Application Note

Calibrations in TI Low-Power mmWave Radar Sensors

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ABSTRACT

TI's Low Power mmWave Radar Sensors have been built internally into subsystems like FECSS and APPSS which, by design, support various calibrations methods and topologies. Calibration routines makes sure that the performance of the radar front end is maintained across operational temperature range and process variations across devices. This application note describes the various types of calibrations supported in low power mmWave radar sensors and also details about the software configurability of these calibrations.

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1 Acronyms Used in This Document

Acronym	Description
APLL	Analog Phase Locked Loop
APPSS	Application Sub System
BIST	Built-in Self Test
CLPC	Closed Loop Power Control
FECSS	Front End Controller Sub System
FMCW	Frequency Modulated Continuous Wave
IF	Intermediate Frequency
IFA	Intermediate Frequency Amplifier
LNA	Low Noise Amplifier
LO Dist	Local Oscillator Distribution
LUT	Lookup Table
OLPC	Open Loop Power Control
PA	Power Amplifier
PD	Power Detector
VCO	Voltage Controlled Oscillator

2 Introduction

TI's low-power mmWave Radar sensors includes a radar front end and Front-End Controller subsystem (FECSS) where various calibrations are performed to stabilize the RF performance across temperature and process variations. The user application has complete control over running the calibrations. The FECSS also enables the sensor’s functional safety by determining RF/analog performance parameters and detecting functional failures by running monitors.

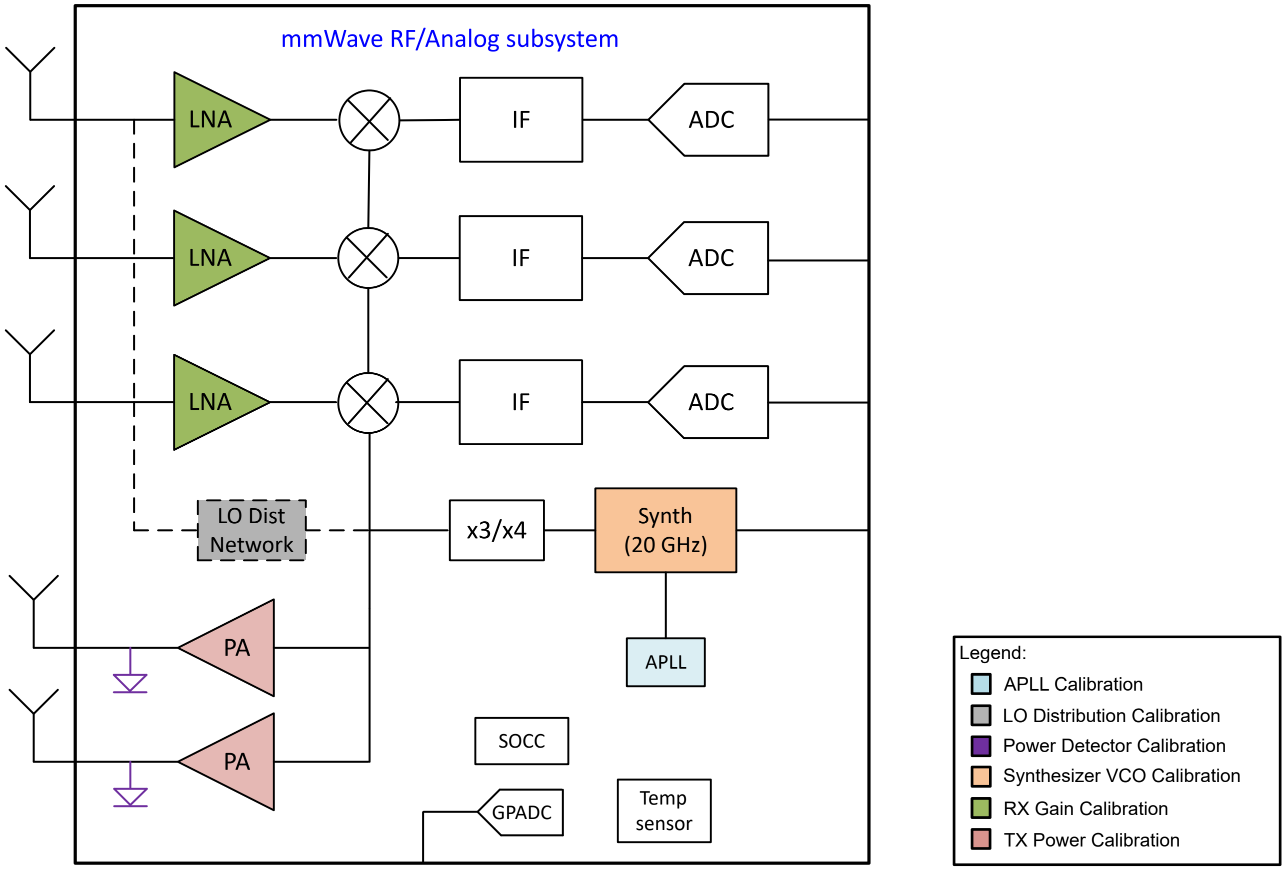

Figure 2-1. mmWave Front-End Architecture

The RF front-end architecture of low power mmWave sensor is illustrated in Figure 2-1. The performance parameters of the LNA, IF amplifier, PA, Synthesizer and the clock sources (APLL) can vary with process and temperature across devices.

