Application Note:

Selecting the Optimal Reference Clock

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1 Introduction

Semtech RF transceivers generally require an external clock reference in order to generate the high frequency clocks for the RF and digital operations. Most of these devices are equipped with an on-chip crystal oscillator that enables them to utilize a simple external crystal (XTAL) to complete the reference clock circuitry. However, for applications that require greater frequency stability and accuracy over temperature, external temperature-compensated crystal oscillators (TCXO) can be supported.

1.1 Purpose of this Document

This document highlights some of the pros and cons of using a crystal and a TCXO and provides guidance on the optimal clock source for a given hardware and application.

Semtech recommends that you read the following document in conjunction with this application note:

- AN1200.74 LoRa Edge™ Clock Requirements

1.2 Scope of this Document

This document applies to LoRa® transceivers and gateway reference designs (not Legacy FSK only transceivers):

- LoRa sub-GHz Transceivers
  - SX1272/3[1]
  - SX1276/7/8/9[2]
  - SX1261/2/8[3]
  - LLCC68[4]
- LoRa 2.4-GHz Transceivers
  - SX1280/1[5]
- LoRa dual band Transceivers
  - LR1120, LR1121[6]
- LoRa Edge® Platform
  - LR1110, LR1120[7]
- Gateway Platforms
  - SX1302/SX1303 Corecell Reference Design (half/full-duplex design)[8]
  - SX1280 Reference Design for 2.4GHz Gateway[9]
  - SX1301/SX1308 NanoCell/PicoCell Gateway[10]

Most of the hardware uses a single clock source, except the SX1301 based gateway, which needs two: 32MHz clock typically provided by the radio, and a high-speed clock in the range 130-150MHz, to drive the demodulation blocks and data processing. SX1280/1 Transceiver and SX1280 2.4GHz Gateway require a 52.0MHz frequency clock.

[1] https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1272
[2] https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1276
[3] https://www.semtech.com/products/wireless-rf/lora-transceivers/sx1262
[4] https://www.semtech.com/products/wireless-rf/lora-transceivers/llcc68
[5] https://www.semtech.com/products/wireless-rf/24-ghz-transceivers/sx1280
[6] https://www.semtech.com/products/wireless-rf/lora-connect/lr1121
[7] https://www.semtech.com/products/wireless-rf/lora-edge#related-products-list
[8] The Corecell design includes SX1302 baseband with SX1250 radio.
- Full-duplex design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1302cfdxxxgw1
- Half-duplex design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1302cssxxxgw1

[9] https://www.semtech.com/products/wireless-rf/lora-gateways/sx1280zxxxxgw1
[10] The legacy gateway reference design includes SX1301/8 baseband with SX1255/7 radio.
- 490MHz design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1308p490gw
- 868MHz design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1308p868gw
- 915MHz design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1308p915gw

2 Crystal versus TCXO

For a typical crystal unit, the AT-cut method is used. Its frequency-temperature characteristic shows a cubic curve.

A TCXO incorporates a temperature compensation circuit along with the crystal; therefore, it is designed to have greater frequency stability over a wide range of temperatures.

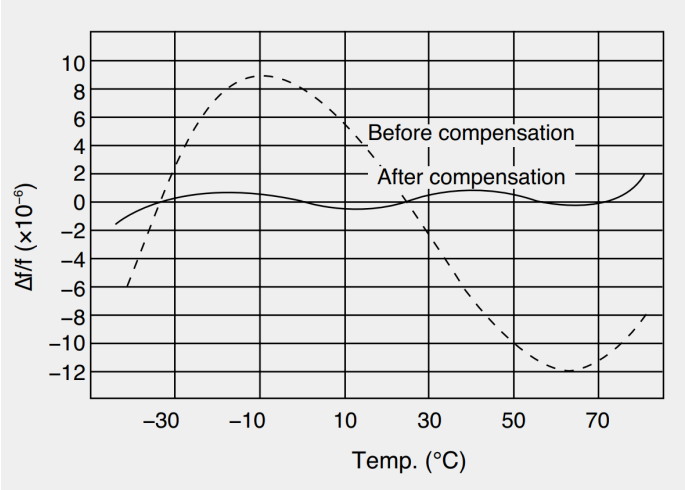

Figure 1 Example of the Frequency-Temperature Characteristic of a TCXO[11]

The benefits of using TCXO as the clock source include:

- Improved frequency stability and accuracy over temperature.
- Potentially saves PCB space since a thermal insulation cutout is not necessary.

