Battery compatibility with Sigfox technology

Application note

Revision history

Rev.	Date	Author / Reviewer	Change description
0.0	2017/04/20	Ludovic Lesur	Preliminary version.
0.1	2017/05/31	Loïc Hubert	Add parts and details.
0.2	2017/07/07	Loïc Hubert Camille Ceuleneer	Add figures on discharging curves.
1.0	2017/09/14	Nicolas Chalbos	Add battery technologies, comparative arrays and calculation examples. First release on build@sigfox.com.
1.1	2017/10/26	Ludovic Lesur Laurence Sellier	Technical and editing changes.

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1 Abstract

Developing the Internet of Things with a low power technology has a significance in case of designing devices with a fully autonomous energy supply, that communicate for several years without periodic maintenance. That is why most of Sigfox connected devices are powered by a battery, whose electrical sizing is critical for the proper functioning and the sustainability of the device.
Despite the very low consumption required by Sigfox communication, not all batteries are compliant for a Sigfox device. The goal of this document is thus to present the main selection criteria of a battery for designing a Sigfox connected device.

2 Accumulator parameters

Accumulators are split in two families: primary cells which can't be recharged, and secondary cells which are rechargeable. Both have common electrical characteristics, listed in the following table.

Parameter	Symbol	Unit
Nominal voltage	U_{nom}	V
Capacity	C	A.h
Maximum continuous current	I_{cont}	A
Maximum pulse current	I_{pulse}	A
Internal series resistor	R_{int}	Ω
Internal parallel resistor	R_{self}	Ω
Self-discharge rate	a	% / year
Mass density	ρ_m	$W.h.kg^{-1}$
Energy density	ρ_e	$W.h.L^{-1}$
Technology		
Package		
Minimum operating temperature	T_{min}	°C
Maximum operating temperature	T_{max}	°C

Secondary cells have additional parameters given below.

Parameter	Symbol	Unit
Number of charge and discharge cycles	N_{ch}	
Ageing rate	b	% / year
Charge voltage	U_{ch}	V
Charge current	I_{ch}	A

2.1 Nominal voltage

Nominal voltage U_{nom} is the potential difference observed at the terminals of a battery, generated by electrochemical reaction. However, as explained thereafter, the available supply voltage is lower, and depends on the required current and the internal resistor of the battery.

Batteries are generally composed of one or several elementary cells, thus nominal voltage is sometimes given per cell. Several cells in series yield a higher voltage (a multiple of the base nominal voltage), while several cells in parallel provide a greater current capability. To describe those associations, the xSyP notation is used, where x is the number cells in series and y the number of cells in parallel.
As shown in the following table, each chemical technology yields a specific nominal voltage per elementary cell.

Battery family	Technology	Chemical composition	U_{nom} (V)
Primary	Alkaline	Zn-MnO2	1.5
	Lithium-Manganese-Dioxyde	Li-MnO2	3.0
	Lithium-Thionyl-Chloride	Li-SOCl2	3.6
Secondary	Nickel-Metal-Hybrid	Ni-MH	1.2
	Lead-Acid	Pb-SO4	2.1
	Lithium-Ion Cobalt-Oxide	Li-CoO2	3.7
	Lithium-Ion Iron-Phosphate	Li-FePO4	3.2
	Lithium-Ion Manganese-Oxide	Li-MnO2	3.9
	Lithium-Ion Sulfur	Li2S8	2.1
	Nickel-Cadmium	Ni-Cd	1.2
	Lithium-Polymer	Li-Po	3.7

2.2 Capacity

Capacity C represents the quantity of energy contained in the battery, and allows the designer to estimate its operating time depending on the required power. Capacity is expressed in A.h or mA.h (1A.h = 1000 mA.h). 1A.h means providing a 1A continuous current for an hour. Since this relation is proportional, any parameter derives simply from the other two. An accumulator with a capacity C, which provides a continuous current I will operate for a time t_f:

$$C = I \times t_f \qquad \textbf{[1]}$$

The discharge current of a battery (in other words, the current it provides for a given application), is sometimes expressed relatively to its capacity. For instance, a 1A.h battery delivering 500mA is working at 0.5C.