3 Purpose of Calibrations

The purpose of calibrations is illustrated in Figure 3-1 using TX power as an example. The gain of the TX PAs varies from device to device due to manufacturing process variations and also across temperature. The purpose of calibration is to ensure that the radar front end parameters are maintained as configured by the user despite of variations in process and temperature. To achieve this, the internal processor adjusts the mmWave circuit configurations when factory calibrations are performed (to mitigate effects of process variations). Similarly, at runtime (to mitigate effects of temperature drifts) whenever the user application makes a decision to perform runtime calibrations. Figure 3-1 illustrates how calibration can be used to maintain the TX output Power close to the configured settings across temperature drifts. This chart is illustrative and is possible that the chart does not reflect actual device performance. Even with these calibrations done across temperature, there are some gain variations between devices, which must be considered in the user application.

Figure 3-1 illustrates the Tx output power variation normalized with respect to room temperature, with and without performing Tx Power CLPC calibration for a Tx back-off of 5dB.

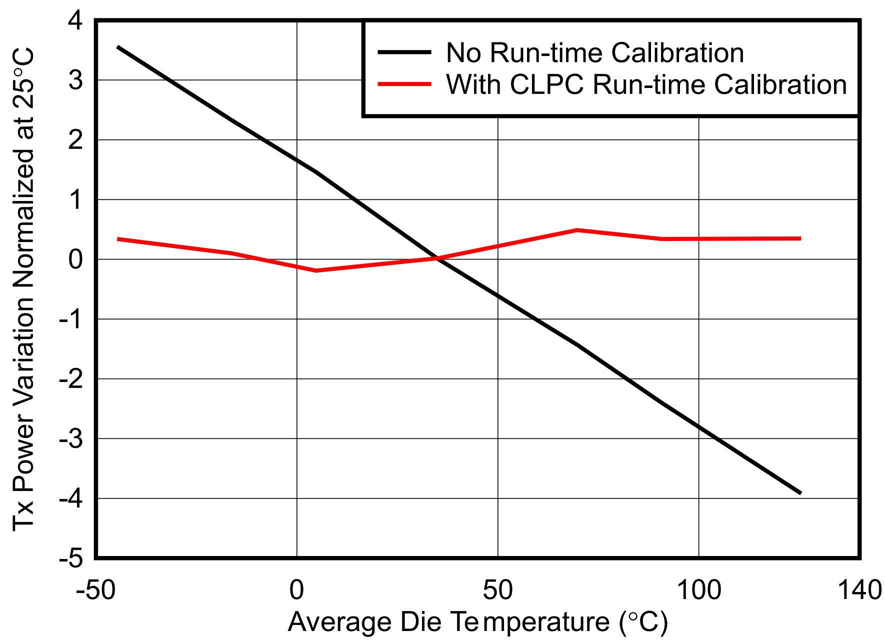

Figure 3-1. Tx Power Variation Without and With Calibration Across Temperature

4 Typical Stages of Calibration

TI's Low Power mmWave Radar sensors supports various types of calibrations (detailed in Section 5) that can be performed at various stages listed below in Table 4-1.

Table 4-1. Calibrations Performed at Different Stages

Calibration	Factory (Compensate for process variations)	Runtime(In-Field calibrations for temperature variations)
APLL Hardware Calibration	✓	✓(one-time Cal at cold boot)
Synthesizer VCO Calibration	✓	✓
LO Distribution Calibration	✓	✓
Power Detector Calibration	✓	✓
Tx Power Calibration	✓	✓
Rx Gain Calibration	✓	✓

4.1 Factory Calibrations

Factory calibrations are performed to compensate for manufacturing process variation effects. Factory calibrations are recommended to be performed in a controlled environment(an RF interference-free environment) at user's factory. These are typically performed between junction temperatures of 10°C to 50°C (preferably at 25°C). Once the factory calibrations are performed the Rx gain codes and Tx PA codes are derived for three temperature bins (Table 4-2). The user application can store the calibration results in non-volatile memory and restore at cold boot. If the end user system does not have capability to store factory calibration results, then the calibrations need to be run at every cold boot. Figure 6-1 in Section 6.1 talks about various stages and steps for factory calibrations to be performed by user application.

