Monarch physical interface description and hardware device requirements

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1. Abstract

This document describes the radio link of the Monarch feature. It provides details about the Monarch signal modulation/demodulation principle and the specific Monarch signal characteristics. This document also focuses on the device HW requirements to support the Monarch feature.

2. Monarch modulation/demodulation principle

The aim of the Monarch feature is to provide a way for Sigfox devices to know what kind of Sigfox radio configuration (RC) to apply wherever they are in the world. The Sigfox approach of IoT is to keep the devices as low-cost and as low-power as possible thanks to an undisciplined protocol (i.e. the core network serves the devices, not the other way round). One of the biggest challenges for the Monarch feature is to broadcast an information to a large fleet of non frequency-synchronized devices without enslaving them.

A special modulation scheme is used to avoid frequency-synchronization of devices while maintaining the same coverage area as the existing Sigfox downlink service.

OOK modulation/demodulation scheme is known to not require frequency synchronization as long as the modulated signal is in the reception filter of the receiving device. But it is also known to have lower sensitivity compared to phase/frequency modulations such as BPSK or GFSK: the noise contribution of the radio channel having more impact over the amplitude of the transmitted signal than over its phase/frequency.

As an OOK demodulator is mainly an envelope detector followed by an energy discriminator for symbol recovery, in order to reduce this lack of sensitivity, instead of generating an ASK signal the classical way, one can try to generate an encoded signal maximizing peak-to-average power ratio (PAPR).

For example, by summing multiple evenly frequency-spaced carriers, we obtain a serie of evenly time-spaced pulses. Here is what we get when summing 20 carriers with a fixed frequency difference of 1kHz between adjacent carriers:

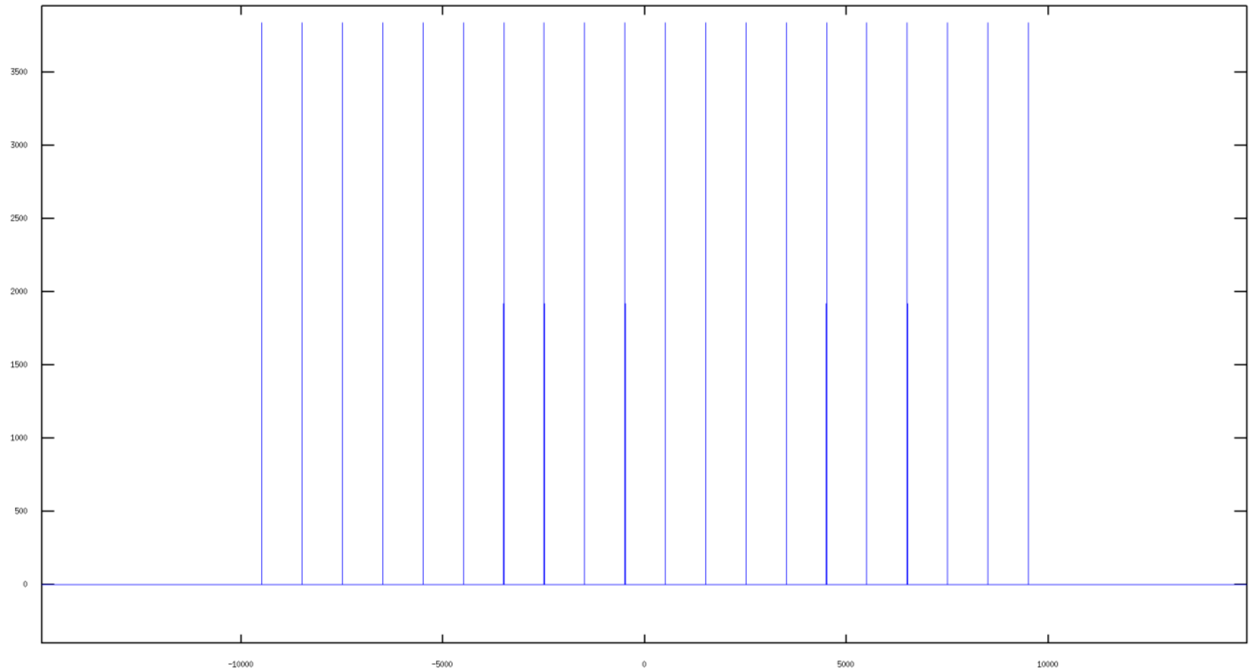


Figure 1: Frequency plot of an evenly spaced 20-carriers signal

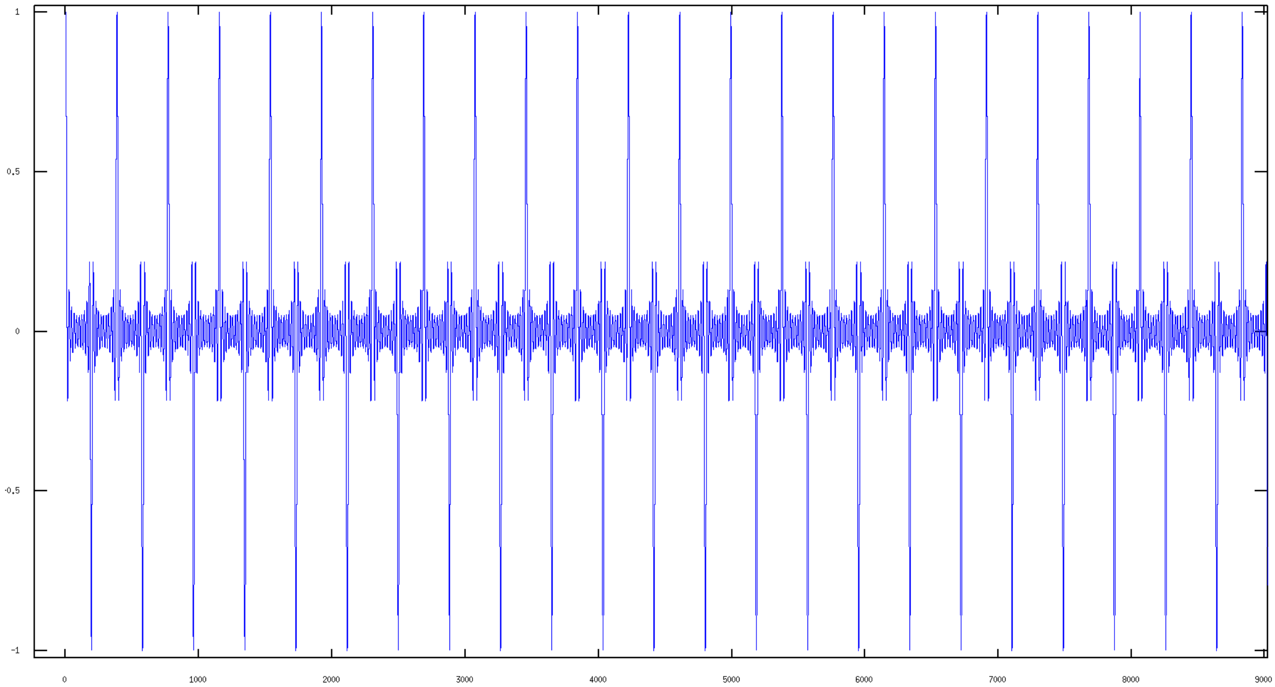


Figure 2: Time plot of an evenly spaced 20-carriers signal

The higher the number of carriers, the shorter the duration of the pulses, the higher the amplitude of the pulses, the higher the PAPR.
Compared to a classic OOK signal of equal power, such signal has a much higher PAPR

as the bursts of energy occur on much shorter time intervals. Therefore, for the same power, this makes the energy discrimination much more robust to noise after the envelope detector.

Whatever the center frequency of the group of evenly-spaced carrier, demodulating such a signal with an OOK demodulator shifts the spectrum to baseband and produces the described pulses with a period inversely equal to the frequency difference between two adjacent carriers.
By coding information in the carrier spacing (or pulse spacing), we can reach much better sensitivity than classic OOK modulation and still without frequency synchronization of the receiver.

Most Sigfox transceivers embed an OOK demodulator so they can demodulate any OOK-modulated signals. Nevertheless, they cannot decode all data formats. In particular, they cannot decode such kind of pulse-density coded information as defined above. Therefore, to decode this signal, the transceiver can be configured to output this pulse-density coded baseband signal from the Sigfox transceiver (if the transceiver supports it) to the device micro-controller. A simple GPIO line is enough as there is no information in the peak amplitude of the described signal. This GPIO line is called in this document the Monarch GPIO.
By sampling the Monarch GPIO, the device micro-controller can perform a software detection of the expected pulse-pattern and decode the transmitted information.