2.3 Maximum continuous current

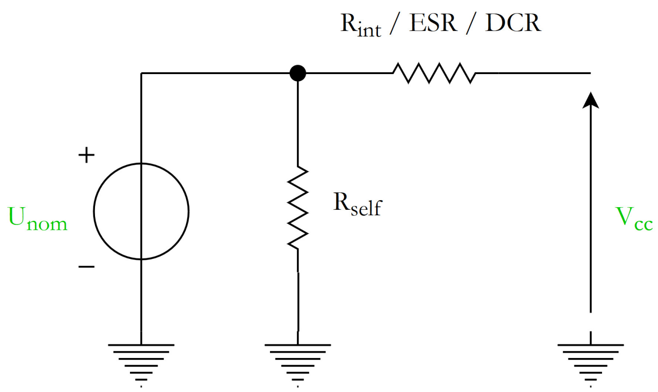
Maximum continuous current I_{cont} is the maximum output current that the battery can continuously provide without damage.

2.4 Maximum pulse current

Maximum pulse current I_{pulse} is the maximum output current that the battery can provide for a short time without damage.

2.5 Internal series and parallel resistors

A battery is a non-ideal voltage source and has a series and a parallel parasitic resistors, as shown in the figure below.



The series resistor R_{int} (also known as DCR or ESR) characterises the voltage drop as a function of the output current. The higher is the internal resistor, the more impacted is the voltage when high current is required, indeed $V_{cc} = U_{nom} - R_{int}\ I_{out}$. The internal resistor is a critical parameter because it sets the supply voltage available for the electronic circuitry. If I_{max} is the maximum output current required by the application, the supply voltage never drop under:

$$V_{cc(min)} = U_{nom} - R_{int} \times I_{max} \qquad \textbf{[2]}$$

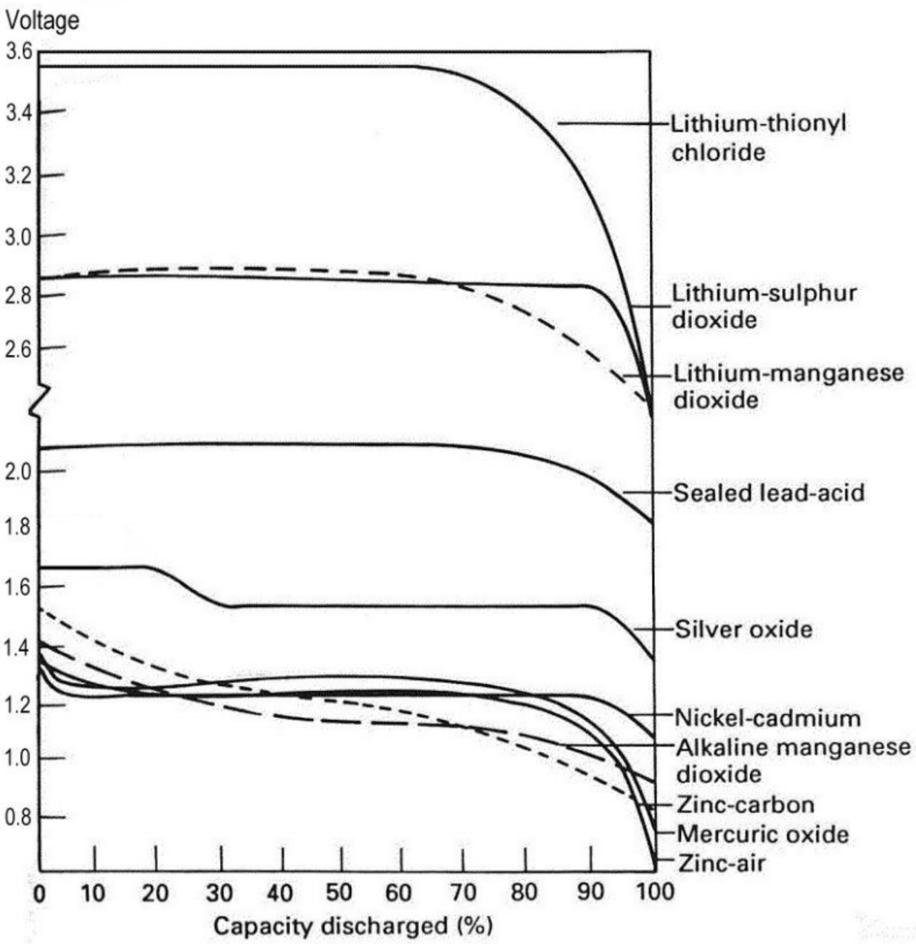
Note that U_{nom} is not constant, and decreases with time according to a specific discharging curve (cf. **section 2.6**). In formula **[2]**, the designer selects the minimum value $U_{nom(min)}$ for which the hardware operates.