Note

In xWRL1432 and xWRL6432, RX IFA calibration is not needed as the IFA stage calibration is already done in TI's Factory and the calibration data is effused.

4.2 APLL Calibration

APLL (or cleanup PLL) calibration must be performed by the user application at every cold boot. APLL calibration is not required for warm boot as the previous calibration holds good across entire operating range of temperature.

Note

The term Cold boot refers to complete power cycle(off to on) or Hardware reset(toggling nReset pin). Whereas Warm boot refers to the Deep sleep exit or Software reset or no interruption in power supply.

4.3 Runtime Calibrations

Runtime calibrations are performed to reduce the variations in performance of the front end caused by change in temperature. These calibrations need to be performed at every cold boot and depending on the change in temperature and respective temperature bin index. The user application can make a decision to enable the runtime calibrations. The decision criteria of which calibrations need to be performed during the runtime based on the temperature change is detailed in Section 7. The various stages and steps for runtime calibrations to be performed by the user application is described in Section 6.2.

Table 4-2. Temperature Bin Index

Temperature Bin	Device Junction Temperature (J_T)
Low	-40°C ≤ T < 0°C
Mid	0°C ≤ T < 85°C
High	85°C ≤ T < 125°C

5 List and Description of Calibrations

TI's low power mmWave radar devices supports the following calibrations, which are described below. These calibrations can be performed in the factory as well as during runtime (In-field operation).

5.1 APLL Hardware Calibration

TI's Low Power mmWave Radar has an APLL (or cleanup PLL) which is a closed loop PLL that takes the reference clock as input and generates multiple clocks required for the processors, digital blocks (Peripherals, GPIO, DMA, Bus Matrix), ADCs, DACs and a high frequency reference clock for the FMCW synthesizer . APLL calibration is performed to keep the system clock robustly locked at a constant frequency irrespective of process variations and temperature.

5.2 Synthesizer VCO Calibration

The Synthesizer VCO generates an RF signal which is fed to a multiplier to get the desired ramp frequency in the range of 57 to 64GHz and 76 to 81GHz in 60GHz & 77GHz low power mmWave sensor family, respectively. The Synthesizer VCO calibration is performed to keep the ramp frequency locked irrespective of process variations and temperature.

5.3 LO Distribution Calibration

A set of buffers are used to distribute the high frequency RF signals to the Rx and Tx sections. The buffer's output signal swing is maintained and optimized using a temperature-based look up tables.

5.4 Power Detector Calibration

The power detectors aim to provide an absolute voltage and power reference throughout the radar chip. Power detectors allow monitoring of voltage stress on the RF nodes, and quantify the output power at both the TX output and RF inputs. This allows for accurate RF BIST and impedance measurements (critical for safety monitors). To make these measurements accurate, the power detectors must be calibrated for variation in temperature. This calibration is carried out for all critical power detectors, especially the ones used for TX power calibration.

For functional safety compliant devices monitoring of analog and RF circuits, operation is essential. Safety monitors relies on power detectors, hence performing the Power Detector Calibration is important.

5.5 TX Power Calibration

TX power calibration is performed to ensure that the device is transmitting at the configured transmit power by the user. TX power calibration can be done in Open Loop Power Control (OLPC) or Closed Loop Power Control (CLPC) modes during runtime(In-field) operation.

During factory calibration stage, Tx PA codes (2 stages) are derived for three temperature bins(Table 4-2) for the respective back-off configured. In the field, the user application needs to restore the factory calibration data from nonvolatile memory.

During runtime calibrations, In OLPC mode, the TX PA codes are set based on the temperature bin index (Low, Mid, High). In CLPC mode, the actual TX power is measured using the peak detectors and the TX stage codes are refined to achieve the desired TX power accuracy.

5.6 RX Gain Calibration

The RX chain consists of two amplifiers, that is, LNA and IFA. The RX chain gain is sum of gains from these two stages. The RX gain is calibrated to ensure that the overall RX gain is retained across process variations and change in temperature. RX factory calibration is done by feeding a signal level of known amplitude from the synthesizer to the Rx chain through on-chip loopback path. The Rx gain is analyzed by processing the ADC data amplitude and the Rx chain gain codes for desired gain are derived for three temperature bins, accordingly. These gain codes are applied during the runtime calibrations according to the respective temperature bin index.

6 Software configurability of Calibrations

mmWaveLink APIs provide API interface to the FECSS (Front End Controller Sub System) RF front end. mmWave link APIs internally call FECSSLib drivers to perform the API functionality and return the status to the application. This section describes the software configurability part of the calibrations by listing the necessary APIs that are used and functionality of each APIs and the recommended API sequences.

6.1 Software Sequence for Factory Calibrations

Figure 6-1 describes the recommended mmWaveLink API sequence that needs to be followed to perform the factory calibrations and store the calibration data. The Calibration data can be stored in a non-volatile memory and restored in the field.