The benefits of using crystal include:

- Reduced BOM cost
- Lower power consumption
- Faster start-up time

The rest of this document compares the crystal and TCXO specifications that Semtech selected for the SX1262 EVK design in the 915MHz band.

[11] Figure courtesy of NDK, available at https://www.ndk.com/catalog/AN-CO_GG_e.pdf

Table 1 Sample Comparison of TCXO and Crystal Typical Specifications

Device Type	Crystal	TCXO
Part Number	NX2016SA-32MHz-EXS00A-CS06465[12]	NT2016SF-32MHz-END4263D[13]
Nominal Frequency	32MHz	32MHz
Supply Voltage	None Required	Typically 1.65V-3.65V
Supply Current	None	2mA (max)
Output Type	-	Clipped Sine wave
Output Voltage	-	$0.8V_{P-P}$
Temperature Stability	+/- 10ppm for -20 to +70°C +/- 30ppm for -40 to +85°C	+/- 2.5ppm for -30 to 85°C
Aging	+/- 3ppm for 1st year +/- 5ppm for 5 years +/- 10ppm for 10 year +/- 15ppm for 15 year	+/- 1ppm 1 year +/- 3ppm for 5 year +/- 5ppm per 10 year
Phase Noise	-	-94dBc/Hz @ 10Hz offset -119dBc/Hz @ 100Hz offset -141dBc/Hz @ 1kHz offset -154dBc/Hz @ 10kHz offset -158dBc/Hz @ 1MHz offset
G Sensitivity	2.0ppb/G	2.0ppb/G
Load Impedance	10kΩ||10pF	10kΩ||10pF
Start-up time	150us with the oscillator in SX1262	2ms (More than 90% of final output voltage) This specification is not related to the frequency stability of the TCXO!

[12] Used in Semtech PCB_E428V03A – SX1262 Evaluation Module with Crystal
[13] Used in Semtech PCB_E449V01A – SX1262 Evaluation Module with TCXO

3 Frequency Accuracy Requirements

These clock accuracy requirements apply to LoRa, GFSK, and LoRa Edge GNSS devices and Applications.

The device should fulfil the requirements of all potential applications, in all conditions within the design specification.

3.1 LoRa Radio

All listed requirements should be fulfilled for LoRa modulation between the transmitter and receiver.

- The carrier frequency between the Tx/Rx should be within ±25% of BW
- +/- 50ppm for SF12
- +/- 100ppm for SF11
- +/- 200ppm for SF10

Table 2 LoRa Radio Clock Absolute Accuracy Requirement in ppm (US915 Band, Single-Sided)[14]

Bandwidth (kHz)	**31.25**	**62.5**	**125**	**250**	**500**
SF5 to SF10	8.5	17.1	34.2	68.3	136.6
SF11	8.5	17.1	34.2	68.3	100.0
SF12	8.5	17.1	34.2	50.0	50.0

The ppm offset in Table 2 indicates the required reference clock accuracy of the combined offset between the transmitter and receiver. For example, if the receiver operating at 125kHz bandwidth has a +/- 5ppm offset, then the transmitter frequency error must be less than +/- 31.2ppm in order to satisfy the required in Table 2.

The following also has to be satisfied for the frequency drift while the packet is being transmitted. The total frequency drift over the packet transmission time should be less than $\frac{LoRa\_BW}{3\times 2^{SF}}$ if low data rate optimization is disabled, and less than $16 \times \frac{LoRa\_BW}{3\times 2^{SF}}$ if low data rate optimization is enabled. Depending on the payload size, the low data rate optimization is usually recommended when a LoRa® symbol time is equal to or above 16.38ms.

Table 3 LoRa Radio Intra-Packet Clock Accuracy Requirement in Hz (Single-Sided)

	LDRO Disabled		**LDRO Enabled**	
Bandwidth (kHz)	**125**	**500**	**125**	**500**
SF7	325.5	1302.1	5208.3	20833.3
SF8	162.8	651.0	2604.2	10416.7
SF9	81.4	325.5	1302.1	5208.3
SF10	40.7	162.8	651.0	2604.2
SF11	--	81.4	325.5	1302.1
SF12	--	40.7	162.8	651.0

[14] No sensitivity degradation expected if requirement is met

3.2 FSK Radio

For FSK modulation, the following condition is generally applicable to all transceivers.