The parallel resistor R_{self} causes self-discharge of the battery: a small current is continuously drained from the battery even if it remains in open-circuit. The smaller R_{self}, the higher the parasitic current I_{self} and the faster the self-discharge. Self-discharge is expressed as a percentage a of the initial capacity lost per year:

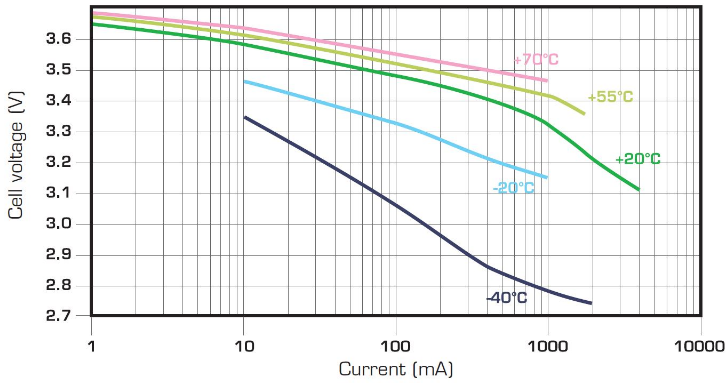
$$\frac{a}{100} \times C = I_{self} \times 365 \times 24 \quad \Rightarrow \quad I_{self} = \frac{a \times C}{876000} \qquad \textbf{[3]}$$

2.6 Discharging curves

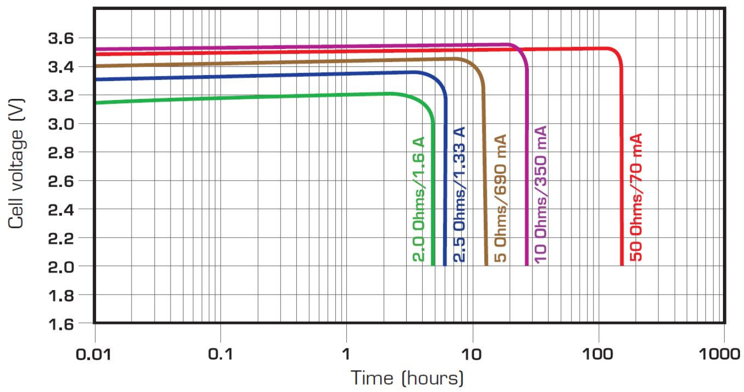
Primary and secondary cells present different discharging curves depending on their technology. Discharge is measured by observing the voltage drop as a function of capacity decrease. The graph below shows the discharging curve of various common technologies (at a given temperature).



The shape of those curves is very important. For example, when the voltage decreases quickly under the nominal voltage whereas the battery still has electrical energy, a DC-DC converter should be added to the electronic circuit to boost the output voltage and use the accumulator over a larger period.