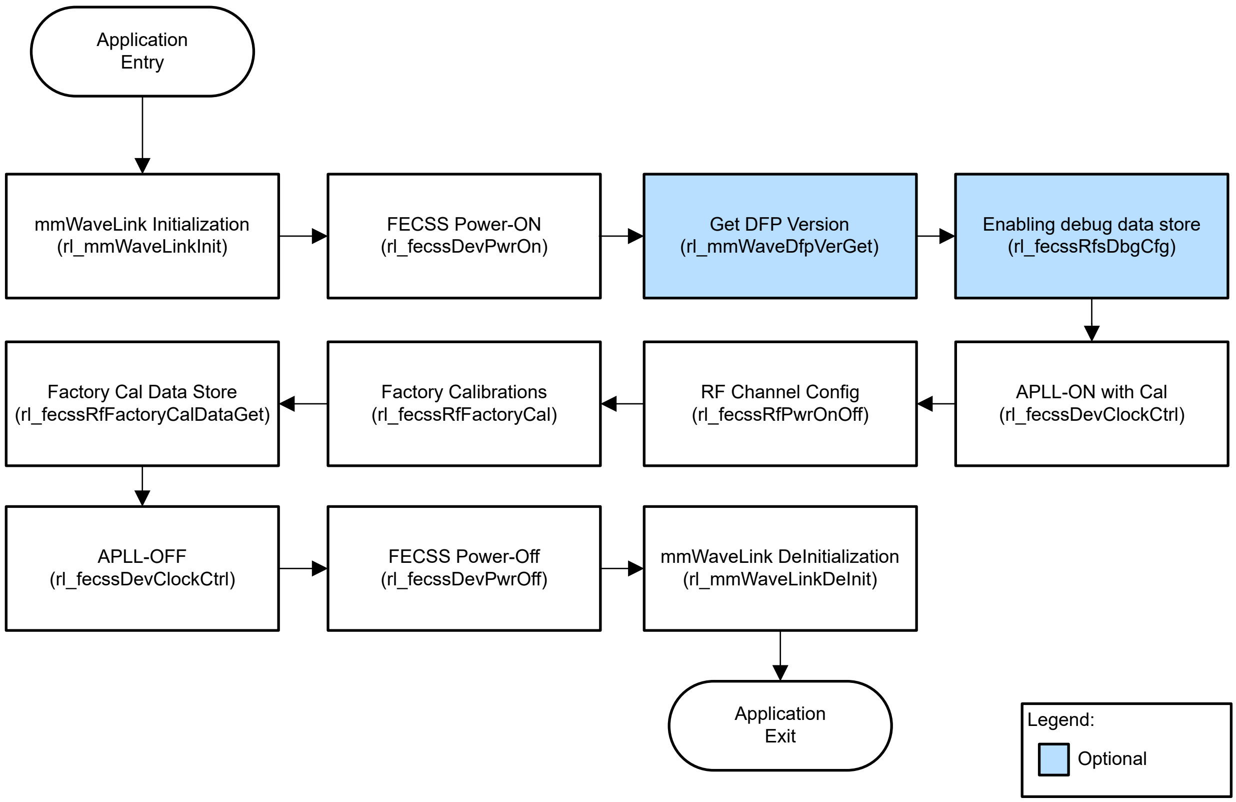

Figure 6-1. Recommended API Flow to Perform Factory Calibrations

6.1.1 mmWaveLink Initialization

The *rl_mmWaveLinkInit* API initializes all the interface call-back functions and client context handlers for mmwaveLink and FECSSLib.

6.1.2 FECSS Power-On

The *rl_fecssDevPwrOn* API is used for power-on control, power modes and clock configuration settings. The application can use this API to powerup the FECSS before issuing any other functional APIs. The FECSS powerup must be performed in cold boot mode and the fast clock source needs to be selected.

6.1.3 APLL Power-On and Hardware Calibration

The *rl_fecssDevClockCtrl* API configures the device clock source selection settings. The application can use this API to switch the FECSS clock source based on the device power state. The configuration structure of this API has a sub field, *c_ApllClkCtrl*, which can be used to power up the APLL and perform an APLL calibration.

Note

APLL calibration must be done before performing any other factory calibrations.

6.1.4 RF Channel Configuration

The *rl_fecssRfPwrOnOff* API is used to configure the RF channels and other miscellaneous control settings. The application must issue this API before any other functional APIs, which configure the RF settings. All the Tx and Rx channels which are used in runtime(in-field) must be enabled to perform the calibrations.