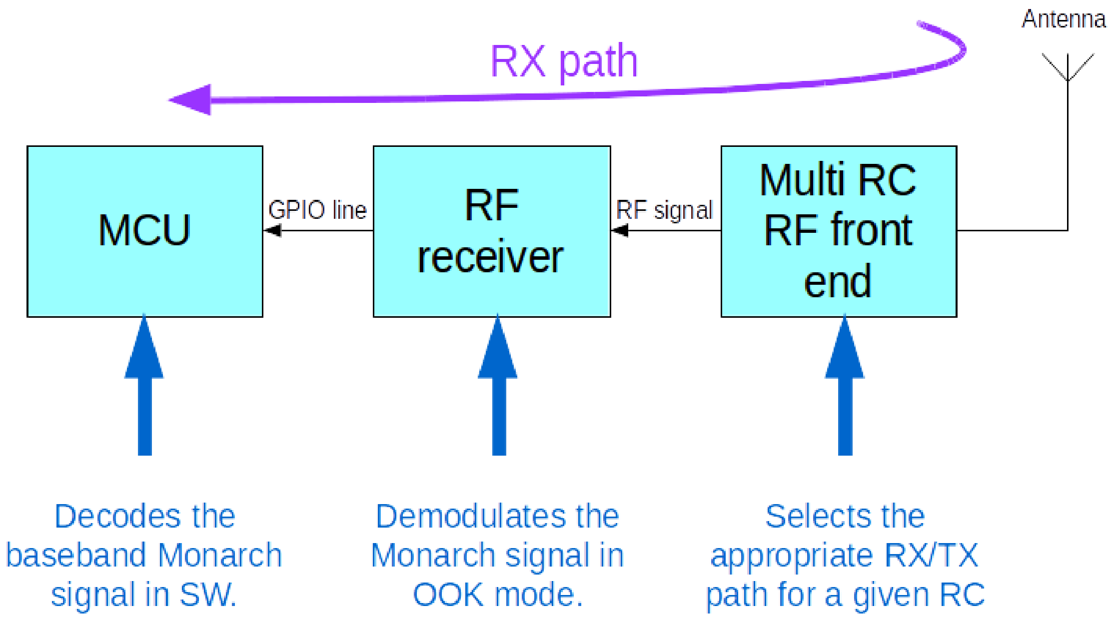


Figure 3: Summary of the Monarch decoding chain

3. Monarch signal description

3.1. Waveform

The Monarch signal is based on the principle described in the previous section: it is a sequence of two evenly spaced twelve-carriers patterns with a different carrier spacing between the two patterns.
The first pattern duration is 362ms whereas the second pattern duration is only 38ms, making a total duration of 400ms. Note that a device can take advantage of the longer duration of the first pattern to sleep in-between acquisition windows and hence to increase battery autonomy.