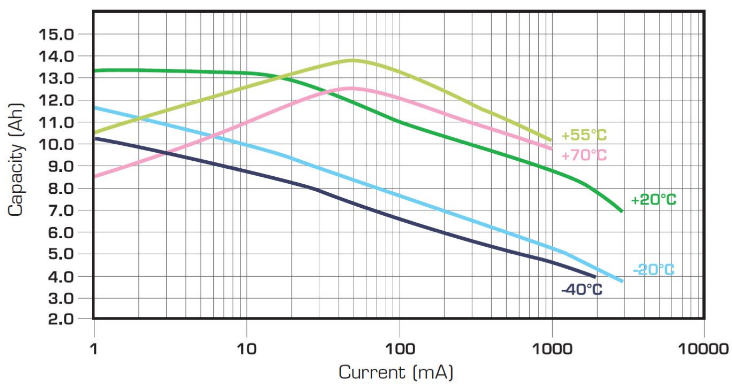


Voltage plateau versus Current and Temperature (at mid-discharge)



Typical discharge profiles at +20°C

For a given battery, the discharging curve also depends on ambiant temperature and the current it provides. The following figures illustrate those characteristics for the Saft LSH20 reference. Therefore capacity also depends on discharge current and temperature, as shown in the graph below (Saft LSH20 datasheet continued).



Restored Capacity versus Current and Temperature (2.0 V cut off)

2.7 Mass density

Mass density ρ_m is the ratio between the energy a battery provides and its weight, expressed in $W.h.kg^{-1}$. For a given energy capability, the higher the mass density, the lighter the battery.

Battery family	Technology	Mass density ($W.h.kg^{-1}$)
Primary	Alkaline	85 — 190
	Lithium-Manganese-Dioxyde	150 — 330
	Lithium-Thionyl-Chloride	700
Secondary	Nickel-Metal-Hybrid	30 — 80
	Lead-Acid	30 — 40
	Lithium-Ion Cobalt-Oxide	90 — 140
	Lithium-Ion Iron-Phosphate	90 — 130
	Lithium-Ion Manganese-Oxide	160
	Lithium-Ion Sulfur	300
	Nickel-Cadmium	40 — 60
	Lithium-Polymer	

2.8 Energy density

Energy density is the ratio between energy capability and the volume of the battery, expressed in $W.h.L^{-1}$. For a given energy capability, the higher the energy density, the smaller the battery.

Battery family	Technology	Energy density ($W.h.L^{-1}$)
Primary	Alkaline	250 — 430
	Lithium-Manganese-Dioxyde	300 — 710
	Lithium-Thionyl-Chloride	1200
Secondary	Nickel-Metal-Hybrid	140 — 300
	Lead-Acid	60 — 75
	Lithium-Ion Cobalt-Oxide	220 — 350
	Lithium-Ion Iron-Phosphate	350
	Lithium-Ion Manganese-Oxide	270
	Lithium-Ion Sulfur	400
	Nickel-Cadmium	50 — 150
	Lithium-Polymer	

2.9 Ageing and number of charge cycles

The capacity of secondary cells decreases with time: every time the accumulator is charged and discharged, its capacity decreases. Therefore, secondary cells are designed for a specific number of charge and discharges cycles. Generally ageing is not quantified in the datasheets, but can be modeled as a capacity loss *b* expressed as self-discharge, in % / year.

Battery family	Technology	Energy density ($W.h.L^{-1}$)
Secondary	Nickel-Metal-Hybrid	1500
	Lead-Acid	500 — 800
	Lithium-Ion Cobalt-Oxide	1200
	Lithium-Ion Iron-Phosphate	1000 — 2000
	Lithium-Ion Manganese-Oxide	1200
	Lithium-Ion Sulfur	
	Nickel-Cadmium	2000
	Lithium-Polymer	

2.10 Operating temperatures

A battery has specific storage and operating temperature ranges, which are critical for outdoor applications.