6.1.5 Trigger Factory Calibrations

The *rl_fecssRfFactoryCal* API configures and triggers the RF factory calibrations. The application must use this API to perform one-time RF configuration-dependent calibrations and store the results in non-volatile memory. The API's configuration structure allows the user to configure the desired front end parameters like Rx gain, Tx Power, Start frequency, Chirp slope etc.

6.1.6 Factory Calibration Data Store

The *rl_fecssRfFactoryCalDataGet* API can be used to store the factory calibration data to flash or external memory. Calibration data can be restored later using *rl_fecssRfFactoryCalDataSet* API. This API can be used to store the latest calibration data and avoid re-running the factory calibrations during runtime (In-field) operation.

6.1.7 APLL Power-Off

The *rl_fecssDevClockCtrl* API configures the device clock source selection setting. After storing the factory calibration data successfully this API can be used to Power-Off the APLL.

6.1.8 FECSS Power-Off

The *rl_fecssDevPwrOff* API is used to power down the FECSS. FECSS power down must be done without retaining the memory.

6.1.9 mmWaveLink De-Initialization

The *rl_mmWaveLinkInit* API De-initializes all the interface call-back functions and client context handlers for mmwaveLink and FECSSLib.

6.2 Software Sequence for Runtime (In-Field) Operation

Runtime calibrations are performed to compensate for runtime variations like temperature. Figure 6-2 describes the recommended mmWaveLink API sequence for the Infield operation.

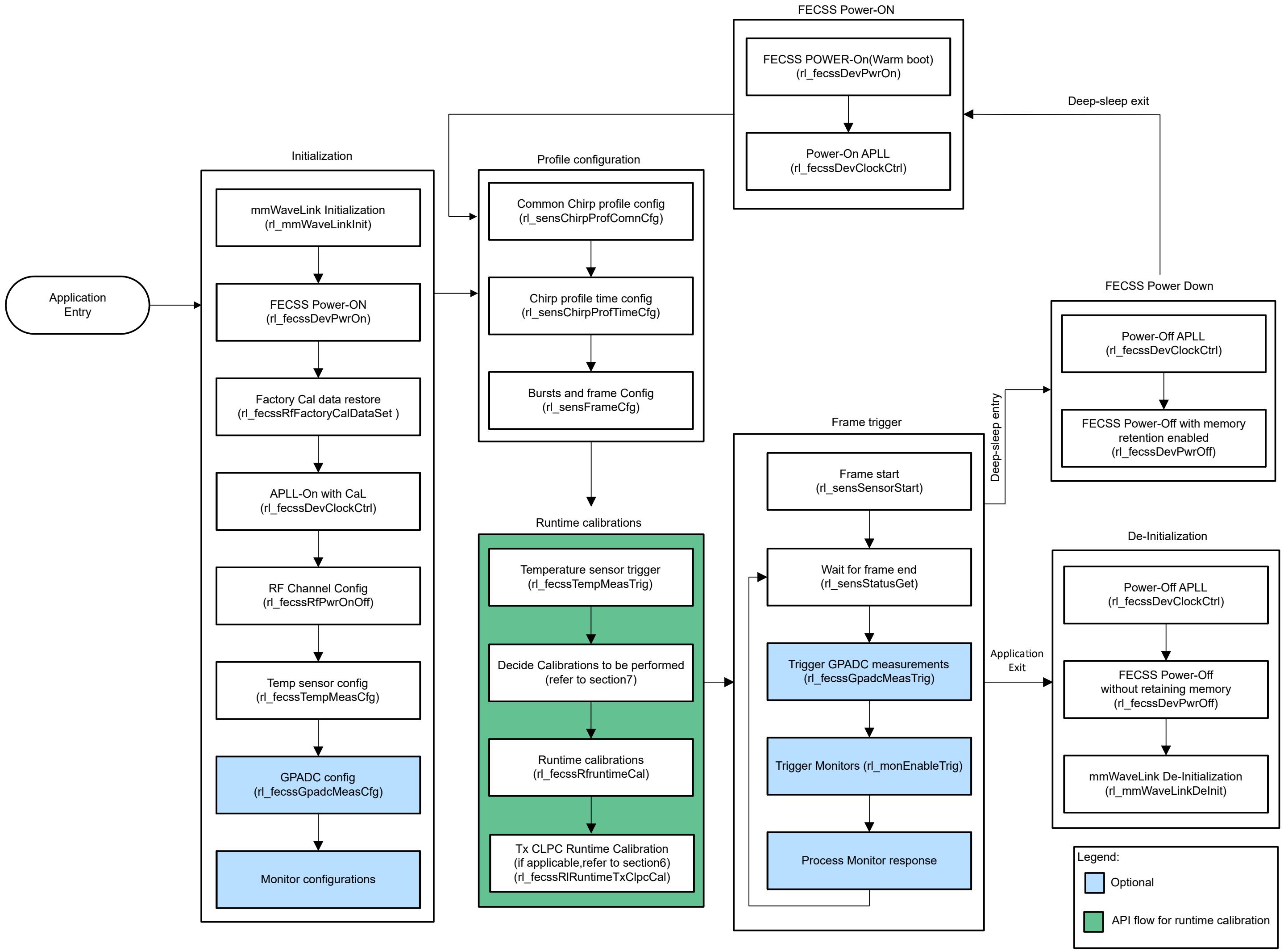

Figure 6-2. Recommended API Flow for Runtime (In-field) Operation

6.2.1 Initialization

6.2.1.1 mmWaveLink Initialization

The *rl_mmWaveLinkInit* API initializes all the interface call-back functions and client context handlers for mmwaveLink and FECSSLib.

