# PE44951 Multiband Look-up Tables and Beamforming Guidelines

*Application Note 116*

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Headquarters: 9369 Carroll Park Dr, San Diego, CA 92121

# Introduction

The PE44951 is a dual-channel RF beamforming IC that integrates a 2-way RF splitter, digital phase control, digital attenuation control, and a serial peripheral interface (SPI) into a single device. The part is optimized for phased-array and beam-steering applications, providing independent phase and amplitude control on two RF paths derived from a common RF input. Depending on the selected operating band, the phase-shifter response and insertion loss characteristics vary with frequency, requiring frequency-band-specific calibration data to achieve optimum beamforming accuracy.

This application note describes how to select the correct operating band, configure the LUT selection registers, generate and load external LUTs when required, compensate for frequency and temperature variation, and perform system calibration to achieve optimum beam-steering performance across the supported frequency range.

## Key features

- Dual-channel beamforming IC
- Integrated RF splitter
- Phase and amplitude steering
- Extended 4.4–8.5 GHz support
- Fine DPS resolution: 1.4°/2.8°/5.6°
- Fine DSA resolution: 0.0625/0.25 dB
- Switching speed: ~320 ns
- Input power handling: +25 dBm

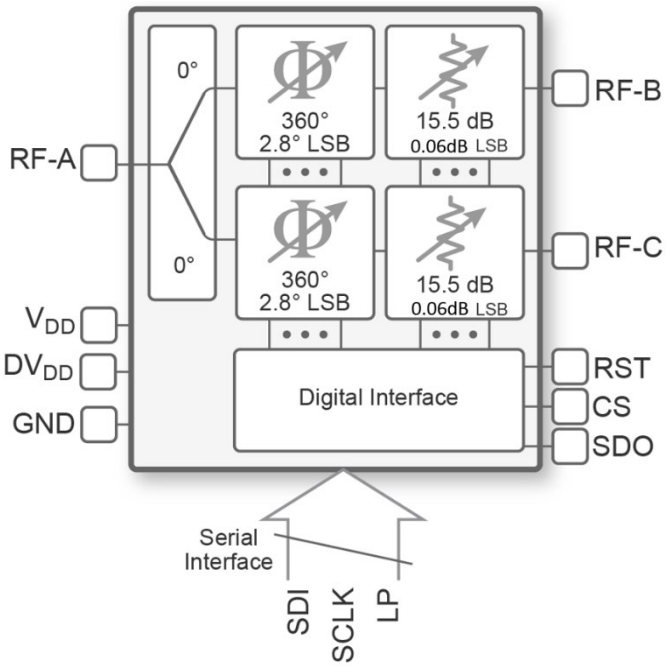


*Figure 1. Digital phase shifter (DPS) with attenuation block diagram*

# Summary

One PE44951 die covers several bands: The RF ports are retuned per band with at most a few passive components, and a band-specific external look-up table (LUT) corrects the remaining phase and amplitude error.

In direct DPS mode (LUT SEL = direct DPS mode), every target phase state is written from a pSemi-supplied external LUT that holds the BF (phase), COR (fine trim), and DSA (amplitude) settings, for both channels.

Temperature-compensated tables (−40, 0, 25, 85, and 115 °C), per-channel array calibration in the phase domain, and SPI update-time planning make the same flow usable in large, phased arrays and radar systems.

# External matching per band

This section describes the PE44951 tuning for each frequency band.

## External RF tuning for multiband operation

This section describes band-specific RF tuning for optimized beamforming performance.

**One part, many bands**: The same PE44951 die is retuned for each band with at most a few passive parts on the PCB: one 0.12 pF capacitor on RF_A for 6–8.5 GHz, no parts at all for 7.1–9 GHz, and a small LC network for 4.9–7.15 GHz. A system designer can cover several platforms or frequency plans with a single qualified part, one layout, and a BOM change, instead of a new IC per band.

**Consistent match on every phase state**: In a phased array, each element steps through all 256 phase states as the beam moves. With the ports tuned for the band, return loss stays near or below -10 dB across those states, so reflections between the phase shifter, the antenna or front end, and the combining network change little with the steering state. Smaller state-dependent ripple means lower RMS phase and amplitude error, more accurate beam pointing and lower sidelobes, and less of the error budget is left for calibration to absorb.

**Uniform, manufacturable arrays**: The matching tolerates ±0.02 pF capacitors and a ±0.05 nH inductor, so element-to-element variation from the matching itself stays small across hundreds of channels. In radar this keeps the channels coherent from pulse to pulse and preserves receive sensitivity and isolation, and the tuned port pairs directly with the band-specific external LUT that corrects the remaining phase and amplitude error.

Table 1. Tuning overview

| Band or item | External tuning |
|---|---|
| 6–8.5 GHz | 0.12 pF shunt C on RF_A |
| 7.1–9 GHz | No external parts |
| 4.9–7.15 GHz | Series L + shunt C on RF_A<br>Shunt C on RF_B/ RF_C |
| Tolerance | ±0.02 pF, ±0.05 nH |
| Option | DSA = 1 dB improves RF_B/RF_C return loss |

## External tuning for the 6–8.5 GHz band

### Components

- One 0.12 pF SMD capacitor on RF_A (tolerance ±0.02 pF).
- No components on RF_B or RF_C.

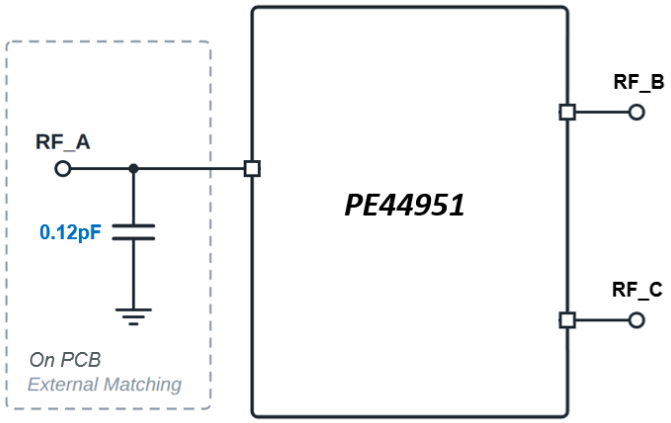


*Figure 2. External matching for the 6–8.5 GHz band*

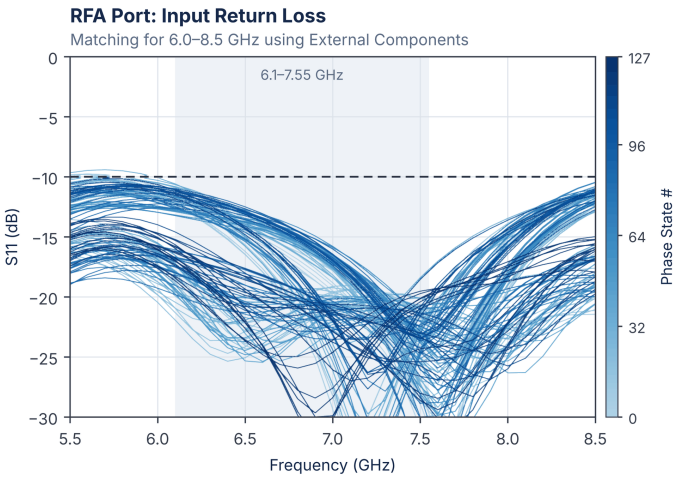


*Figure 3. Return loss, 6–8.5 GHz band with external tuning: RFA input*

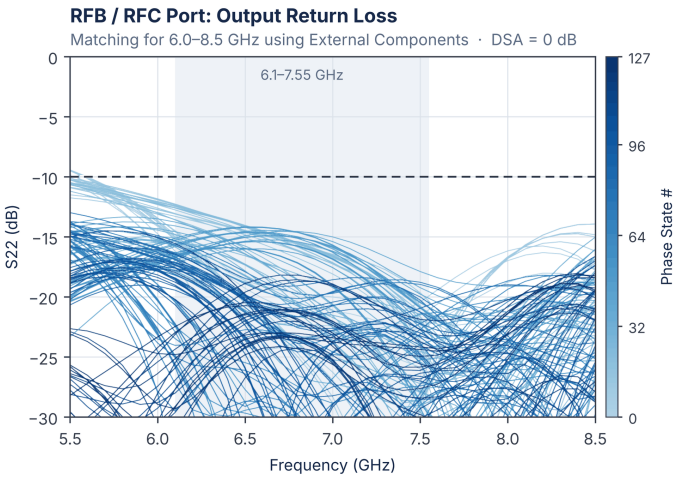


*Figure 4. RFB/RFC outputs all phase states*

## External tuning for the 7.1–9 GHz band

### Components

- No external matching components are required.
- The default port match gives adequate return loss from 7.1–9 GHz.