3 Choice of a suitable battery for a Sigfox device

3.1 Simplified consumption model

As an initial approach, the current drain of a Sigfox device derives from two sources:

- The modem, which ensures radio communication thanks to a transceiver, active filters, low noise amplifiers, etc. This part causes current pulses required to send (uplink) and receive (downlink) messages from Sigfox network.
- The application, for instance composed of a microcontroller, various sensors, etc. This part causes an average continuous applicative current, depending on the active components and the embedded software.

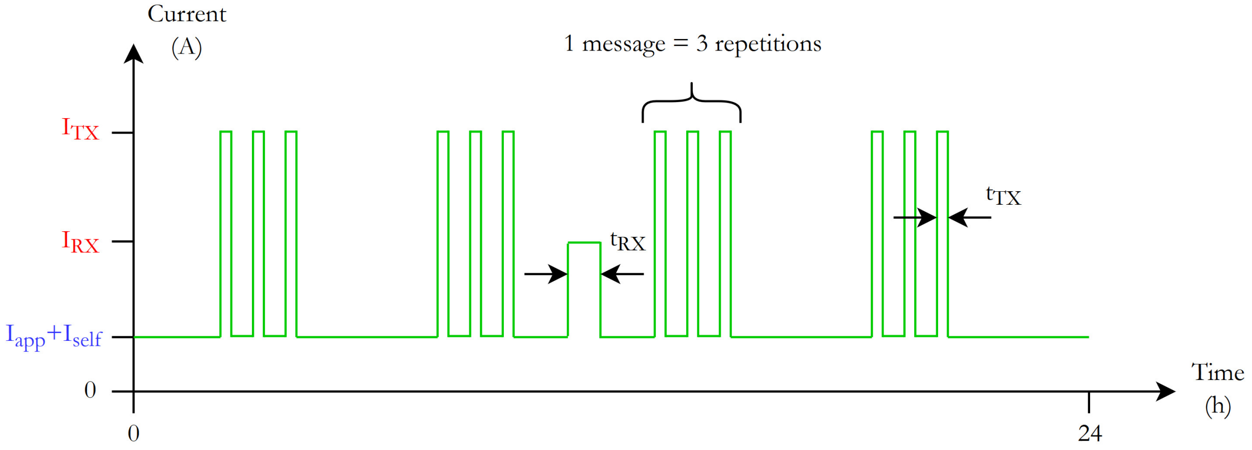
Therefore the current drain profile of a Sigfox device can be modeled according to the following input parameters:

SIGFOX MODEM UPLINK PARAMETERS		
Parameter	**Description**	**Unit**
t_{TX}	Maximum duration of frame emission (1 message = N_{rep} frames).	s
N_{TX}	Maximum number of daily TX messages.	messages/day
I_{TX}	Value of the current peak required to send a frame.	A
N_{rep}	Number of TX frame repetitions per message (default N_{rep} = 3).	repetitions/message

SIGFOX MODEM DOWNLINK PARAMETERS		
Parameter	**Description**	**Unit**
t_{RX}	Maximum duration of frame reception.	s
N_{RX}	Maximum number of daily RX messages.	messages/day
I_{RX}	Value of the current peak required to receive a frame.	A

APPLICATION PARAMETERS		
Parameter	**Description**	**Unit**
I_{app}	Average value of the applicative continuous current.	A
N_{aut}	Number of days of autonomy.	days
I_{self}	Self-discharge current of the selected battery.	A

The graph below exemplifies this consumption model with N_{TX} = 4 and N_{RX} = 1.



3.2 Primary or secondary ?

The first choice of the device maker is the type of the battery.
When the device has periodic access to an energy source, or can be easily recharged through an external connection (like an USB cable), a secondary cell can be selected. Note that charging a battery requires some additional electronic components in order to regulate charge current and voltage. Many integrated circuits exist, but the more integrated they are, the more expensive they will be.
On the contrary, when the device is autonomous for several years without any maintenance, a primary cell should is prefered.

