AN1200.59

Selecting the Optimal Reference Clock

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1 Introduction and Objective

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.

The purpose of this documentation is to highlight some of the pros and cons of using a crystal and a TCXO, and provide guidance on the optimal clock source for a given hardware and application.

The scope of this documentation is limited to LoRa transceivers and gateway reference designs:

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

Most of the hardware uses a single clock source, except that the SX1301 based gateway needs two[10].

Legacy FSK only transceivers are not within the scope of this document.

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[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-transceivers/lr1110
[7] 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/sx1302cxxxgw1
[8] https://www.semtech.com/products/wireless-rf/lora-gateways/sx1280zxxxxgw1
[9] The legacy gateway reference design includes SX1301/8 baseband with SX1255/7 radio.
490-MHz design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1308p490gw
868-MHz design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1308p868gw
915-MHz design: https://www.semtech.com/products/wireless-rf/lora-gateways/sx1308p915gw
[10] SX1301 based design requires two clocks:

- A 32MHz clock typically provided by the radio
- A high-speed clock in the range 130-150MHz, to drive the demodulation blocks and data processing.
- The SX1301-based device is more sensitive to the 32MHz clock accuracy.

2 Comparing Crystal and TCXO

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

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

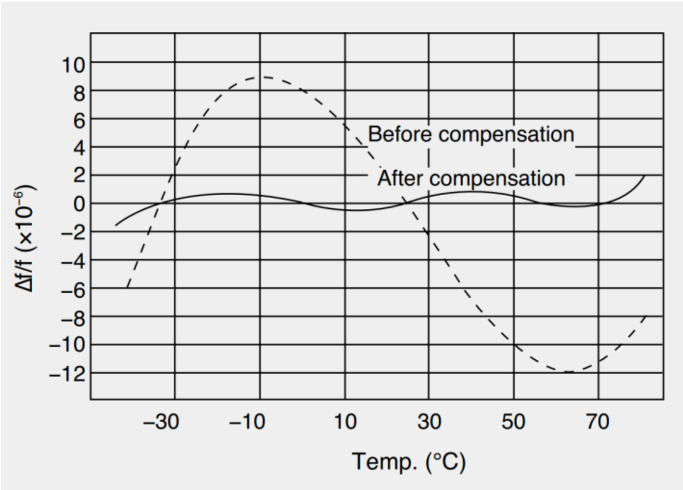

Figure 1 Example of the Frequency-Temperature Characteristic of a TCXO[11]

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 benefit of using crystal includes:

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

For more detailed information on the selection of a suitable crystal oscillator for LoRa applications, please refer to the AN1200.14 Crystal Oscillator Guidance LoRa Modulation application note.

Here we compare the crystal and TCXO specifications 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 Specifications

Device Type	Crystal	TCXO
Part Number	NX2016SA-32MHz-EXS00A-CS06465[12]	NT2016SA-32MHz-END4263A[13]
Nominal Frequency	32MHz	32MHz
Supply Voltage	None Required	Typically 1.65V-3.65V
Supply Current	None	2mA
Output Type	-	Clipped Sine wave
Output Voltage	-	0.8 V_{P-P}
Temperature Stability	+/- 10 ppm for -20 to +70°C +/- 30 ppm for -40 to +85°C	+/- 2.5 ppm for -30 to 85°C
Aging	+/- 3 ppm for 1st year +/- 5 ppm for 5 years +/- 10 ppm for 10 year +/- 15 ppm for 15 year	+/- 1 ppm 1 year +/- 3 ppm for 5 year +/- 5 ppm per 10 year
Phase Noise	-	-86dBc/Hz @ 10Hz offset -114dBc/Hz @ 100Hz offset -137dBc/Hz @ 1kHz offset -149dBc/Hz @ 10kHz offset
G Sensitivity	2.0 ppb/G	2.0 ppb/G
Load Impedance	10kΩ||10pF	10kΩ||10pF
Start-up time	150us with the oscillator in SX1262	2 msec
Operating Temperature		-40 to 85°C

3 Frequency Accuracy Requirements for LoRa, GFSK, and GNSS Applications

Here we have listed the required clock accuracy for LoRa devices and applications.

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

3.1 LoRa Radio Requirement

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
- +/- 50 ppm for SF12
- +/- 100 ppm for SF11
- +/- 200 ppm for SF10

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

[12] Used in Semtech PCB_E428V03A – SX1262 Evaluation Module with Crystal
[13] Used in Semtech PCB_E449V01A – SX1262 Evaluation Module with TCXO
[14] No sensitivity degradation expected if requirement is met

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 +/- 5 ppm offset, then the transmitter frequency error must be less than +/- 31.2 ppm 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 16.38 ms.

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

3.2 FSK Radio Requirement

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

[15] No sensitivity degradation expected if requirement is met

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 Requirement

The required overall frequency stability of the LR1110 and LR1120 for the GNSS scanning application is +/- 6ppm.