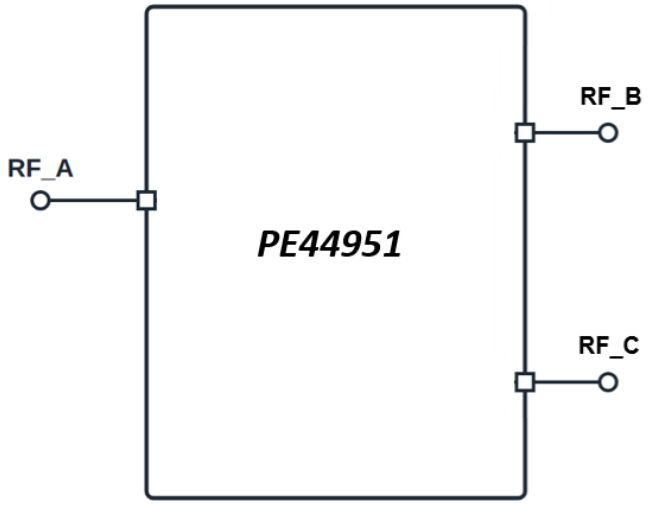


*Figure 5. No external matching for the 7.1–9 GHz band*

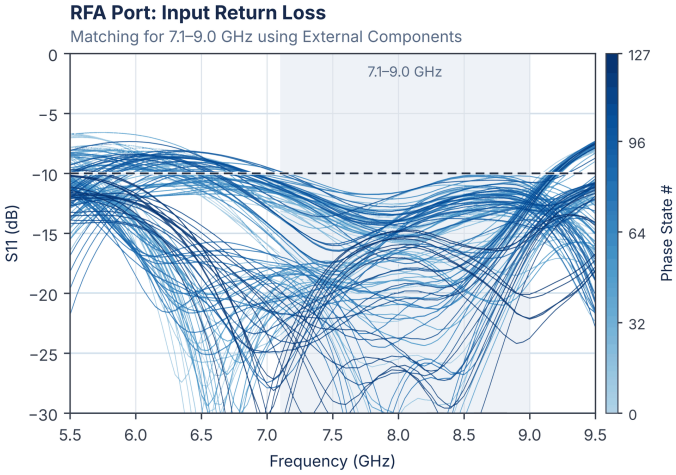


*Figure 6. Return loss, 7.1– 9 GHz band with no external components: RFA input*

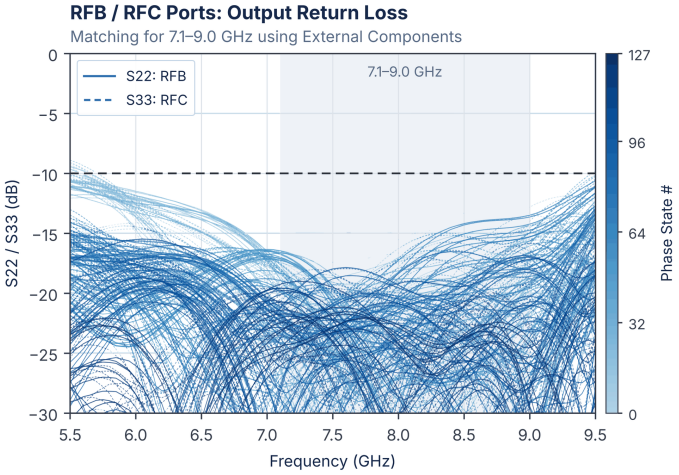


*Figure 7. RFB/RFC outputs*

## External tuning for the 4.9–7.15 GHz band

Components

- Matching components on RF_A and RF_B/RF_C as shown
- Tolerance: RF_A inductor ±0.05 nH; capacitors ±0.02 pF
- Higher DSA attenuation improves the RF_B/RF_C return loss

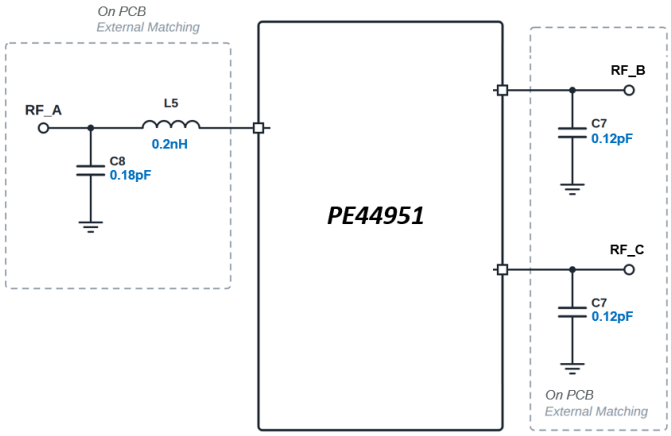


*Figure 8. External matching for the 4.9–7.15 GHz band (series L and shunt C on RF_A; shunt C on RF_B and RF_C)*

### DSA = 0 dB

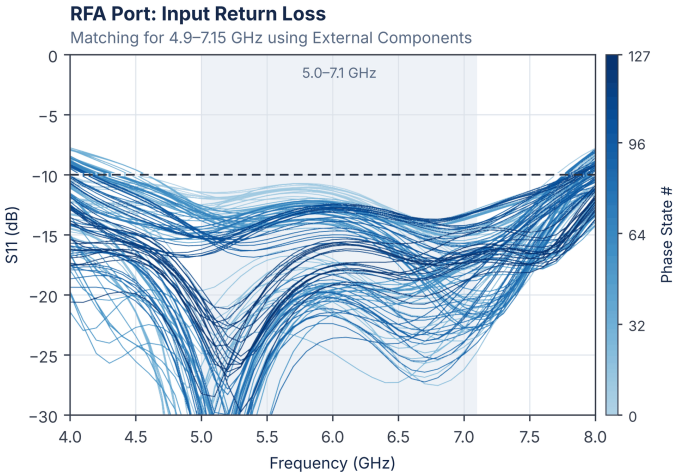


*Figure 9. Return loss, 4.9–7.15 GHz band with external tuning, DSA = 0 dB: RFA input*

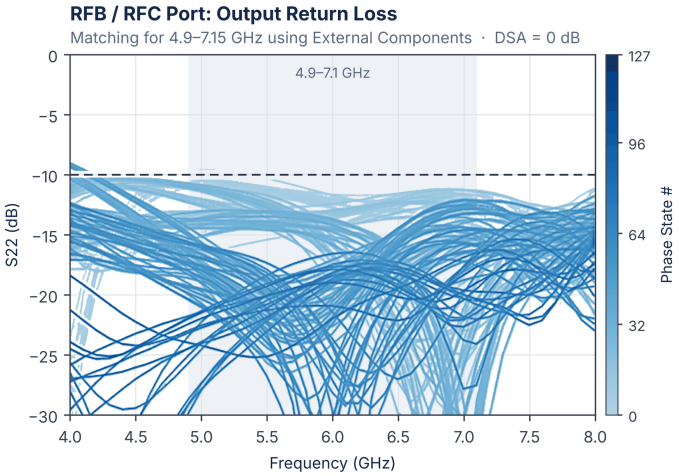


*Figure 10. RFB/RFC outputs*

## DSA = 1 dB

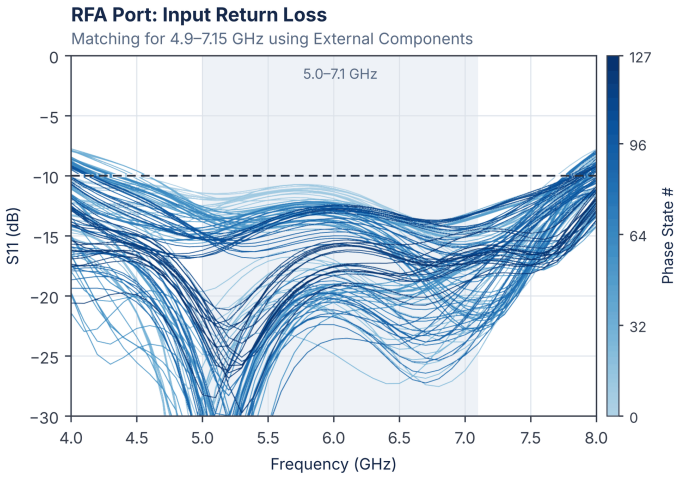


*Figure 11. Return loss, 4.9–7.15 GHz band with external tuning, DSA = 1 dB: RFA input*

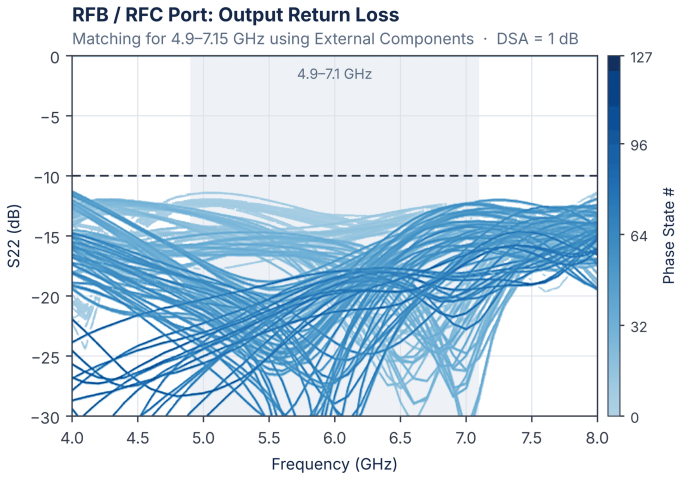


*Figure 12. RFB/RFC outputs*

DSA = 1 dB improves the RF_B/RF_C return loss. RF_A is unchanged.