3.3 Nominal voltage selection

Nominal voltage is chosen in accordance to the active electronic parts employed. It must comply with the operating voltage ranges of the integrated circuits.
With a secondary battery, a charge circuit is required to control charge voltage and current. The charge voltage is always higher than the nominal voltage. Thus, either the electronic circuitry must be isolated of the charge voltage, or integrated circuits should withstand the charge voltage.

3.4 Capacity sizing

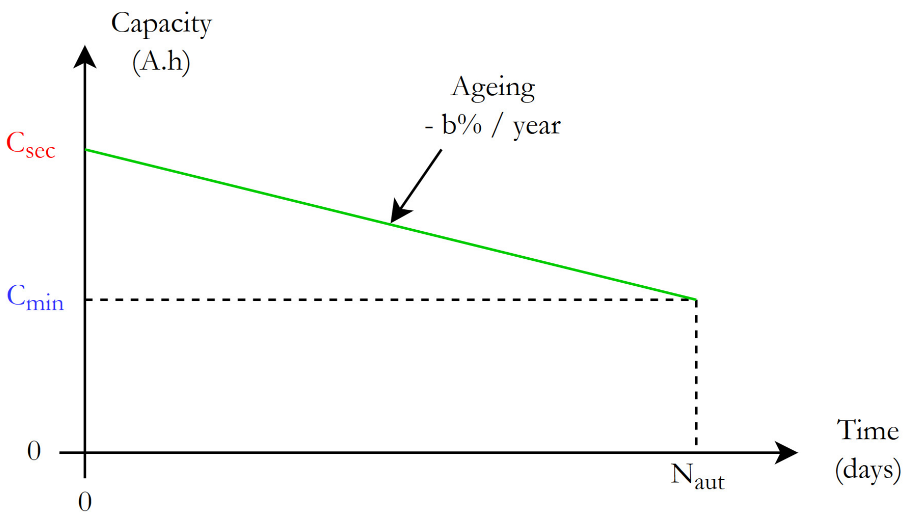
From the previous graph (cf. **section 3.1**), the formula below gives the main criteria to select the capacity and the self- discharge rate of a battery for a desired operating time:

$$C \geq N_{aut}\left(24\left(I_{app}+I_{self}\right)+N_{rep}N_{TX}I_{TX}\frac{t_{TX}}{3600}+N_{RX}I_{RX}\frac{t_{RX}}{3600}\right) \quad \textbf{[4]}$$

By replacing Iself with equation [3] and using an equality, the criteria leads us to the minimum capacity required for a Sigfox application:

$$C_{min}=\frac{\left(\left(24I_{app}+N_{rep}N_{TX}I_{TX}\frac{t_{TX}}{3600}+N_{RX}I_{RX}\frac{t_{RX}}{3600}\right)N_{aut}\right)}{1-\frac{24\,a\,N_{aut}}{876000}} \quad \textbf{[5]}$$

For a secondary battery, charge cycles and ageing introduce a coefficient $x=f(N_{ch})$: when a secondary battery is subject to charge and discharge cycles, the capacity at full charge goes gradually down. In this case, the previous C_{min} corresponds to the effective capacity of the battery after N_{aut} operating days. Even if ageing is not a linear phenomenon, the loss can be estimated and averaged by a linear decrease and its coefficient b, as illustrated in the following graph:



The minimum initial capacity (brand-new battery) is thus:

$$C_{sec}=\frac{1}{N_{ch}}\frac{36500\,C_{min}}{36500-b\,N_{aut}} \quad \textbf{[6]}$$

3.5 Internal resistor check

Internal resistor has an impact on the available supply voltage when a high current peak is required. The worst case is the generally the TX current.