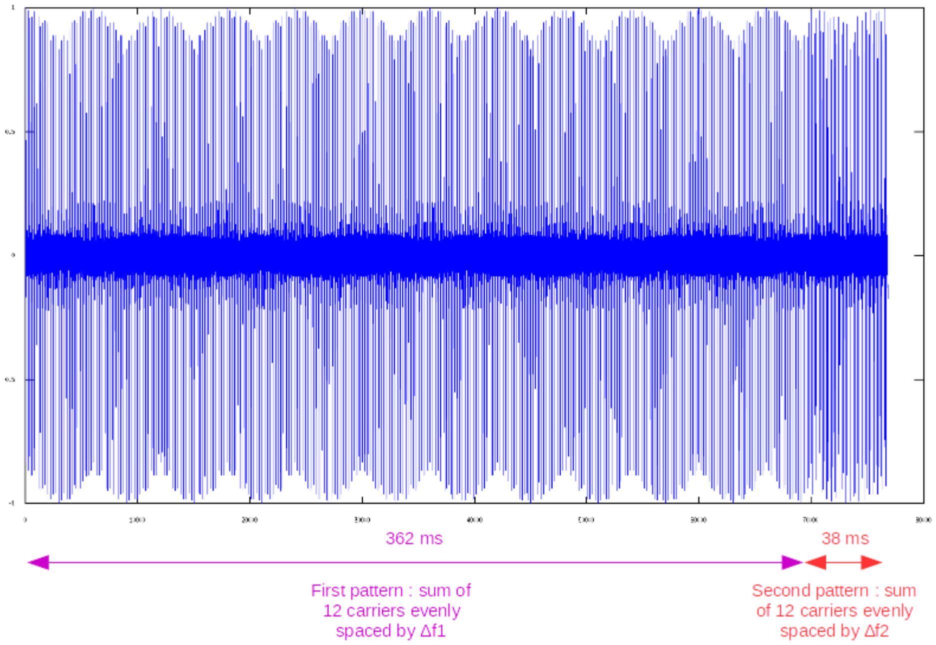


Figure 4: Time plot of a Monarch signal example

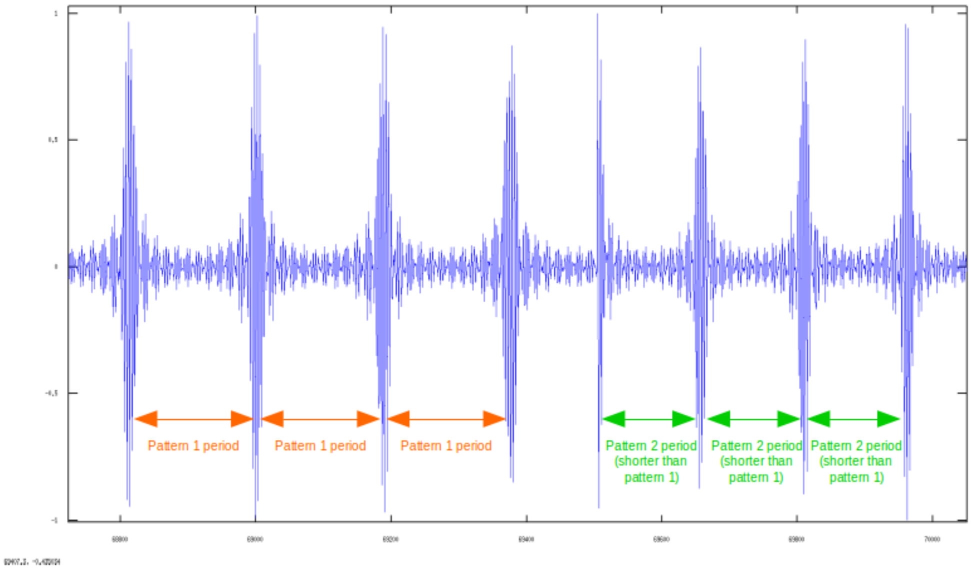


Figure 5: Zoom on the transition between the two patterns

For each pattern, the spacing between two carriers of a twelve-carriers pattern can be one of the three following Δf values:

- Δf_1= 1024Hz
- Δf_2 = 1260.3077Hz
- Δf_3 = 1489.454545 Hz

After OOK demodulation, sampling such patterns at baseband level by an MCU with a sampling frequency of 16384Hz (common crystal frequency value for MCU RTC) gives the following peak periodicities:

- 16384/1024 = 16 samples
- 16384/1260.3077 = 13 samples
- 16384/1489.454545 = 11 samples

3.2. RC encoding

The combination of the three following Monarch signal parameters encodes a Sigfox RC:

- Center frequency
- First pattern carrier spacing
- Second pattern carrier spacing

By scanning a limited set of center frequencies and by detecting baseband patterns on each of them, a mobile Sigfox device retrieves the current RC.

RC	Monarch center frequency	Pattern 1	Pattern 2
RC1	869.505MHz	Pattern Δf_1	Pattern Δf_2
RC2	905.180MHz	Pattern Δf_1	Pattern Δf_2
RC3	922.250MHz	Pattern Δf_1	Pattern Δf_2
RC4	922.250MHz	Pattern Δf_2	Pattern Δf_3
RC5	922.250MHz	Pattern Δf_1	Pattern Δf_3
RC6	866.250MHz	Pattern Δf_1	Pattern Δf_3

Note that new RCs may be added to the table above in the future.