# Internal and external look-up table selection

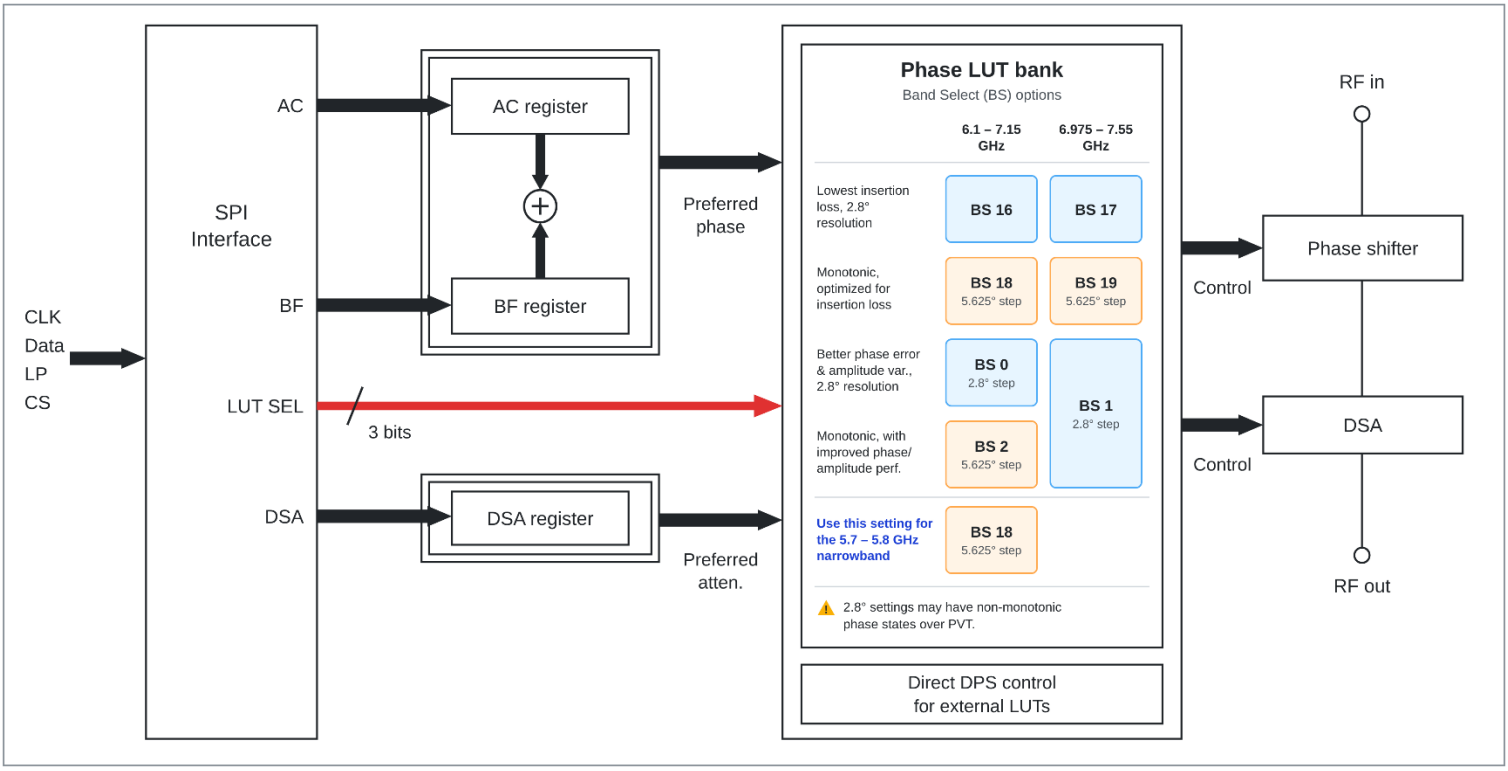


*Figure 13. PE44951 block diagram*

The PE44951 supports both internal and external look-up table (LUT) operation. In Internal LUT mode, program the band select field, LUT_SEL, in the COR1 register at address 110h to select the correct LUT for the operating frequency range and performance priority. The band select and trim controls share this register. For operation from 6.1 GHz to 7.15 GHz, 6.975 GHz to 7.55 GHz, and 5.7 to 5.8GHz, use the band select settings from Table 2.

For tighter phase accuracy or temperature-calibrated performance, use direct DPS mode with an external LUT. The external LUT defines the phase, attenuation, and trim settings for every phase state, and pSemi supplies the required BF/DSA/COR programming data in CSV format for the supported bands. To control the two channels independently in external LUT mode, program COR1 at address 110h for Channel 1 and program COR2 at address 111h for Channel 2. Temperature-calibrated external LUTs can be made available for 4.9 GHz to 7.55 GHz, including the required sub-bands, and LUTs for the 4.4 GHz to 5.0 GHz and 7.5 GHz to 8.5 GHz bands are available upon request.

Table 2: Internal look-up table selection summary[1][2]

| Operating requirement | 6.1–7.15 GHz | 6.975–7.55 GHz |
|---|---|---|
| Lowest insertion loss with 2.8° resolution | Band select 16 | Band select 17 |
| Monotonic operation optimized for insertion loss | Band select 18<br>5.625° step size | Band select 19<br>5.625° step size |
| Better phase error and amplitude variation with 2.8° resolution | Band Select 0<br>2.8° step size | Band select 1<br>2.8° step size |
| Monotonic operation with improved phase/amplitude performance | Band select 2<br>5.625° step size | |
| Key limitation | The available 2.8° settings can have non-monotonic phase states over PVT. | |

Notes:
1. To select the look-up table, write to the register at address 110. Address 010 and onwards are not latched by the load signal.
2. For the 5.7–5.8 GHz band, use band select 18, which provides a 5.625-degree step size.

Table 3. Look-up table programming and availability

| LUT mode/function | Frequency range | Register/address | LUT availability | Programming and recommended use |
|---|---|---|---|---|
| Internal LUT selection | Device-supported internal LUT ranges 1, 2, and 3. | LUT_SEL field<br>Address: 110h | Built into the device | Program LUT_SEL to select the internal LUT for the required frequency range. The band select and trim settings share the COR1 register. |
| External LUT, Channels 1 and 2 | 4.9–7.55 GHz, including required sub-bands | COR1: 110h<br>COR2: 111h | Available from the pSemi website | Program the pSemi-provided phase, attenuation, and trim data. Program COR1 and COR2 for independent control of Channels 1 and 2, respectively. |
| External LUT, Channels 1 and 2 | 4.4–5.0 GHz and 7.1–8.5 GHz, including required sub-bands | COR1: 110h<br>COR2: 111h | Available from pSemi upon request | Use when an internal LUT is unavailable or does not meet the application requirements. |

Table 4. PE44951 register map

| Address | Register | D7 | D6 | D5 | D4 | D3 | D2 | D1 | D0 |
|---|---|---|---|---|---|---|---|---|---|
| 000(1) | BF1 | Beamformer phase 1 × 1.4° (typ) | | | | | | | |
| 001(1) | BF2 | Beamformer phase 2 × 1.4° (typ) | | | | | | | |
| 010(1)(2) | AC1 | AC phase 1 × 1.4° (typ) | | | | | | | |
| 011(1) | AC2 | AC phase 2 × 1.4° (typ) | | | | | | | |
| 100 | DSA1 | Ignored | Attenuator control 1 × 0.125 dB (typ). Ignore the LSB for the 0.125-dB step size. | | | | | | |
| 101 | DSA2 | Ignored | Attenuator control 2 × 0.125 dB (typ). Ignore the LSB for the 0.125-dB step size. | | | | | | |
| 110(3) | Band select + CH1 trim <7:5> | To select the required look-up table, use the three LSBs. | | | | | | | |
| 111(4) | CH2 trim | CH2 trim bits <7 to 5> control bits 2.8, 1.4, and 0.7-CH2 trim degrees, respectively. | | | | | | | |

Notes:
1. To directly control the eight DPS bits to implement external look-up tables, first program 00000101 into the band select register, then write to these DPS registers directly.
2. Address 010 and onwards are *not* latched by the load signal.
3. For band 4 onwards, the device requires external LUTs, which pSemi can provide. Writing an external LUT involves writing to the BF and DSA registers. If more accuracy is required, write to the trim bits.
4. To control the 2.8, 1.4, and 0.7-degree trim DPS bits—to improve the accuracy of the phase shifter—use bits 7, 6, and 5, respectively.

Table 5. SPI command format

| 23 | 22 | 21 | 20 | 19 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R/W | – | Addr1[2:0] | | | Addr2[2:0] | | | Data1[7:0] | | | | | | | | Data2[7:0] | | | | | | | |

- The band select bits (LUT SEL) determine which frequency band internal look-up table (LUT) is used to control the device. The band select register address is the same as the trim register address (COR1 for channel 1). Address 110h (COR1).
- In the external look-up table mode, the data to be written into the LUT_SEL (COR1) and COR2 is provided in a CSV file by pSemi for all the bands needed.
- In external look-up table mode, write to both the COR1 and COR2 registers because they control both channels independently:
  - Channel 1: address 110h (COR1)
  - Channel 2: address 111h (COR2)
- The LUT SEL 0, 1, 2, or 10 values select the internal frequency band tables as shown above. The selected table sets the digital phase shifter (DPS) step size and frequency range for the device.
- LUT SEL is the direct DPS mode, in which the device is controlled using an external look-up table that provides the complete phase, attenuation, and trim settings for each target phase state.

For each target phase in the first column of Table 6, write the BF, COR, and DSA to both channels.

Table 6. Example external look-up table

| Target phase deg | BF | COR | DSA | Relative phase S21 $f_{LOW}$ deg | Relative phase S21 $f_{CENTER}$ deg | Relative phase S21 $f_{HIGH}$ deg |
|---|---|---|---|---|---|---|
| 0 | 0 | 5 | 20 | -0.05 | 0.04 | -0.05 |
| 1.40625 | 0 | 69 | 29 | 1.32 | 1.46 | 1.33 |
| 2.8125 | 1 | 69 | 32 | 2.90 | 2.91 | 2.79 |
| 4.21875 | 2 | 5 | 18 | 4.27 | 4.41 | 4.10 |
| 5.625 | 2 | 69 | 30 | 5.55 | 5.81 | 5.54 |
| 7.03125 | 3 | 69 | 28 | 6.94 | 7.17 | 7.03 |
| 8.4375 | 5 | 5 | 31 | 8.17 | 8.39 | 8.57 |
| 9.84375 | 2 | 165 | 19 | 10.02 | 9.66 | 9.91 |
| 11.25 | 3 | 165 | 19 | 11.47 | 11.05 | 11.42 |
| 12.65625 | 7 | 37 | 14 | 12.56 | 12.75 | 12.78 |
| 14.0625 | 7 | 69 | 17 | 13.84 | 14.16 | 14.24 |
| 15.46875 | 6 | 133 | 14 | 15.71 | 15.21 | 15.46 |
| 16.875 | 7 | 133 | 14 | 17.14 | 16.61 | 16.98 |
| 18.28125 | 7 | 165 | 14 | 18.18 | 17.93 | 18.50 |
| 19.6875 | 7 | 197 | 17 | 19.42 | 19.35 | 19.97 |
| 21.09375 | 7 | 229 | 17 | 20.45 | 20.65 | 21.50 |
| 22.5 | 10 | 133 | 12 | 21.81 | 22.17 | 23.01 |

## Using external look-up tables in direct DPS mode

Direct DPS mode is selected with LUT SEL = direct DPS mode. Figure 14 shows the steps to load and apply an external table.