6.2.1.2 FECSS Power-On

The *rl_fecssDevPwrOn* API is used for power-on control, power modes and clock configuration settings. The application can use this API to powerup the FECSS before issuing any other functional APIs. The FECSS powerup must be performed in cold boot mode and the fast clock source needs to be selected.

6.2.1.3 APLL Power-On and Hardware Calibration

The *rl_fecssDevClockCtrl* API configures the device clock source selection settings. The application can use this API to switch the FECSS clock source based on the device power state. The configuration structure of this API has a sub field, *c_ApllClkCtrl*, which can be used to power up the APLL and perform an APLL calibration.

Note

APLL calibration must be performed only at every cold boot.

6.2.1.4 Factory Calibration Data Restore

The *rl_fecssRfFactoryCalDataSet* API is used to restore/update the factory calibration data which was stored earlier using *rl_fecssRfFactoryCalDataGet* API. This API only restores the calibration data and does not apply the data to hardware registers.

To apply the calibration data to respective registers, the *rl_fecssRfRuntimeCal* API must be issued after restoring the calibration data.

6.2.1.5 Temperature Sensor Configuration

The *rl_fecssTempMeasCfg* API is used to configure the on-chip temperature sensor measurements. This API gives control over the temperature sensors to enable or disable them.

6.2.2 Profile Configuration

6.2.2.1 Profile Common Configuration

The *rl_sensChirpProfComnCfg* API is used to configure the FMCW radar chirp profile common parameters that are common across all the chirps in a frame.

6.2.2.2 Profile Time Configuration

The *rl_sensChirpProfTimeCfg* API is used to configure the FMCW radar chirp profile timing parameters like idle time, ADC start time, Tx start time, RF slope, start frequency etc.

6.2.2.3 Frame Configuration

The *rl_sensFrameCfg* API is used to group the chirps in a frame. Using this API, the application can configure parameters such as number of chirps, burst, frames, and timings related to the chirps, bursts, and frames.

6.2.3 Runtime Calibration

6.2.3.1 Temperature Sensor Trigger

The *rl_fecssTempMeasTrig* API can be used to measure the on-chip temperature. TI recommends to issue this API when the device exits deep sleep and before the functional frames are triggered.

6.2.3.2 Runtime Calibration Configure and Trigger

The *rl_fecssRfRuntimeCal* is used to configure and trigger the runtime calibrations. The configuration structure of this API allows you to choose the necessary calibrations which need to be performed based on the temperature bin and change in temperature (see Section 7). The application can read the device temperature using *rl_fecssTempMeasTrig* API and provide the bin index to the configuration structure of this Runtime Cal API. Run time calibration status is obtained as a response once this API is triggered.

For the duration required to complete each calibrations, refer to the 'Calibration Execution Time' section in the Interface control document.

6.2.3.3 Tx CLPC Calibration

When *rl_fecssRfRuntimeCal* API is triggered to perform runtime calibrations, the FECSS performs Tx power calibration in OLPC mode. For back-offs greater than 3dB, TI recommends to perform the calibration in CLPC mode using *rl_fecssRlRuntimeTxClpcCal* to get better accuracy in Tx output power.

This *rl_fecssRlRuntimeTxClpcCal* API can be used to calibrate the Tx channels during in-field operation. The API calibrates Tx channels using CLPC algorithm and immediately applies the results to the hardware registers.

6.2.4 Frame Trigger

6.2.4.1 Sensor Start

The *rl_sensSensorStart* API controls the frame trigger logic and triggers the frames.

6.2.4.2 Sensor Status

The *rl_sensStatusGet* API can be used to read the current sensor state parameters such as chirp, burst and frame counts.

6.2.4.3 Sensor Stop

Once the sensor status is obtained, the *rl_sensSensorStop* API can be used to stop the device transmission by sending stop signals to the frame timer and chirp timer modules.

6.2.5 Deep Sleep Entry and Exit

Once all the functional chirps are transmitted, the *rl_fecssDevClockCtrl* API can be used to power-off the APLL while entering deep sleep. The *rl_fecssDevPwrOff API* can be used for power down the FECSS. FECSS power down must be done with retaining the memory.