3.3. Periodicity

Note also that to help devices reducing their Rx scan time and to increase their battery autonomy, the 400ms-long Monarch signal is sent at a random time within a ten seconds window occurring every *beacon_period* in all areas covered by the Monarch feature.
The *beacon period* is a network parameter which default value is 5 minutes.
Thanks to this mechanism, once a Monarch signal occurrence date is known by the device (by several means: RTC initialization at factory time, RTC initialization through Sigfox downlink, detection of the Monarch signal in a *beacon_period* long scan, …), the device can deduce next occurrences. Thus, it can wake-up at the appropriate time to scan for a new Monarch signal in a calculated time window taking into account the ten seconds uncertainty and the cumulated device error.

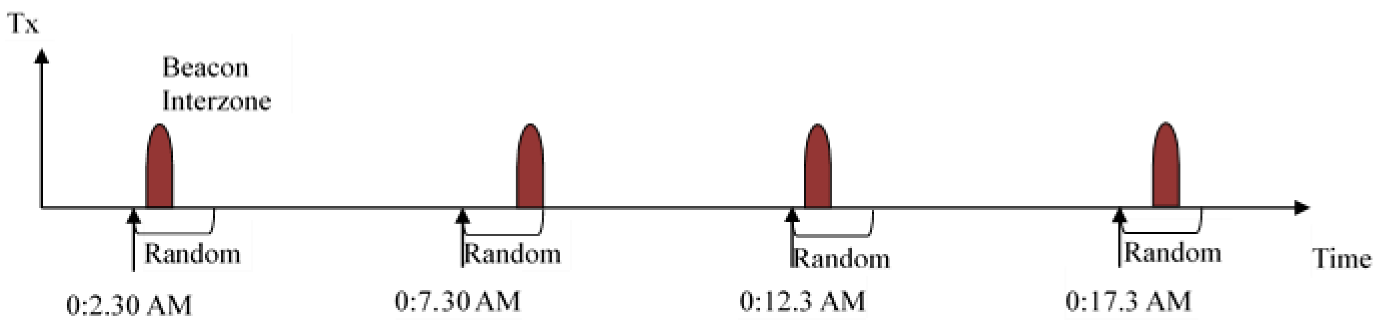


Figure 6: Scheduling of the Monarch signal by a Sigfox base station

4. General Monarch device requirements

To decode the Monarch signal described in the previous paragraph, several approaches are possible: integrated or discrete electronic design for the RF transceiver, software or hardware filtering of the baseband signal, …
Sigfox provides a hardware and software design as an implementation example making use of resources commonly found in existing Sigfox devices. This design is described in the "Monarch modulation/demodulation principle" section.

Whatever the selected implementation, the device is required to fulfill a set of criteria in order

to operate properly over the Sigfox network. In the following paragraphs, we describe these requirements.
Note: hereinafter, the RF chain refers to the complete electronic section of the device from antenna connector to baseband GPIO output responsible for demodulating RF signals.

REQ-4.1.1. Monarch center frequencies

The device shall be able to configure the RF chain to receive RF signal on all supported Monarch center frequencies.

REQ-4.1.2. Sensitivity to Monarch signal

The device sensitivity to the Monarch signal on supported radio configurations shall be equal or better than the associated Sigfox downlink sensitivity on the chosen radio configurations.

Note 1: this requirement ensures that the budget link is the same for downlink and Monarch services, hence that a device detecting the Monarch signal can operate on Sigfox network.

Note 2: as for all demodulation schemes, sensitivity to Monarch signal depends on the quality of the Rx chain: noise figure of the LNA, frequency bandwidth of the Rx filter which is itself impacted by the precision of the RF local oscillator, …

Note 3: Sigfox downlink sensitivity per Sigfox RC is described in RC device requirements available here:
https://build.sigfox.com/sigfox-verified-certification

REQ-4.1.3. Robustness to interferers

When decoding a given Monarch signal, the device shall not detect any other supported Monarch signals as well as the following interferers:

Signal	Test levels	Frequency
CW Carrier	- Sensitivity +3dB - Max. Acceptable Transceiver power - Max Acceptable transceiver power -50dB	All Monarch center frequencies (see table above)
AM Modulation 99,9% 1024Hz	- Sensitivity +3dB - Max. Acceptable Transceiver power - Max Acceptable transceiver power -50dB	All Monarch center frequencies (see table above)
AM Modulation 99,9% 1260.3077Hz	Up - Sensitivity +3dB - Max. Acceptable Transceiver power - Max Acceptable transceiver power -50dB	All Monarch center frequencies (see table above)
AM Modulation 99,9% 1489.4545Hz	- Sensitivity +3dB - Max. Acceptable Transceiver power - Max Acceptable transceiver power -50dB	All Monarch center frequencies (see table above)

Note: this list of interferers is a minimal set but it is recommended to test as much signals similar to the Monarch signals as possible to avoid fake detections.