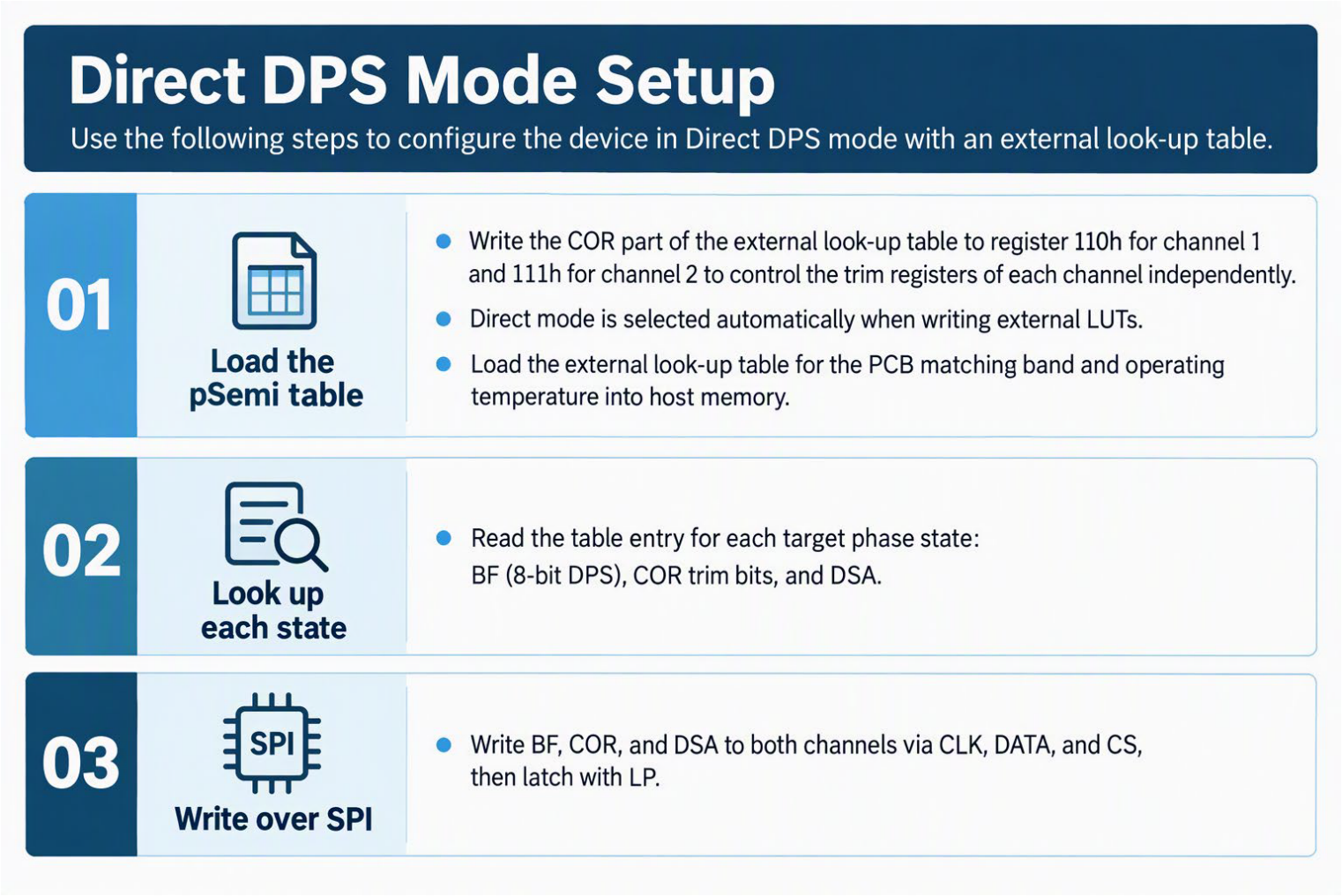


*Figure 14. Direct DPS mode setup*

## Why use an external look-up table

- Covers any band set by PCB matching, not just the bands built into the internal tables
- Provides amplitude stabilization: Each phase state carries its own DSA correction, so the gain stays flat while steering
- Tables can be updated in software for new bands or temperatures

## RF band and sub-band tree for the 4.9–7.1 GHz band

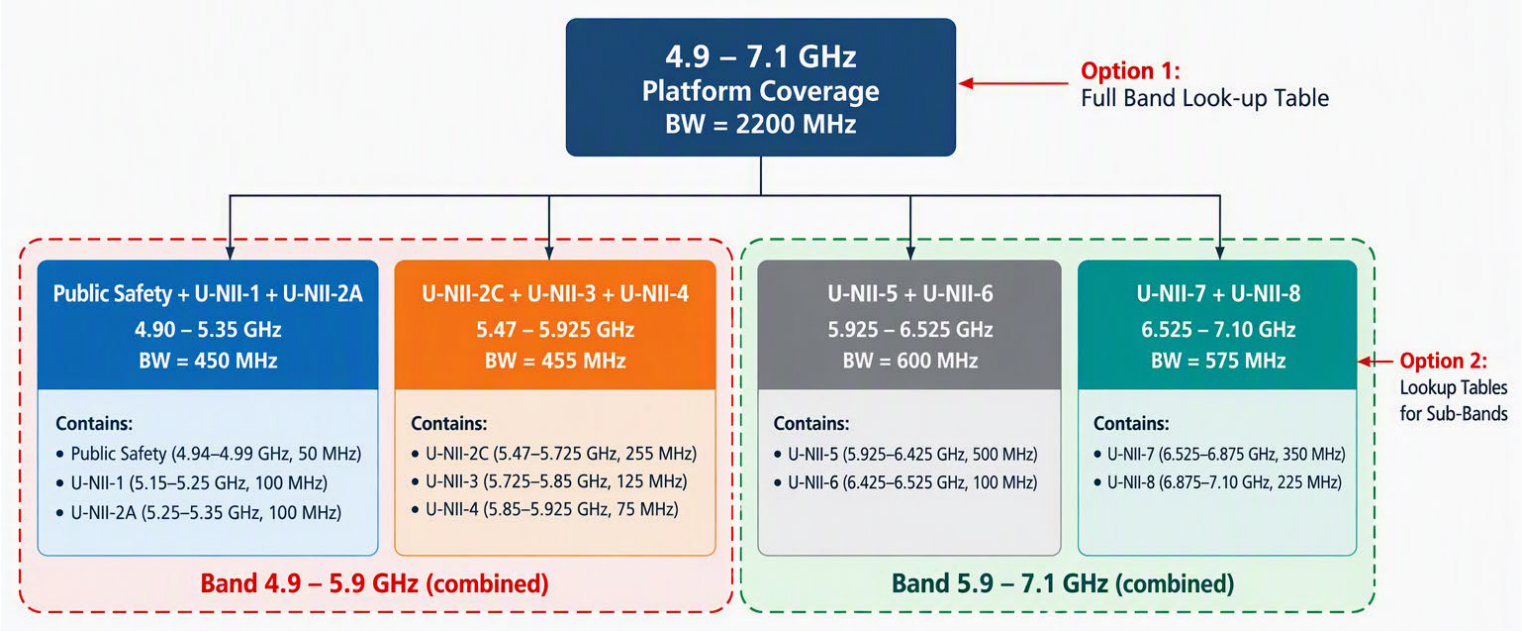


*Figure 15. RF band and sub-band tree for the 4.9–7.1 GHZ band*

- 4.9–7.15 GHz spans ~2.25 GHz, beyond the primary optimization bandwidth: One wideband LUT cannot hold insertion loss, return loss, isolation, amplitude, phase, and group delay flat across it.
- Option 1: Full-band LUT: Simplest control.
- Option 2: Sub-band LUTs: Band 1 (4.9–5.35 GHz), Band 2 (~5.45–5.95 GHz), Band 3 (~5.9–6.55 GHz), Band 4 (~6.5–7.15 GHz), or combined Band 12 and Band 34; tighter amplitude, phase, phase-step, and gain-flatness control.
- Option 3: pSemi can provide the look-up table for smaller sub-bands which can help to improve the phase error, step error, and insertion loss variation vs. phase states.
- Each LUT entry gives BF (phase), COR (fine trim) and DSA for one desired phase; write it to both channels (BF1/BF2, COR1/COR2, DSA1/DSA2; AC1/AC2 auxiliary phase).
- SPI: 24-bit word = R/W bit + page bit + two 3-bit register addresses + two 8-bit data fields (1 + 1 + 3 + 3 + 8 + 8 = 24 bits); the controller selects the LUT for the active band and writes the full setting.