The designer has to check that the power supply never fall below the minimum operating voltage of all the integrated circuits used in the device, in order to avoid an hardware reset at each frame sending. If *m* is the lowest minimum operating voltage among all the active components, the requirement is:

$$Vcc_{min} > m \quad \Rightarrow \quad R_{\text{int}} < \frac{U_{nom} - m}{max(I_{TX}, I_{RX})} \qquad \textbf{[7]}$$

3.6 Maximum continuous current sizing

The battery shall sustain the continuous applicative current:

$$I_{cont} > I_{app} \qquad \textbf{[8]}$$

3.7 Maximum pulse current sizing

The battery shall sustain the maximum current required by the application (usually TX current):

$$I_{pulse} > max(I_{TX}, I_{RX}) \qquad \textbf{[9]}$$

4 Operating time of an existing Sigfox application

By inverting equations **[5]**, we can approximate the operating time of a given primary battery powering a Sigfox device, with a capacity *C* and a self-discharge rate *a* (assuming the accumulator is suitable for the application):

$$N_{aut} = \frac{C}{24\left(I_{app} + \frac{a C N_{ch}}{876000}\right) + N_{rep} N_{TX} I_{TX} \frac{t_{TX}}{3600} + N_{RX} I_{RX} \frac{t_{RX}}{3600}} \quad \textbf{[10]}$$

For a secondary battery, inverting equation **[6]** leads to a second order polynomial equation, which simplifies into (by ignoring ageing):

$$N_{aut} = \frac{C N_{ch}}{24\left(I_{app} + \frac{a C N_{ch}}{876000}\right) + N_{rep} N_{TX} I_{TX} \frac{t_{TX}}{3600} + N_{RX} I_{RX} \frac{t_{RX}}{3600}} \quad \textbf{[11]}$$

5 Sizing examples

5.1 ETSI uplink-only application

The following table shows example statistics of a European (RC1 zone) uplink-only application.

Parameter	Value	Unit
N_{TX}	10	messages/day
N_{RX}	0	messages/day
I_{app}	10	µA
N_{aut}	365	days

Next subsections aim at sizing a battery for this example application using two different approaches.

5.1.1 Worst case sizing

The first approach is to consider the worst case values regarding the battery consumption: maximum currents (non-optimized transceiver) and maximum message length (12 bytes payloads, causing maximum frame durations). The following table gives usual values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	2.08	s
I_{TX}	50	mA

For a self-discharge rate a = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 408\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 408	mA.h
I_{cont}	> 10	µA
I_{pulse}	> 50	mA

Note: if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 50mA.

5.1.2 Nominal case sizing

The second approach is to consider more flexible values, taking into account payload length (for example 2 bytes instead of 12) and the use of low-power transceivers. The following table shows example values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	1.28	s
I_{TX}	25	mA

For a self-discharge rate a = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 108\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 108	mA.h
I_{cont}	> 10	µA
I_{pulse}	> 25	mA

Note: if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 25mA.

5.2 ETSI uplink-downlink application

The following table shows example statistics of a European (RC1 zone) application using both uplink and downlink messages.

Parameter	Value	Unit
N_{TX}	10	messages/day
N_{RX}	1	messages/day
I_{app}	10	µA
N_{aut}	365	days

Next subsections aim at sizing a battery for this example application using two different approaches.

5.2.1 Worst case sizing

The first approach is to consider the worst case values regarding the battery consumption: maximum currents (non-optimized transceiver) and maximum message length (12 bytes payloads, causing maximum frame durations). The following table gives usual values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	2.08	s
I_{TX}	50	mA
t_{RX}	25	s
I_{RX}	20	mA

For a self-discharge rate *a* = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 459\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 459	mA.h
I_{cont}	> 20	mA
I_{pulse}	> 50	mA

Note: in case of downlink, the battery must withstand I_{RX} as a continuous current because listening time can't be considered as a pulse. Moreover, if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 50 mA.