REQ-4.1.4. Monarch center frequency determination

When decoding a Monarch signal, the device shall determine on which Monarch center frequency the decoded Monarch signal was transmitted whatever the received Monarch signal power.

Note 1: this requirement ensures the reuse of Monarch pattern combinations over several frequency bands to encode different RCs. Without this requirement, a Sigfox device may mistake a Monarch signal from another RC that is outside its reception filter with a Monarch signal sent within its reception filter.

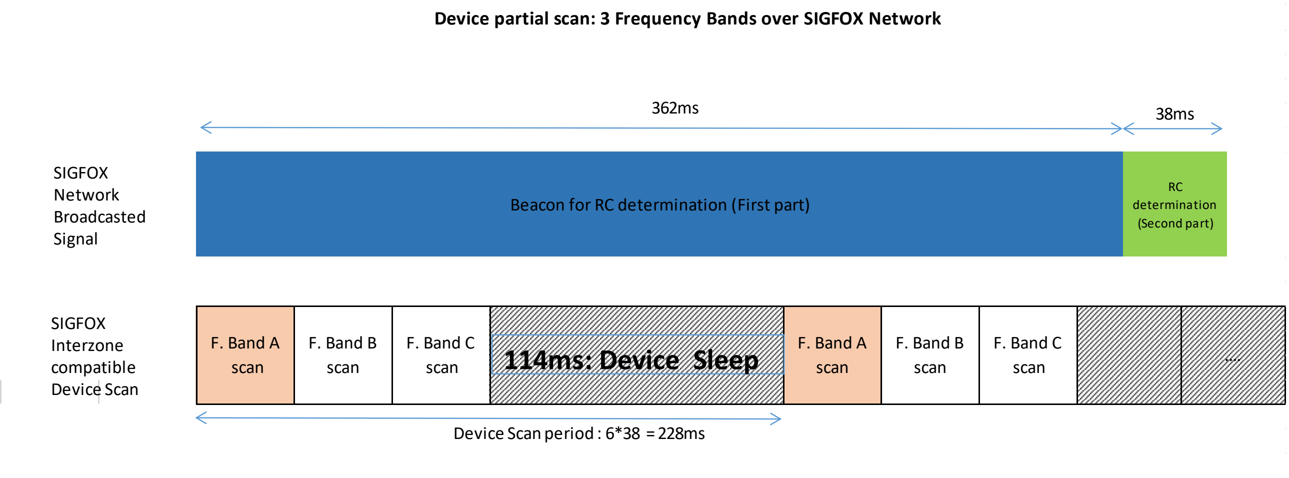
Note 2: this requirement does NOT imply that the Monarch center frequency discrimination relies on the performance of the radio Rx filter. For instance, in case of a radio receiver with a standard 50dB-rejection capability, if a Monarch signal is received with a signal strength so high that it cannot be rejected by the radio Rx filter whatever the programmed center frequency, the requirement can still be met by comparing the RSSI level on all known Monarch center frequencies where the Monarch signal was detected: the device can compare the RSSI of these multiple detection occurrences, deduce on which frequency the Monarch signal was indeed transmitted (i.e. highest RSSI) and on which frequencies a detection occurred due to signal leakage in the Rx filter and thus reject the detections due to radio leakage.

Note 3: the maximum Tx output power of Sigfox base stations is RC-dependent. For information, the maximum Tx output power over all RCs is +36dBm EIRP.