- $Frequency\ Error[DSB] \leq RX\ BW[DSB] - BR - 2 * FrequencyDeviation$

Table 4 FSK Radio Clock Accuracy Requirement in ppm (US915 Band, Single-Sided)[15]

Baud Rate (kbps)	Frequency Deviation (kHz)	Receiver Bandwidth (kHz)	Accuracy Requirement (ppm)
0.6	0.8	4.8	1.4
1.2	5	19.5	4.5
4.8	5	23.4	4.7
50	25	117.3	9.5
50	25	156.2	30.7
150	62.5	312	20.2

Narrow-band FSK generally can achieve high link budget and transmission range. However, it typically requires the use of a TCXO in order to satisfy the stringent frequency accuracy requirement.

3.3 Asset Tracking Application

The required overall frequency stability of the LR11xx for the GNSS scanning application is +/- 6ppm.

[15] No sensitivity degradation expected if requirement is met

4 Selecting the Optimal Clock Source

Selecting the optimal clock source requires the designer to consider multiple factors, including:

- Applications of the chipset: LoRa communication, FSK communication, geo-location, or any of the combinations.
- The intended operating conditions (temperature, humidity, movement)
- The design specifications and constraints (cost, size).
- The expected life span of the hardware.
- The importance of the hardware in the system.
- The reliability requirement (mission critical, safety).

4.1 Crystal

A crystal implementation is usually applicable to the following deployments:

- *Devices with limited output power*. For example, typically up to 14dBm for the SX1261 and LLCC68, and up to 20dBm for the SX127x family.
- *Indoor devices with high output power* (SX1262/LR11xx up to 22dBm) that have implemented the recommended thermal cutout on the PCB or technique for tuning the reference frequency through the capacitor banks.
- LR11xx location reporting devices that only utilize passive Wi-Fi scan.
- *Properly designed end-devices known to communicate with a gateway with a high-quality clock*, and the combined frequency offset satisfies the requirement listed in Section 3. This applies to most indoor/outdoor end-devices using LoRaWAN.

4.2 Crystal With Compensation Technique

Many Semtech RF transceivers, such as the SX126x and SX127x, have an internal crystal oscillator equipped with programmable capacitor banks which allows the user to fine tune the reference frequency by up to +/-30ppm (typ.).

The frequency characteristics of the crystal oscillator for a given crystal can be fully characterized over the desired operating temperature range. Equipped with this information, the designer can implement a compensation algorithm to “re-center” or correct for frequency error at various operating conditions. For example, capacitor trim values for minimum frequency error could be calibrated and stored during production for minimum, typical, and maximum temperatures.

With the help of an onboard temperature sensor, the device would automatically apply the pre-determined capacitor trim value based on the current temperature. Obviously, the downside of this technique is extra development and increased production test time.

4.3 TCXO

A TCXO is usually mandatory if any of the following conditions apply:

- Devices that need to work in extreme conditions and maintain high reliability.
  The extreme conditions include extremely high or low temperature. For example, a TCXO is suggested for LoRa enabled fire/smoke detectors and outdoor smart meters.
- Devices that support narrowband communication (i.e. LR-FHSS or FSK)
  Due to the tight frequency error tolerance of narrowband signals, a TCXO is usually required in order to satisfy the ppm requirement even in non-extreme working conditions. See details in Table 2 and Table 4.
- Devices that are mission critical and/or communicates as the master with other devices.
  For example, typical outdoor/indoor gateways use TCXO since any excessive frequency drift will affect multiple end-devices.
- Devices whose performance and power efficiency are sensitive to their clock accuracy.
  For example, the LoRa Edge LR11xx platform will consume more power in GNSS scanning mode with increased frequency drift. Therefore, it is necessary to use a TCXO for accurate frequency reference and maximize power efficiency in GNSS scanning applications.
- Devices with limited PCB area that cannot maintain a stable condition for the crystal.
  When the RF transceiver is transmitting high output power, the power amplifier could dissipate a significant amount of heat that could transfer to the crystal and result in an undesirable frequency drift. It is for this reason that we recommended the deployment of a PCB cutout around the crystal on SX1262 solutions that deliver 22dBm. In cases where the thermal cutout is not possible due to size constraints, then a TCXO is required in order to satisfy the required frequency stability for the maximum time on air.