After successfully entering deep sleep and while exiting deep sleep, the *rl_fecssDevPwrOn* can be used to power up the FECSS. FECSS powerup must be done in warm boot mode. The configuration structure of the *rl_fecssDevClockCtrl* API has a sub field, *c_ApllClkCtrl*, that can be used to powerup the APLL. APLL hardware calibration is not needed during the warm boot or after exiting deep sleep.

6.2.6 De-Initialization

While exiting the application after all the functional frames are transmitted, the *rl_fecssDevClockCtrl* API can be used to power-off the APLL. The *rl_fecssDevPwrOff* API can be used for power down the FECSS. FECSS power down must be done without retaining the memory.

The *rl_mmWaveLinkInit* API de-initializes all of the interface call-back functions and client context handlers for mmwaveLink and FECSSLib.

7 Recommended Calibration Sequence: OLPC vs CLPC

This section describes TI recommended calibration sequences for various applications to perform the calibration during runtime (in-field) operation. When the device wakes up from cold boot or after deep sleep exit, the application must check the temperature and pass the temperature as an argument (Temp bin index) to *rl_fecssRfRuntimeCal* to trigger the runtime calibrations.

7.1 Safety Application With OLPC Tx Power Cal

The application can decide the calibrations that need to be performed by following the recommended flowchart Figure 7-1. For safety applications using Tx OLPC Calibration, PD runtime calibration is mandatory. Tx Power, Rx Gain and LO-Dist calibrations are LUT updates. Therefore the execution time for these calibrations(LUT updates) is minimal and on the order of a few µs.

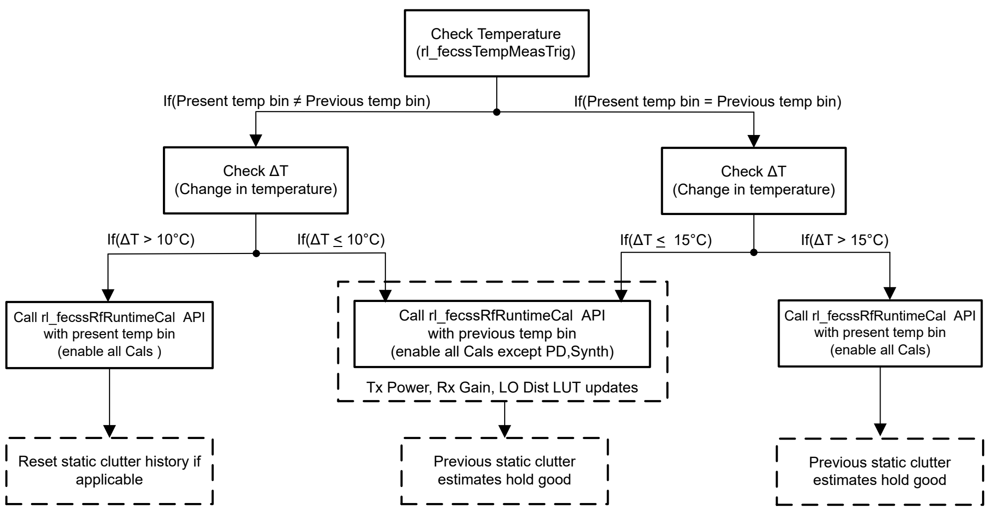

Figure 7-1. In-Field Runtime Calibration Sequence for Safety Applications With TX OLPC Cal

7.2 Non-Safety Application With OLPC Tx Power Cal

The application can decide the calibrations that need to be performed by following the recommended flowchart, Figure 7-2. Tx Power, Rx Gain and LO-Dist calibrations are LUT updates. Therefore, the execution time for these calibrations(LUT updates) is minimal and on the order of a few µs.