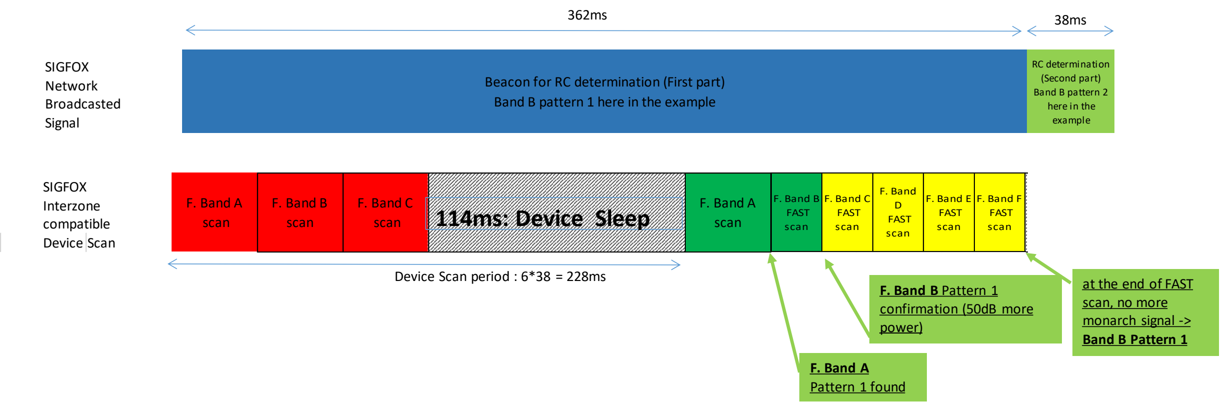
5. Annex: Sigfox application note pre-requisites

To facilitate the development of Sigfox devices supporting Monarch service, Sigfox provides an application note describing a hardware and software implementation example making use of resources commonly found in existing Sigfox devices.
This design is based on the decoding chain described in the “Monarch modulation/demodulation principle” section. It takes advantage of the long duration of the first pattern: within the 362ms of the first pattern, the device switches over each scanned Monarch center frequencies during 38ms and attempts a Monarch pattern detection in these

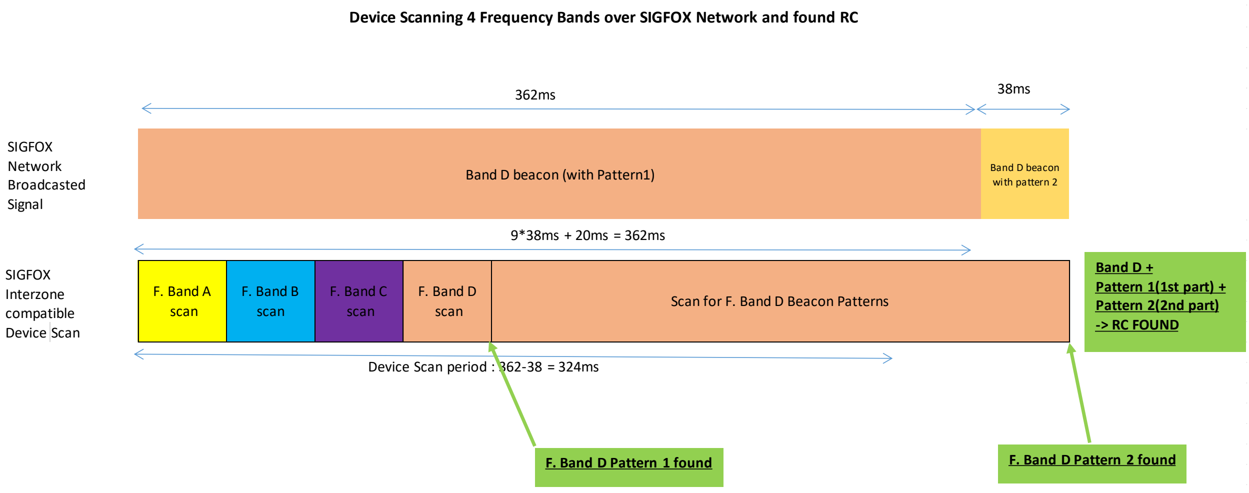
short windows.



In case the first pattern detection is successful, it performs a quick RSSI and detection check over all scanned Monarch frequencies to confirm that this detection did occur on the considered scanned frequency and is not due to RF leakage (i.e. see note 2 of REQ-4.1.4).



To finalize the Monarch signal detection, once the first pattern is confirmed, the device will attempt to decode the second Monarch pattern within the next 362ms on the Monarch center frequency determined for the first pattern.



More information can be found in this application note.

Devices relying on this implementation example shall follow the pre-requisites detailed in the next paragraphs.