Please note that even if the structure of the TCXO control block indicated in the SX126x and LR11xx Datasheets and User Manuals allows to comply with the chips requirements, the user shall ensure that the ATCXO amplitude voltage specification from the SX126x and LR11xx chips is respected. The value of the series capacitance on XTA pin might need to be modified to comply with this specification if required.

5 Recommendations

5.1 Recommended Clock Source

Table 5 Recommendations for the Clock Source

Related Part# or Ref Design	Application	Device and Application Scenario	Recommendation
SX1272/3 **SX1276/7/8/9** **SX1261/2** **LLCC68** **SX1280** **LR11xx**	LoRaWAN	Typical indoor/outdoor devices	Crystal
		Devices could be exposed to extreme temperature conditions	TCXO
		Devices could communicate with a gateway that may have excessive frequency drift	TCXO
	LoRa Radio Non-LoRaWAN	Low cost typical indoor/outdoor devices	Crystal
		Devices could use LoRa bandwidth that smaller than 62.5kHz	TCXO
	General LoRa Radio	High power device with limited PCB area and non-sufficient thermal insulation	TCXO
		Devices with output up to 14dBm	Crystal
	FSK Radio	Devices could use narrowband FSK modulations	TCXO
LR1110/20	Asset tracking	Wi-Fi only trackers	Crystal
		GNSS enabled trackers	TCXO
SX1272/3 **SX1276/7/8/9** **SX1261/2** **LLCC68** **SX1280**	Gateway	Single-channel indoor gateway	Crystal
		Single-channel outdoor gateway	TCXO
SX1302/3-based Corecell Gateway **SX1280-based 2.4GHz Gateway** **SX1308-based PicoCell Gateway** **SX1301-based Macro Gateway**	Gateway	Typical multi-channel indoor/outdoor gateway	TCXO

5.2 Recommended 32MHz TCXOs for Radio Operation

Table 6 Recommended 32MHz TCXOs for Radio Operation

Manufacturer	Part Number	Package Size	Qualification
NDK	NT2016SF-32MHz-END4263D [16] (recommended)	2.0x1.6mm	Qualified
NDK	NT2016SA-32MHz-END4263A [16] (old reference)	2.0x1.6mm	Qualified
Rakon	RST2016N 32.000000MHz - Ref.: T6395 [16] (recommended)	2.0x1.6mm	Qualified
Rakon	IT2105 32.000000MHz [16] (old reference)	2.0x1.6mm	Qualified
KDS	DSB211SDN-32MHz - Ref.: 7EF03200A0S [16] (new)	2.0x1.6mm	Qualified
KDS	DSB211SDN-32MHz - Ref.: 1XXD32000PCA [16]	2.0x1.6mm	Qualified
KDS	DSB211SP-32MHz - Ref.: 7EF03200A1G [16]	2.0x1.6mm	Qualified
Epson	TG2016SMN-32MHz – Ref.: X1G005441010525 [16]	2.0x1.6mm	Qualified
Kyocera	KT1612A32000AAW28TAK [16]	1.6x1.2mm	Qualified
Geyer	12.71028 [16]	2.0x1.6mm	Qualified
Golledge	GTXO-203T/HS Ref.: MP10472 [16]	2.0x1.6mm	Qualified
Golledge	GTXO-203T/ES Ref.: MP09965 [16]	2.0x1.6mm	Qualified
Raltron	RTX-2016BD32-S-32.000-TR-NS1 [16]	2.0x1.6mm	Qualified
Raltron	RTX-2016AF3F-S-32.000-TR [16]	2.0x1.6mm	Qualified
RFMi	XTC7031 [16]	2.0x1.6mm	Qualified
Abracon	ASTX-13-D-32.000MHz-I05-T [16]	2.0x1.6mm	Qualified
Taitien	S0197-T-004-3 [16]	3.2x2.5mm	Qualified
TXC	7Z32070002 [16]	2.0x1.6mm	Qualified

It is very important to note that the recommended TCXOs in this table were only validated/qualified based on Semtech's limited samples of platforms and operating conditions. It is ultimately the responsibility of the developer to fully validate and qualify the chosen reference clock for the given design. The TCXOs specifications must be aligned with the requirements of the application, regarding operating temperature range, supply voltage, and electrical characteristics.