5.2.2 Nominal case sizing

The second approach is to consider more flexible values, taking into account payload length (for example 2 bytes instead of 12) and the use of low-power transceivers. The following table shows example values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	1.28	s
I_{TX}	25	mA
t_{RX}	12.5	s
I_{RX}	10	mA

For a self-discharge rate *a* = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 121\,mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 121	mA.h
I_{cont}	> 10	mA
I_{pulse}	> 25	mA

Note: in case of downlink, the battery must withstand I_{RX} as a continuous current because listening time can't be considered as a pulse. Moreover, if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 25 mA.

5.3 FCC uplink-only application

The following table shows example statistics of an FCC (RC2 zone) uplink-only application.

Parameter	Value	Unit
N_{TX}	10	messages/day
N_{RX}	0	messages/day
I_{app}	10	µA
N_{aut}	365	days

Next subsections aim at sizing a battery for this example application using two different approaches.

5.3.1 Worst case sizing

The first approach is to consider the worst case values regarding the battery consumption: maximum currents (non-optimized transceiver) and maximum message length (12 bytes payloads, causing maximum frame durations). The following table gives usual values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	347	ms
I_{TX}	220	mA

For a self-discharge rate a = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 323\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 323	mA.h
I_{cont}	> 10	µA
I_{pulse}	> 220	mA

Note: if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 220mA.

5.3.2 Nominal case sizing

The second approach is to consider more flexible values, taking into account payload length (for example 2 bytes instead of 12) and the use of low-power transceivers. The following table shows example values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	214	ms
I_{TX}	180	mA

For a self-discharge rate a = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 112\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 112	mA.h
I_{cont}	> 10	µA
I_{pulse}	> 180	mA

Note: if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 180mA.

5.4 FCC uplink-downlink application

The following table shows example statistics of an FCC (RC1 zone) application using both uplink and downlink messages.

Parameter	Value	Unit
N_{TX}	10	messages/day
N_{RX}	1	messages/day
I_{app}	10	µA
N_{aut}	365	days

Next subsections aim at sizing a battery for this example application using two different approaches.

5.4.1 Worst case sizing

The first approach is to consider the worst case values regarding the battery consumption: maximum currents (non-optimized transceiver) and maximum message length (12 bytes payloads, causing maximum frame durations). The following table gives usual values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	347	ms
I_{TX}	220	mA
t_{RX}	25	s
I_{RX}	20	mA

For a self-discharge rate a = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 374\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 374	mA.h
I_{cont}	> 20	mA
I_{pulse}	> 220	mA

<u>Note:</u> in case of downlink, the battery must withstand I_{RX} as a continuous current because listening time can't be considered as a pulse. Moreover, if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 220 mA.

5.4.2 Nominal case sizing

The second approach is to consider more flexible values, taking into account payload length (for example 2 bytes instead of 12) and the use of low-power transceivers. The following table shows example values for Sigfox technology.

Parameter	Value	Unit
t_{TX}	214	ms
I_{TX}	180	mA
t_{RX}	12.5	s
I_{RX}	15	mA

For a self-discharge rate a = 1%/year (typical self-discharge rate for a Saft lithium battery for instance), the minimum required capacity for a primary battery is:

$$C_{min} = 131\, mA.h$$

The battery must comply with the following characteristics:

Parameter	Required value	Unit
C	> 131	mA.h
I_{cont}	> 15	mA
I_{pulse}	> 180	mA

<u>Note:</u> in case of downlink, the battery must withstand I_{RX} as a continuous current because listening time can't be considered as a pulse. Moreover, if t_{TX} is too long to be considered as a pulse (depending on the battery), the continuous current requirement becomes I_{cont} > 180 mA.

6 Conclusion

The following list recaps the main criteria to select a battery for designing a Sigfox device:

- Primary or secondary cell.
- Technology.
- Nominal voltage.
- Internal resistor.
- Maximum continuous and pulse currents.
- Capacity (regarding self-discharge, ageing, and application requirements).
- Operating temperatures.

Notes