5.1. RF pre-requisites

Reception filter bandwidth

The device shall configure the appropriate bandwidth of the RF chain's Rx filter to ensure that the 20kHz-large Monarch signal centered around all Monarch center frequencies is received by the device.

Note 1: in order to reach the sensitivity requirement, it is recommended to reach a good enough performance for the Rx LNA noise figure and the RF local oscillator accuracy in order to reduce the bandwidth as much as possible and thus the noise injection.

Note 2: whatever the performance of the RF local oscillator, the RX filter bandwidth cannot be inferior to 20kHz as the imprecision of the RF local oscillator will always enlarge the bandwidth of the RX filter.

OOK demodulation support

The device shall configure the RF chain to demodulate OOK signals on all Monarch center frequencies it is set to support.

OOK parameters

The device shall configure the OOK parameters of the RF chain so that each pulse of the received Monarch signal is detected as a 92±30ms pulse on the GPIO direct output line for all RSSI levels of the Monarch signals going from maximum supported RF input power down to sensitivity:

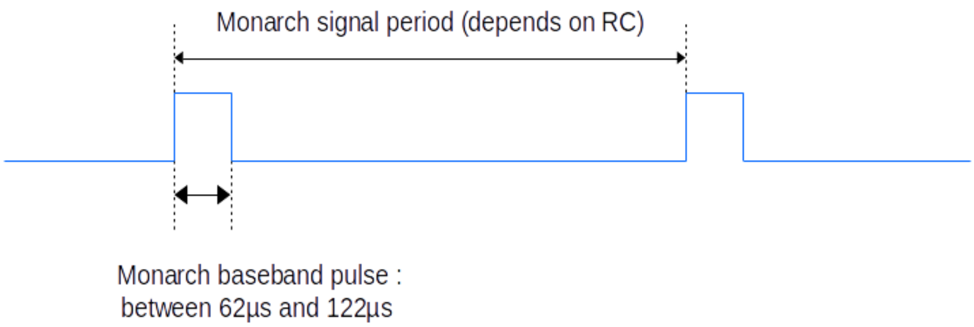


Figure 7: GPIO direct output timing constraints

Note: for low RSSI Monarch signals, many glitches may appear on the GPIO line because of the increased noise level relative to the Monarch signal level. The idea behind this pre-requisite is to ensure that the correct OOK parameters (AGC, threshold…) are set for the pulses to be in the same given duration range (i.e. 62µs to 122µs) on the GPIO line whatever the RSSI level of the Monarch signal.

OOK radio configuration time

When a device configures the RF chain for a new RC, valid baseband samples shall be available in less than 6 ms.

Note: this radio configuration time includes all radio settling time: frequency switch, frequency lock and OOK parameter convergence (AGC, OOK threshold…), etc.

Direct output mode

The device shall configure the RF chain to output the binarized baseband signal demodulated from RF OOK signals on a GPIO pin.

5.2. MCU pre-requisites

GPIO input

The device micro-controller shall have a free GPIO input to acquire the Monarch GPIO signal coming from the RF chain.

GPIO sampling frequency and accuracy

The device micro-controller shall sample the Monarch GPIO line at a sample frequency of

16384 Hz with an accuracy of 200ppm.

Note 1 : if the device MCU supports clock calibration, the required sample frequency accuracy can be obtained by outputing the accurate RF local oscillator from the RF chain and by calibrating one of the MCU clock from it.

Note 2 : the required sample frequency precision can also be obtained by using the MCU RTC oscillator if available.

Note 3 : this requirement applies on the total sample frequency accuracy and includes all possible source of frequency drift (temperature, time, power supply,...).

CPU processing performance

The device micro-controller shall have enough processing power to fulfill the real time constraints of the Monarch detection algorithm.

Note 1 : this pre-requisite basically implies that the processing of each new GPIO sample must take less than 61 µs.

Note 2 : for information, the current maximum CPU load to process a new GPIO sample on a Cortex M0 core with a 24MHz clock is 66%.

Additional RAM & flash size

The device micro-controller shall have enough RAM size and enough flash size to store the additional variables and code of the Monarch software detection algorithm.

Note: for information, the additional RAM size and flash size are respectively 1,4 KBytes and 2,3 Kbytes on a Cortex M0+ core.