0A
Acceleration Event Threshold		54	07 D0
Acceleration Event Grace Period		55	01 2C
Acceleration Event Value to Tx		56	01

References

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