## External LUT performance at 25 °C

Table 7 lists the external LUT performance for every band:

- RFB and RFC combined
- Worst case over all LUT entries
- Test frequencies $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$

Table 7. External LUT performance at 25 °C (RFB and RFC combined, worst case over all LUT entries, and the three test frequencies)

| Parameter | 4.4–4.8 GHz | 4.7–5.0 GHz | 4.90–7.15 GHz full band | 4.90–5.35 GHz | 5.45–5.90 GHz | 5.95–6.50 GHz | 6.55–7.10 GHz | 4.90–5.90 GHz wider sub-band | 5.95–7.15 GHz wider sub-band | Unit |
|---|---|---|---|---|---|---|---|---|---|---|
| Bandwidth | 400 | 300 | 2250 | 450 | 450 | 550 | 550 | 1000 | 1200 | MHz |
| Insertion loss, max (worst case) | 10.56 | 9.54 | 11.43 | 9.91 | 9.52 | 9.86 | 10.80 | 10.38 | 11.01 | dB |
| Return loss RFA, avg | 13.8 | 14.1 | 16.3 | 14.1 | 15.5 | 18.3 | 18.4 | 14.8 | 17.5 | dB |
| Return loss RFB/C, avg | 17.0 | 17.1 | 19.1 | 19.1 | 20.2 | 21.2 | 19.8 | 19.8 | 20.1 | dB |
| Isolation | 24.5 | 26.1 | 27.3 | 27.7 | 30.2 | 36.0 | 36.5 | 27.7 | 36.1 | dB |
| Phase step size | 1.405 | 1.405 | 1.397 | 1.405 | 1.405 | 1.406 | 1.406 | 1.402 | 1.409 | deg |
| Relative phase, max | 358.6 | 358.6 | 358.6 | 358.6 | 358.6 | 358.6 | 358.6 | 358.6 | 358.6 | deg |
| Relative amplitude, P-P | 2.04 | 0.86 | 2.42 | 0.55 | 0.50 | 0.60 | 0.67 | 0.99 | 1.20 | dB |
| Phase error, min/max | -8.65/8.55 | -5.53/5.44 | -10.36/10.13 | -6.37/6.65 | -2.79/2.78 | -1.32/1.41 | -2.44/1.98 | -10.07/9.96 | -3.27/2.73 | deg |
| Phase step error, min/max | -1.03/1.36 | -1.32/1.27 | -5.34/3.69 | -1.35/1.85 | -1.22/1.93 | -1.39/1.95 | -1.15/2.35 | -1.17/2.06 | -3.34/3.78 | deg |
| Gain flatness, S21 (FMAX) –S21 (FMIN) | 0.697 | 0.339 | 2.070 | 0.321 | 0.381 | 0.421 | 0.669 | 0.811 | 1.098 | dB |
| Gain flatness, S21 (FCENTER) – S21 (FMIN) | 0.415 | 0.206 | 0.785 | 0.212 | 0.214 | 0.251 | 0.262 | 0.330 | 0.481 | dB |
| Gain flatness, S21 (FMAX) – S21(FCENTER) | 0.283 | 0.147 | 1.423 | 0.154 | 0.178 | 0.210 | 0.407 | 0.492 | 0.732 | dB |
| Note: * The full-band group delay is reported as −0.346 ns in the source data; shown as magnitude. A negative minimum step means a non-monotonic step in that LUT. | | | | | | | | | | |

## Relative phase

Relative phase vs. target phase, referenced to the 0° entry; dashed line = ideal.

Figures 16 and 17 show the external LUT relative phase at 25 °C, 4.4–4.8 GHz and 4.7–5.0 GHz. Curves shown for RFB (S12); RFC (S13) tracks within 0.08 dB and 0.73°. SN1_3, 25 °C, and TF-TAWS LUT.

### 4.4–4.8 GHz

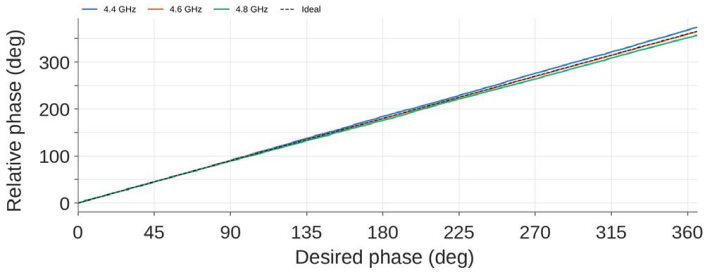


*Figure 16. Spans 0–374.1° at 4.4 GHz down to 0–357.1° at 4.8 GHz for the 365.625° entry; tracks the ideal line*

### 4.7–5.0 GHz

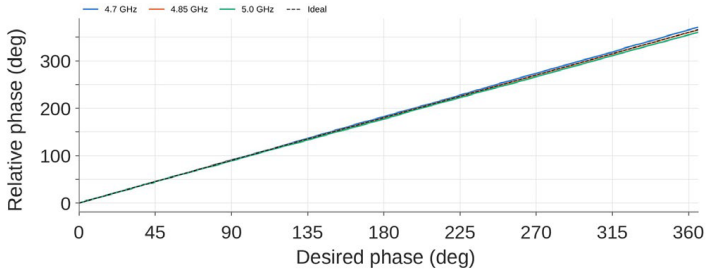


*Figure 17. Spans 0–370.7° at 4.7 GHz down to 0–360.1° at 5.0 GHz for the 365.625° entry; tracks the ideal line*

Figures 18 and 19 show the external LUT relative phase at 25 °C, 4.9–5.35 GHz, and 5.45–5.9 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

### Band 1: 4.9–5.35 GHz

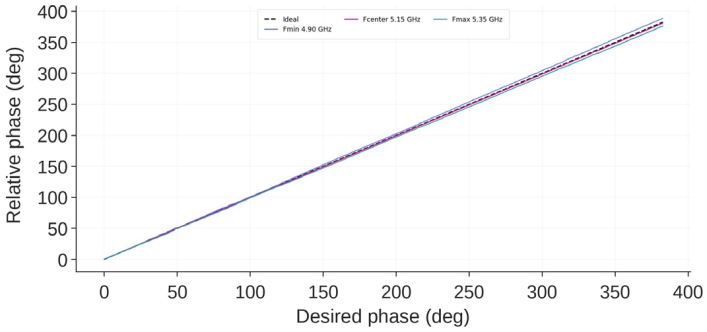


*Figure 18. Relative phase 0–389.1° (LUT 273 (0–382.5°)); monotonic, tracking the ideal line*

### Band 2: 5.45–5.9 GHz

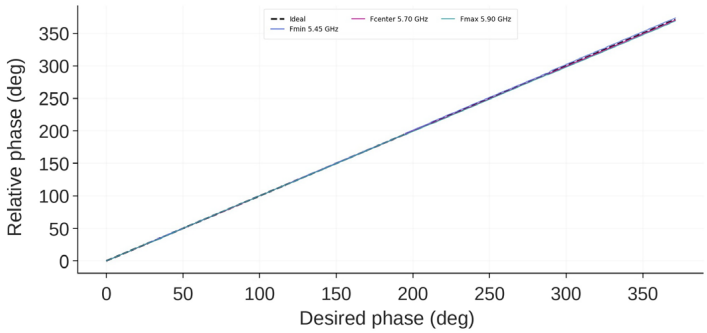


*Figure 19. Relative phase 0–361.4° (LUT 257 (0–360°)); monotonic, tracking the ideal line*

Figures 20 and 21 show the external LUT relative phase at 25 °C, 5.95–6.5 GHz, and 6.55–7.1 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Band 3: 5.95–6.5 GHz**

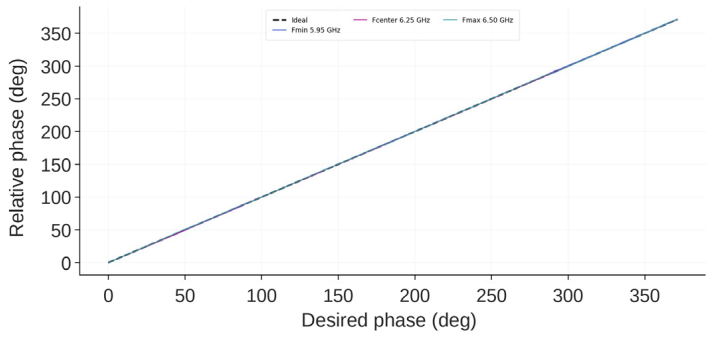


*Figure 20. Relative phase 0–371.7° (LUT 265 (0–371.3°)); monotonic, tracking the ideal line*

**Band 4: 6.55–7.1 GHz**

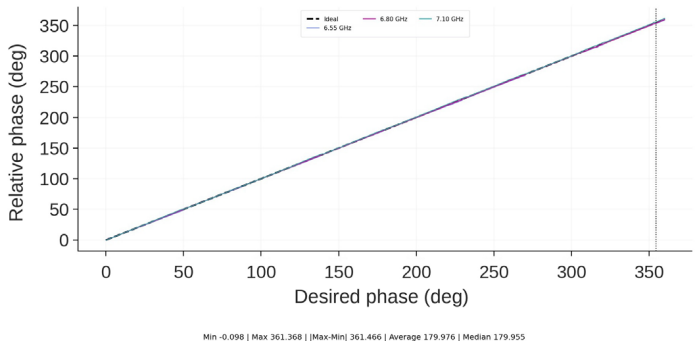


*Figure 21. Relative phase 0–361.4° (LUT 257 (0–360°)); monotonic, tracking the ideal line*

Figures 22 and 23 show the external LUT relative phase at 25 °C, 4.9–5.9 GHz, and 5.95–7.15 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Band 12: 4.9–5.9 GHz**

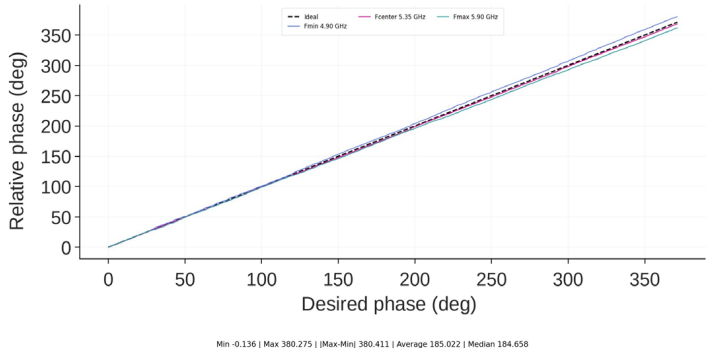


*Figure 22. Relative phase 0–380.5° (LUT 265 (0–371.3°)); monotonic, tracking the ideal line*