[16] TCXO validated for LoRa and GFSK end devices and gateways (LoRa Edge GNSS not included)

5.3 Recommended 32MHz Crystals for Radio Operation

Table 7 Recommended 32MHz Crystals for Radio Operation

Manufacturer	Part Number	Package Size	Qualification
Rakon	FTR5123-B0 [17]	2.0x1.6mm	Qualified
	FTR5092-A3 [17]	3.2x2.5mm	Qualified
NDK	NX2016SA / EX500A-CS06465 [18]	2.0x1.6mm	Qualified
	NX1612SA / EXS00A-CS10665 [18]	1.6x1.2mm	Qualified
	NX2520SA / EXS00A-CS00131 [18]	2.5x2.0mm	Qualified
Epson	FA-128 / Q22FA1280066111 [17]	2.0x1.6mm	Qualified
	FA-128 / Q22FA1280058900 [17]	2.0x1.6mm	Qualified
	FA-128 / Q22FA1280053000 [18]	2.0x1.6mm	Qualified
Taitien	S0197-X-002-3 [17]	3.2x2.5mm	Qualified
KDS	DSX211SH-32MHz 1ZZHAE32000AA0B [17]	2.0x1.6mm	Pre-Qualified
	DSX321G-32MHz 1C232000AA0Q [17]	3.2x2.5mm	Pre-Qualified
Murata	XRCGB32M000F1S2KR0 [17]	2.0x1.6mm	Qualified
	XRCGB32M000F1S2LR0 [17]	2.0x1.6mm	Qualified
Kyocera	CX2016SA32000F0FZZG4 [18]	2.0x1.6mm	Qualified
NSK	NXN32.000AG10F-DKAB12 [17]	2.0x1.6mm	Qualified
Petermann Technik	SMD02016/4 32.000MHz - Ref.: QEU9310084 [18]	2.0x1.6mm	Pre-Qualified
	SMD03025-4 32.000MHz - Ref.: QEU9010927 [18]	3.2x2.5mm	Pre-Qualified
TXC	7M32070024 [17]	3.2x2.5mm	Qualified
	8Y32070018 [18]	2.0x1.6mm	Qualified

It is very important to note that the recommended crystals in this table were only validated/qualified based on Semtech's limited samples of platforms and operating conditions. It is ultimately the responsibility of the developer to fully validate and qualify the chosen reference clock for the given design. The crystals specifications must be aligned with the requirements of the application, regarding operating temperature range, supply voltage, and electrical characteristics.

[17] Crystals with Rs (max) ≤ 40 ohms can be used with SX1272, SX1276, SX1261, SX1262, SX1268, LLCC68 and LR1xx designs
[18] Crystals with Rs (max) ≤ 60 ohms can be used with SX1276 and SX1261, SX1262, SX1268, LLCC68 and LR11xx designs

5.4 Recommended 32MHz TCXOs for LoRa Edge GNSS

LoRa Edge features two GNSS scan modes: legacy scan and advanced scan.

Whereas the legacy scan does not have strong TCXO start-up time requirements, the GNSS advanced scan requires a TCXO start-up time of 15ms minimum for frequency stability. The following TCXOs have been validated on GNSS advanced scan operation with the LoRa Edge Semtech reference design from 1.8V (or minimum defined value in respective TCXO datasheet) to 3.3V, with a TCXO start-up time configured at 15ms. It is recommended to use VTCXO signal coming directly from the LR1110/20 transceiver to supply the TCXO, set at the minimum TCXO supply voltage allowed, to optimize the TCXO settling time.