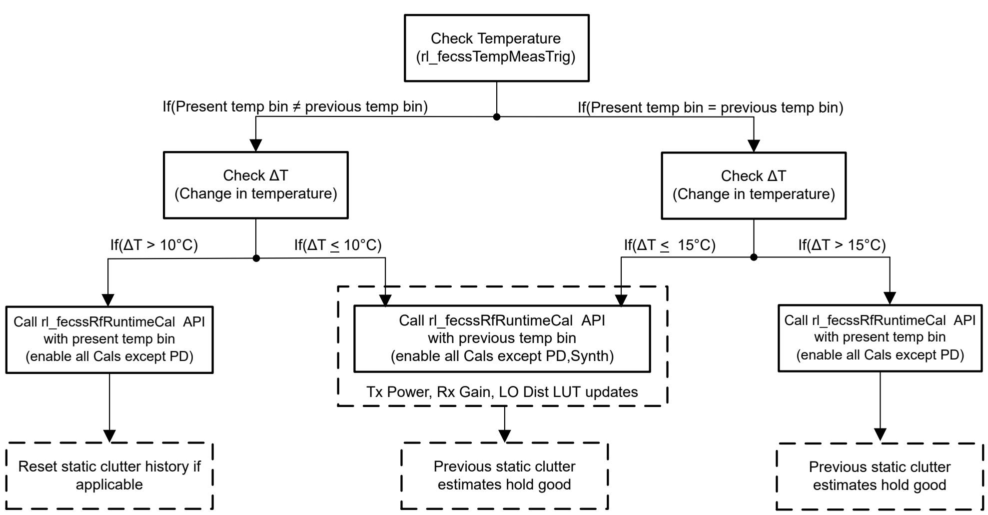

Figure 7-2. In-Field Runtime Calibration Sequence for Non-Safety Applications With TX OLPC Cal

7.3 Application With CLPC Tx Power Cal

Once the on-chip temperature measurements are triggered, the application can decide the calibrations that need to be performed by following the recommended flowchart Figure 7-3. First time after performing the Tx CLPC calibration, the application must save the Tx Bias codes and use them in override mode. Override mode can be used to skip the calibrations and apply the results which were saved by the application previously. Rx Gain and LO-Dist calibrations are LUT updates. Therefore, the execution time for these calibrations (LUT updates) is minimal and on the order of a few μs.

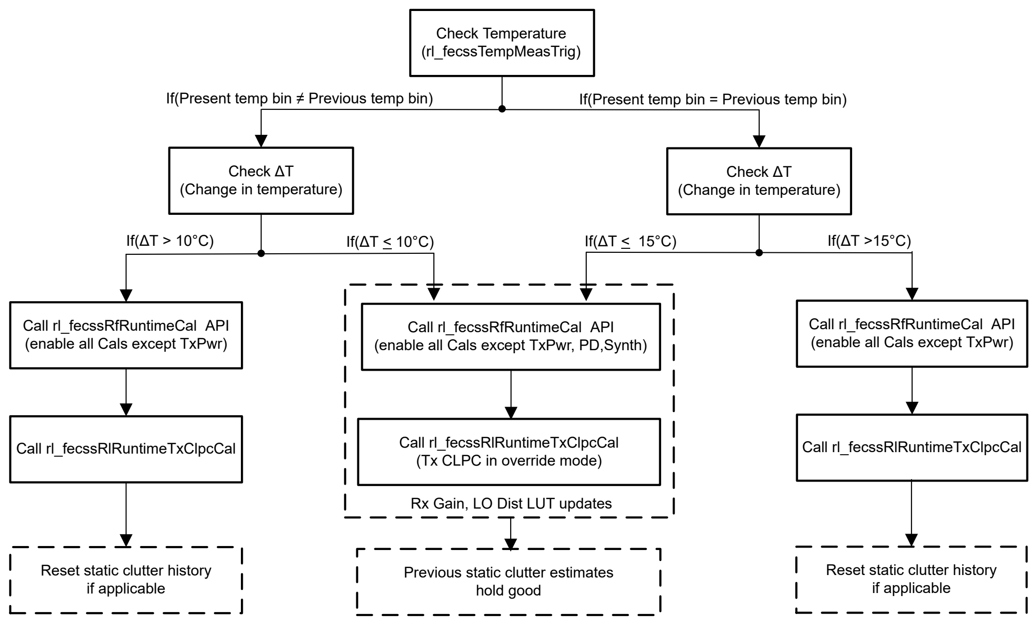

Figure 7-3. In-Field Runtime Calibration Sequence for Applications With TX CLPC Cal

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Note

In the above flowcharts, ΔT is absolute temperature difference between previous calibration temperature and current measured temperature (after deep sleep exit).

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8 Summary

This application note details the different calibration types that are supported in low power mmWave radar sensors and includes recommendations for specific calibrations depending on application. Users can follow the recommended flow described in the application note on when to perform calibrations and what calibrations need to be performed in the end equipment system.

9 References

1. Interface control document: https://www.ti.com/tool/MMWAVE-L-SDK
2. Refer to SDK example code for Factory and Runtime Calibrations (download from ti.com at: https://www.ti.com/tool/MMWAVE-L-SDK).

10 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (June 2024) to Revision A (September 2024) **Page**

- Updated temperature from 20℃ to 15℃ in *In-Field Runtime Calibration Sequence for Safety Applications With TX OLPC Cal* figure....12
- Updated temperature from 20℃ to 15℃ in *In-Field Runtime Calibration Sequence for Non-Safety Applications With TX OLPC Cal* figure.... 12
- Updated temperature from 20℃ to 15℃ in *In-Field Runtime Calibration Sequence for Applications With TX CLPC Cal* figure 13
- Added a note to detail about *Change in Temperature* in the flowcharts....13

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