**Band 34: 5.95–7.15 GHz**

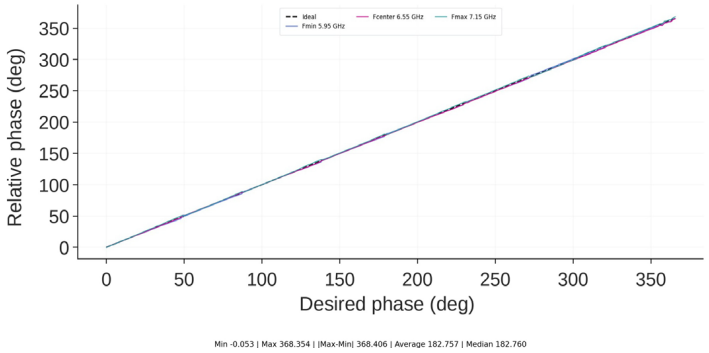


*Figure 23. Relative phase 0–368.4° (LUT 261 (0–365.6°)); tracks the ideal line, with isolated non-monotonic steps*

Figure 24 shows the external LUT relative phase at 25 °C, Full band: 4.9–7.15 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Full band: 4.9–7.15 GHz**

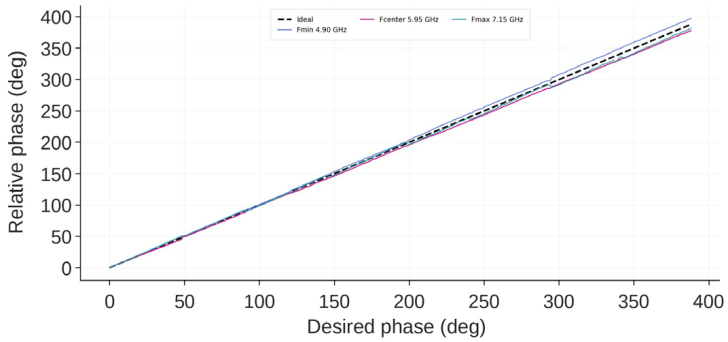


*Figure 24. Relative phase 0–397.7° (LUT 277 (0–388.1°)); tracks the ideal line, with isolated non-monotonic steps*

## Phase error

Phase error vs. the target phase, referenced to the 0° entry.

Figures 25 and 26 show the external LUT phase error at 25 °C, 4.4–4.8 GHz, and 4.7–5.0 GHz. Curves shown for RFB (S12); RFC (S13) tracks within 0.08 dB and 0.73°. SN1_3, 25 °C, TF-TAWS LUT.

### 4.4–4.8 GHz

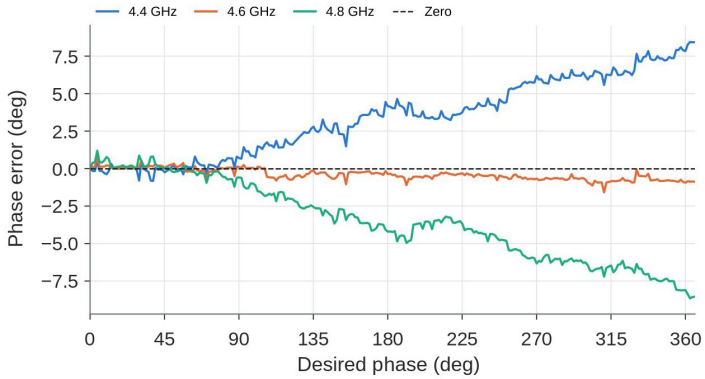


*Figure 25. $F_{CENTER}$ 4.6 GHz: −8.65°/+8.55°. Band edges reach ±8.65° because the phase shift scales with frequency*

### 4.7–5.0 GHz

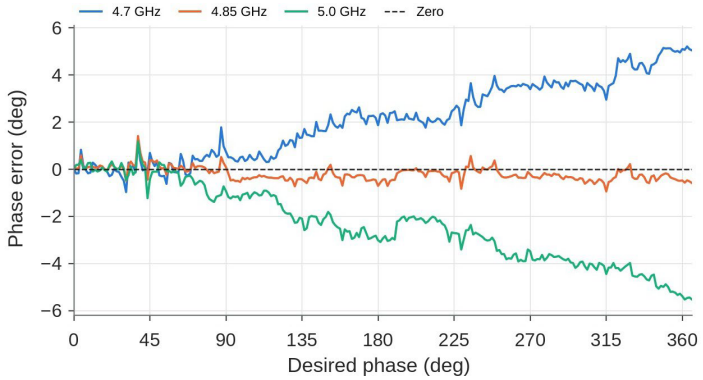


*Figure 26. $F_{CENTER}$ 4.85 GHz: −5.53°/+5.44°. Band edges reach ±5.53° (narrower band, less phase slope)*

Figures 27 and 28 show the eternal LUT phase error at 25 °C, 4.9–5.35 GHz, and 5.45–5.9 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

### Band 1: 4.9–5.35 GHz

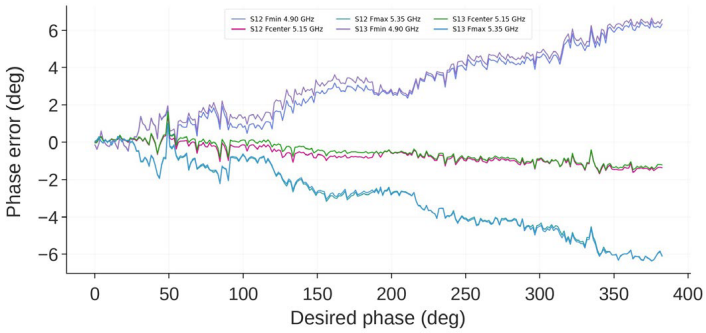


*Figure 27. Phase error −6.37/+6.65° over all entries and frequencies*

### Band 2: 5.45–5.9 GHz

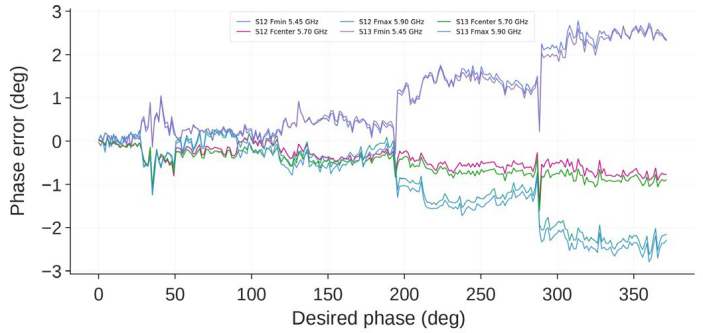


*Figure 28. Phase error −2.79/+2.78° over all entries and frequencies*

Figures 29 and 30 show the external LUT phase error at 25 °C, 5.95–6.5 GHz, and 6.55–7.1 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Band 3: 5.95–6.5 GHz**

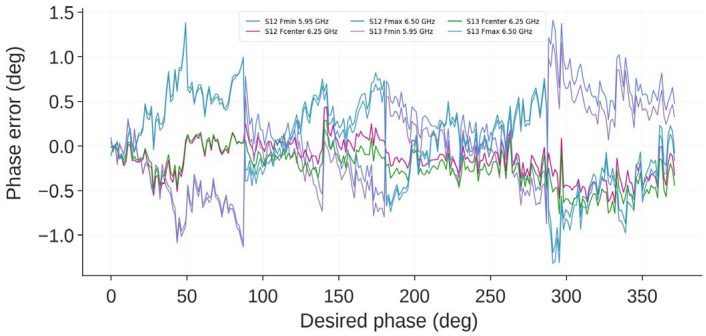


*Figure 29. Phase error −1.32/+1.41° over all entries and frequencies*

**Band 4: 6.55–7.1 GHz**

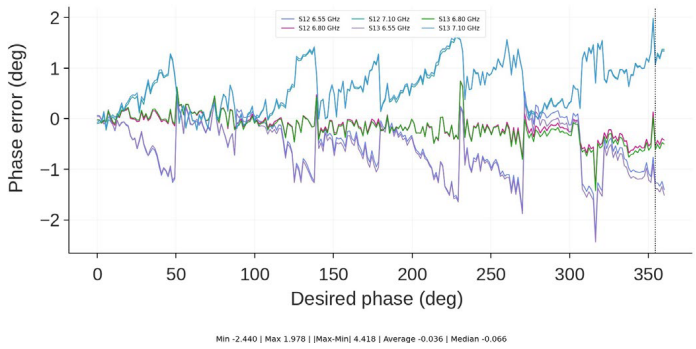


*Figure 30. Phase error −2.44/+1.98° over all entries and frequencies*

Figures 31 and 32 show the external LUT phase error at 25 °C, 4.9–5.9 GHz, and 5.95–7.15 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Band 12: 4.9–5.9 GHz**

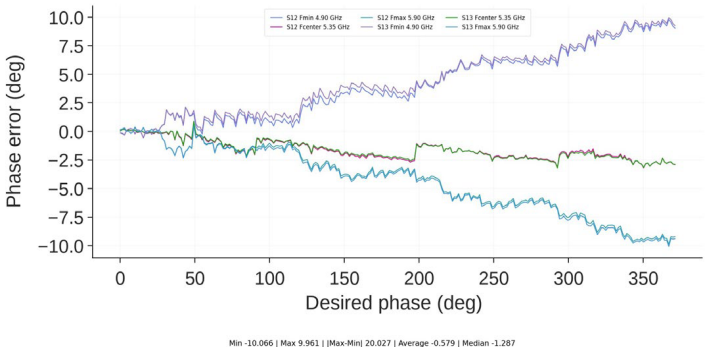


*Figure 31. Phase error −10.07/+9.96° over all entries and frequencies*

**Band 34: 5.95–7.15 GHz**

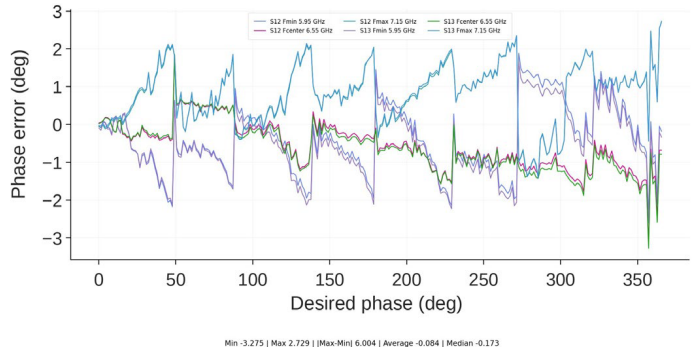


*Figure 32. Phase error −3.27/+2.73° over all entries and frequencies*

Figure 33 shows the external LUT phase error at 25 °C, Full band: 4.9–7.15 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Full band: 4.9–7.15 GHz**