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 Devices Using 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/LR1110/LR1120 up to 22dBm) but have implemented the recommended thermal cutout on the PCB or technique for tuning the reference frequency through the capacitor banks.
- *LR1110/LR1120 location reporting devices that only utilize passive Wi-Fi scan.*
- *Properly designed end-devices known to communicate with a gateway with high-quality clock*, and the combined frequency offset satisfies the requirement listed in Section 3. This applies to most of the indoor/outdoor end-devices using LoRaWAN.

4.2 Devices Using A Crystal With Compensation Technique

Many of Semtech RF transceivers, such as the SX126x and SX127x, the internal crystal oscillator is 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. And with the help of an onboard temperature sensor, the device would automatically apply the predetermined capacitor trim value based on the current temperature. Obviously, the downside with this technique is extra development and increased production test time

4.3 Devices Requiring 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 LR1110/LR1120 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.

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 LR1110 LR1120	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 LR1120	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-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 Recommended 32MHz TCXOs

Table 6 Recommended 32MHz TCXOs

Manufacturer	Part Number	Package Size	Qualification
NDK	NT2016SA-32MHz-END4263A	1.6x2.0mm	Qualified
NDK	NT2016SF-32MHz-END4263D	1.6x2.0mm	Qualified
Rakon	IT2105 32.000000MHz	1.6x2.0mm	Qualified
Rakon	RST2016N 32.000000MHz - Ref.: T6395	1.6x2.0mm	Qualified
Rakon	IT3205CE 32.000MHz	3.2x2.5mm	Qualified
KDS	DSB211SDN-32MHz - Ref.: 1XXD32000PCA	1.6x2.0mm	Qualified
KDS	DSB211SDN-32MHz Ref.: 7EF03200A0S	1.6x2.0mm	Qualified
Epson	TG2016SMN_32MHz_X1G0054410105	1.6x2.0mm	Qualified
Geyer	12.71028	1.6x2.0mm	Qualified
Golledge	GTXO-203T/HS Ref.: MP10472	1.6x2.0mm	Qualified
Raltron	RTX-2016BD32-S-32.000-TR-NS1	1.6x2.0mm	Qualified
Raltron	RTX-2016AF3F-S-32.000-TR	1.6x2.0mm	Qualified
RFMi	XTC7031	1.6x2.0mm	Qualified
Abracon	ASTX-13-D-32.000MHz-I05-T	1.6x2.0mm	Qualified
Taitien	S0197-T-004-3	3.2x2.5mm	Qualified
TXC	7Z32070002	1.6x2.0mm	Qualified

6 Recommended 32MHz Crystals

Table 7 Recommended 32MHz Crystals

Manufacturer	Part Number	Package Size	Qualification
Rakon	FTR5092-A3[16]	3.2x2.5mm	Qualified
	FTR5123-B0[16]	2.0x1.6mm	Qualified
NDK	NX2520SA / EXS00A-CS00131[17]	2.5x2.0mm	Qualified
	NX2016SA / EX500A-CS06465[17]	2.0x1.6mm	Qualified
Epson	FA-128 / Q22FA1280058900[16]	2.0x1.6mm	Pre-Qualified
	FA-128 / Q22FA1280053000[17]	2.0x1.6mm	Pre-Qualified
Taitien	S0197-X-002-3[16]	3.2x2.5mm	Pre-Qualified
KDS	DSX211SH-32MHz 1ZZHAE32000AA0B[16]	2.0x1.6mm	Pre-Qualified
	DSX321G-32MHz 1C232000AA0Q[16]	3.2x2.5mm	Pre-Qualified
Murata	XRCGB32M000F1H17R0[16]	2.0x1.6mm	Pre-Qualified
	XRCGB32M000F1H18R0[16]	2.0x1.6mm	Pre-Qualified
Kyocera	CX2016DB32000F0FFFC2[17]	2.0x1.6mm	Pre-Qualified
NSK	NXN32.000AG10F-DKAB12[16]	2.0x1.6mm	Pre-Qualified
TXC	7M32070024[16]	3.2x2.5mm	Pre-Qualified
	8Y32070018[17]	2.0x1.6mm	Pre-Qualified

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

It is **very important** to note that the recommended TCXOs and crystals in Tables 6 and 7 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 or crystals specifications must be aligned with the requirements of the application, regarding operating temperature range, supply voltage, and electrical characteristics.

7 Summary

- All of Semtech's LoRa end device and gateway platforms are designed to be compatible with crystals and TCXOs as the clock reference source.
- For most LoRaWAN applications, the required frequency accuracy of LoRa modulation can be satisfied 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. [18] In fact, the LLCC68 LoRa transceiver with a crystal could be a good alternative solution to narrow-band FSK with TCXO, in LPWAN applications.

[18] When working with a typical gateway with TCXO

8 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

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