Table 8 Recommended 32MHz TCXOs for LoRa Edge GNSS

Manufacturer	Part Number	Package Size	Qualification
NDK	NT2016SF-32MHz-END4263D (recommended)	2.0x1.6mm	Qualified
NDK	NT2016SA-32MHz-END4263A (old reference)	2.0x1.6mm	Qualified
Rakon	RST2016N 32.000000MHz - Ref.: T6395 (recommended)	2.0x1.6mm	Qualified
Rakon	IT2105 32.000000MHz (old reference)	2.0x1.6mm	Qualified
Epson	TG2016SMN-32MHz – Ref.: X1G005441010525 [19]	2.0x1.6mm	Qualified
KDS	DSB211SP-32MHz - Ref.: 7EF03200A1G	2.0x1.6mm	Qualified
Kyocera	KT1612A32000AAW28TAK [19]	1.6x1.2mm	Qualified
Geyer	12.71028	2.0x1.6mm	Qualified
Raltron	RTX-2016BD32-S-32.000-TR-NS1 [20]	2.0x1.6mm	Qualified
Raltron	RTX-2016AF3F-S-32.000-TR [19]	2.0x1.6mm	Qualified
Abracon	ASTX-13-D-32.000MHz-I05-T [19]	2.0x1.6mm	Qualified
Taitien	S0197-T-004-3 [21]	3.2x2.5mm	Qualified
TXC	7Z32070002	2.0x1.6mm	Qualified

In addition to a 32MHz TCXO, the LoRa Edge GNSS requires a 32.768kHz clock source for advanced scan and dual constellation modes. Additional information on the 32.768kHz clock is provided in the Datasheets and User Manuals of the LoRa Edge products. Please refer to AN1200.74 LoRa Edge Clock Requirements Application Note, for more details on the LoRa Edge™ clock requirements.

It is **very important** to note that the recommended TCXOs in this table were only validated/qualified based on Semtech's limited samples of platforms and operating conditions. It is ultimately the responsibility of the developer to fully validate and qualify the chosen reference clock for the given design. The TCXOs specifications must be aligned with the requirements of the application, regarding operating temperature range, supply voltage, and electrical characteristics.

[19] Validated only at VTCXO=1.8V
[20] Validated only at VTCXO=2.7V
[21] Validated only at VTCXO=3.0V

5.5 Recommended 32.768kHz Low Frequency Crystals for FSK, LoRa and LoRa Edge GNSS Applications

Table 9 Recommended 32.768kHz Low Frequency Crystals

Manufacturer	Part Number	Package Size	Qualification
NDK	NX3215SA-32.768kHz-EXS00A-MU01468	3.2x1.5mm	Qualified
	NX2012SA-32.768kHz-EXS00A-MU00327 [22]	2.0x1.2mm	Qualified
TXC	9H03270089	3.2x1.5mm	Qualified
	9H03270090	2.0x1.2mm	Qualified
Epson	FC-12M X1A000061001000 [22]	2.0x1.2mm	Qualified

A 32.768kHz crystal oscillator for low frequency clock is usually required in FSK, LoRa and LoRa Edge GNSS applications.

Semtech recommends that you read the document AN1200.74 LoRa Edge™ Clock Requirements, in conjunction with this application note. It describes the minimal requirements, specifications, recommendations, and frequency accuracy for 32.768kHz crystals oscillators to obtain best performances.

[22] This 32.768kHz crystal oscillator requires a frequency adjustment comparing to LR11xx Reference Designs, and specific values for crystal external load capacitors.

6 Summary

- All Semtech's LoRa end device and gateway platforms are designed to be compatible with crystals and TCXOs as the clock reference source.
- Most LoRaWAN applications can satisfy LoRa modulation frequency accuracy requirements with the use of a crystal in the end devices and a TCXO in the gateways.
- Compared to narrow-band FSK that requires TCXO as the reference clock due to its narrow frequency offset tolerance, LoRa modulation has a less stringent frequency accuracy requirement and therefore tolerates the use of crystal in most end-devices [23] . In fact, the LLCC68 LoRa transceiver with a crystal could be a good alternative solution to narrow-band FSK with TCXO, in LPWAN applications.

[23] When working with a typical gateway with TCXO

7 Revision History

Revision	Date	Modifications
1.0	01/04/2021	Draft
1.1	01/12/2021	Initial Release
1.2	10/28/2021	Qualified TCXOs updated
1.3	04/05/2022	Added LR1120 information
1.4	07/30/2022	Qualified TCXO updated for LoRa Edge Products
1.5	03/10/2023	Changed LR1110/LR1120 to LR11xx, changed template, updated weblinks and addition of new TCXO P/N. Added requirement of TCXO amplitude voltage in section 4.3.
1.6	08/10/2023	Updated list of qualified Crystals and TCXOs for Radio Operations. Added list of recommended low frequency 32.768kHz crystals for FSK, LoRa and LoRa Edge products.

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