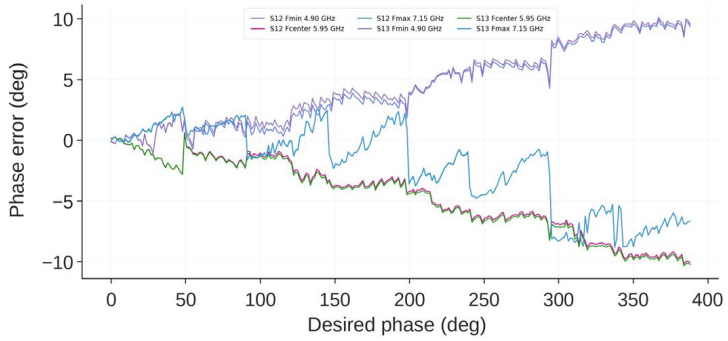


*Figure 33. Phase error −10.36/+10.13° over all entries and frequencies*

## Insertion loss

Insertion loss vs. target phase; the LUT holds the amplitude inside its window.

Figures 34 and 35 show the external LUT insertion loss at 25 °C, 4.4–4.8 GHz, and 4.7–5.0 GHz. Curves shown for RFB (S12); RFC (S13) tracks within 0.08 dB and 0.73°. SN1_3, 25 °C, TF-TAWS LUT.

### 4.4–4.8 GHz

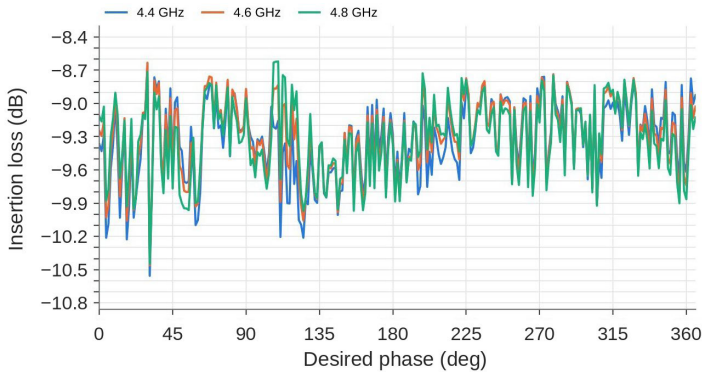


*Figure 34. Insertion loss −8.60 to −10.56 dB; 1.90 dB p-p with a 1.5 dB LUT window*

### 4.7–5.0 GHz

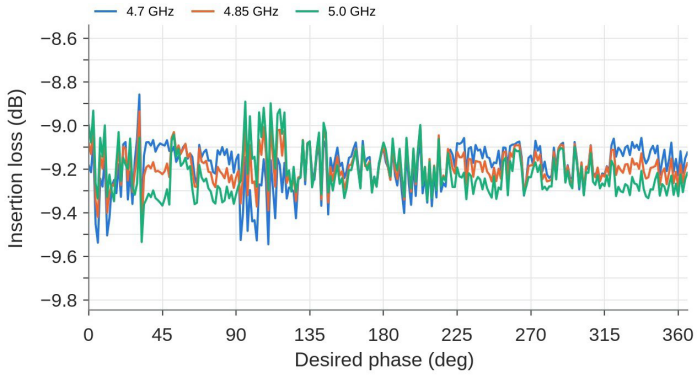


*Figure 35. Insertion loss −8.84 to −9.54 dB; 0.69 dB p-p with a 0.5 dB LUT window*

Figures 36 and 37 show the external LUT insertion loss at 25 °C, 4.9–5.35 GHz, and 5.45–5.9 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

### Band 1: 4.9–5.35 GHz

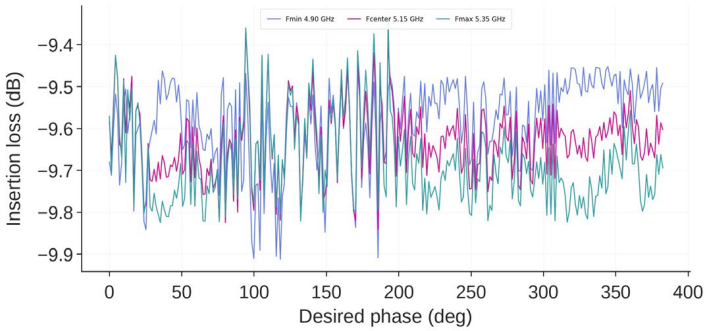


*Figure 36. Insertion loss −9.91 to −9.33 dB; relative amplitude 0.55 dB p-p (window 0.40–0.90 dB)*

### Band 2: 5.45–5.9 GHz

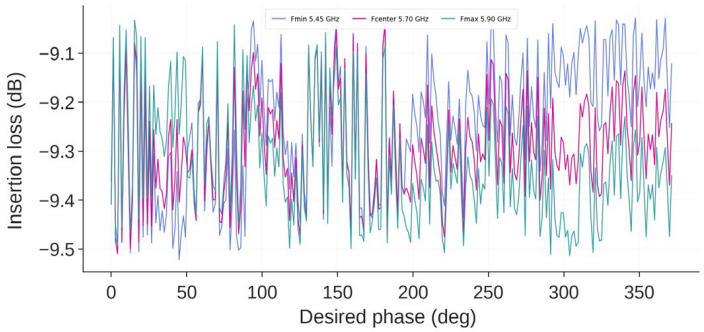


*Figure 37. Insertion loss −9.52 to −9.00 dB; relative amplitude 0.50 dB p-p (window 0.10–0.60 dB)*

Figures 38 and 39 show the external LUT insertion loss at 25 °C, 5.95–6.5 GHz, and 6.55–7.1 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

### Band 3: 5.95–6.5 GHz

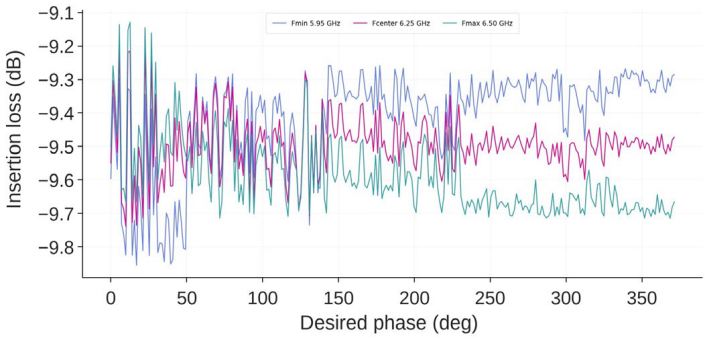


*Figure 38. Insertion loss −9.86 to −9.13 dB; relative amplitude 0.60 dB p-p (window 0.35–0.95 dB)*

### Band 4: 6.55–7.1 GHz

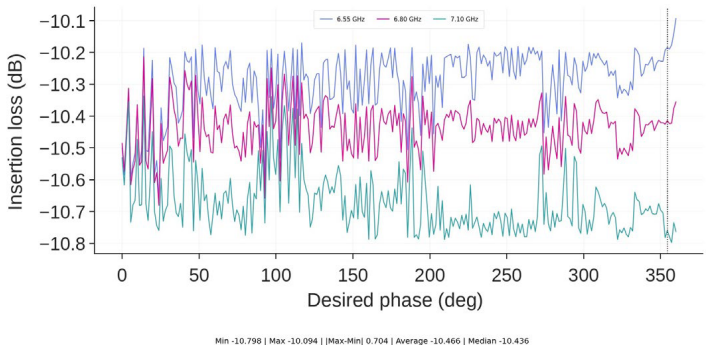


*Figure 39. Insertion loss −10.80 to −10.09 dB; relative amplitude 0.67 dB p-p (window 1.40–2.00 (1.30–2.10 tail) dB)*

Figures 40 and 41 show the external LUT insertion loss at 25 °C, 4.9–5.9 GHz, and 5.95–7.15 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

### Band 12: 4.9–5.9 GHz

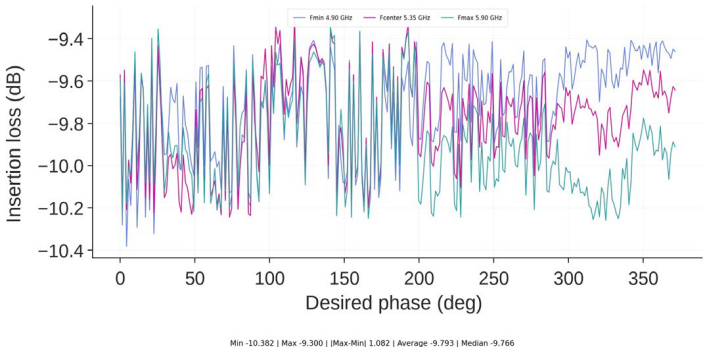


*Figure 40. Insertion loss −10.38 to −9.30 dB; relative amplitude 0.99 dB p-p (window 0.35–1.35 dB)*

### Band 34: 5.95–7.15 GHz

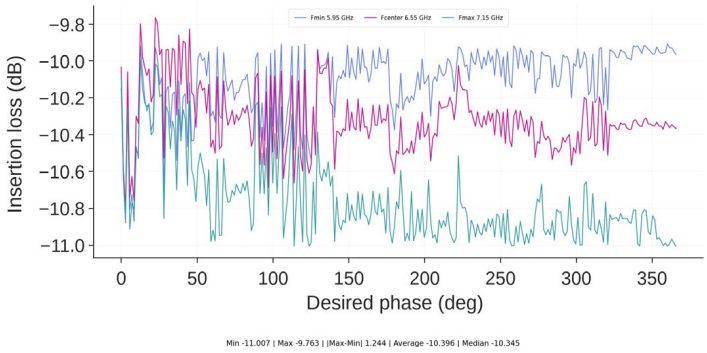


*Figure 41. Insertion loss −11.01 to −9.76 dB; relative amplitude 1.20 dB p-p (window 1.00–2.20 dB)*

Figure 42 shows the external LUT insertion loss at 25 °C, Full band: 4.9–7.15 GHz. Curves shown for RFB (S12); RFC (S13) is the same within the report tolerance. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Full band: 4.9–7.15 GHz**

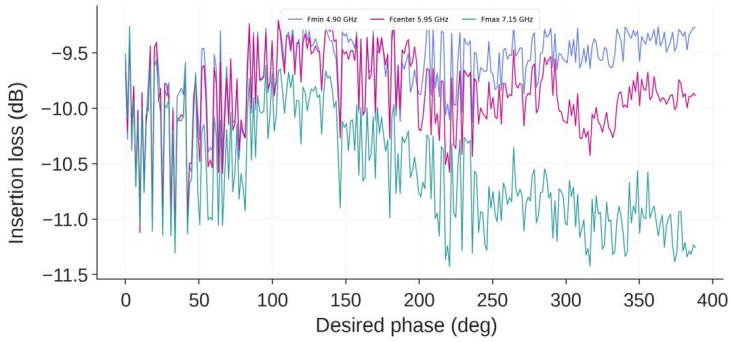


*Figure 42. IL −11.43 to −9.19 dB; relative amplitude 2.42 dB p-p (window 0.20–2.70 dB)*

## Phase step size

Step between adjacent LUT entries; target 1.40625°.

Figures 43 and 44 show the external LUT phase step size at 25 °C, 4.4–4.8 GHz, and 4.7–5.0 GHz. Curves shown for RFB (S12); RFC (S13) tracks within 0.08 dB and 0.73°. SN1_3, 25 °C, TF-TAWS LUT.

### 4.4–4.8 GHz

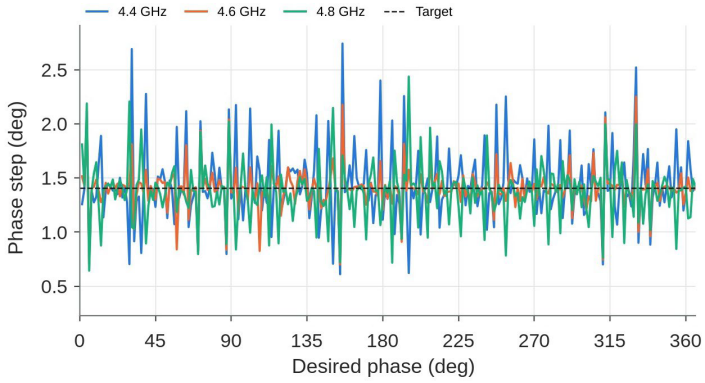


*Figure 43. Average 1.373–1.439° across the band; every step is positive (monotonic)*

### 4.7–5.0 GHz

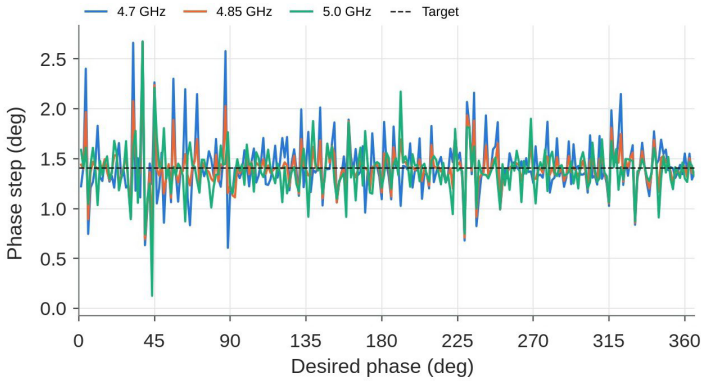


*Figure 44. Average 1.385–1.426° across the band; every step is positive (monotonic)*

Figures 45 and 46 show the external LUT phase step size at 25 °C, 4.9–5.35 GHz, and 5.45–5.9 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

### Band 1: 4.9–5.35 GHz

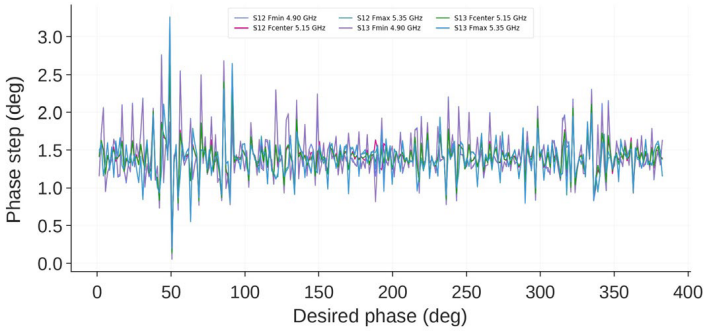


*Figure 45. Average step 1.405° (target 1.406°); minimum step 0.051°*

### Band 2: 5.45–5.9 GHz

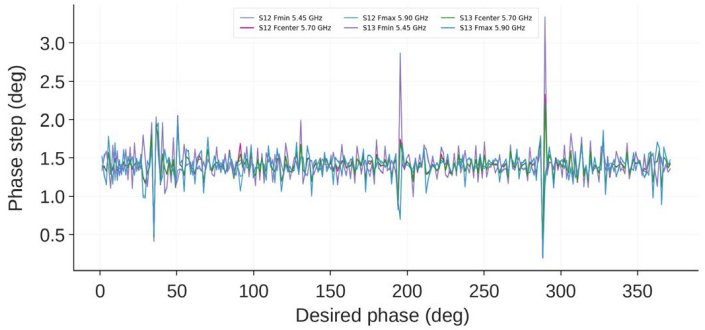


*Figure 46. Average step 1.405° (target 1.406°); minimum step 0.189°*

Figures 47 and 48 show the External LUT phase step size at 25 °C, 5.95–6.5 GHz, and 6.55–7.1 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Band 3: 5.95–6.5 GHz**

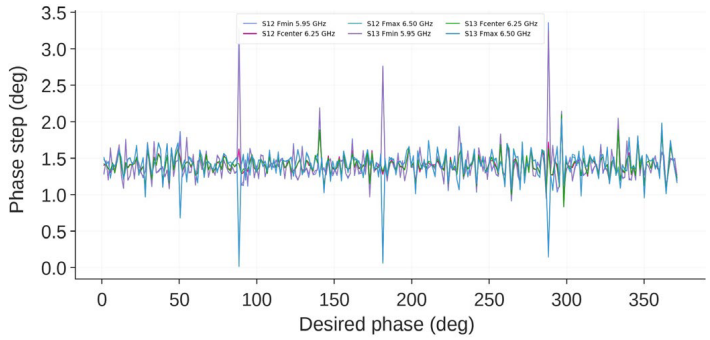


*Figure 47. Average step 1.406° (target 1.406°); minimum step 0.015°*

**Band 4: 6.55–7.1 GHz**

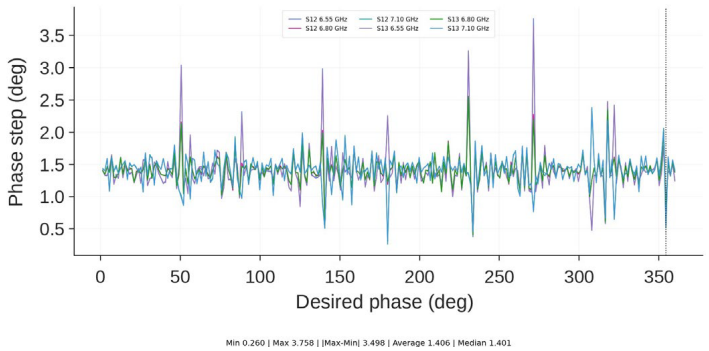


*Figure 48. Average step 1.406° (target 1.406°); minimum step 0.260°*

Figures 49 and 50 show the external LUT phase step size at 25 °C, 4.9–5.9 GHz, and 5.95–7.15 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Band 12: 4.9–5.9 GHz**

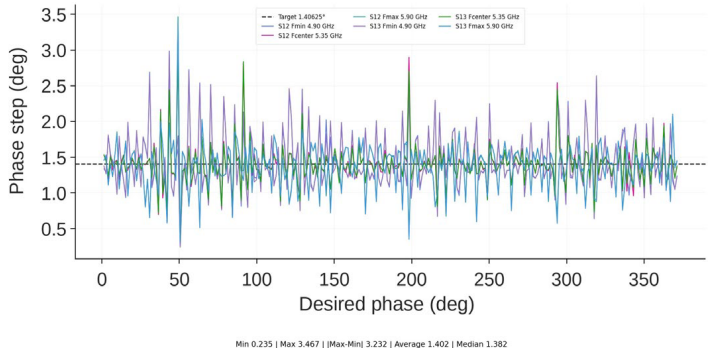


*Figure 49. Average step 1.402° (target 1.406°); minimum step 0.235°*

**Band 34: 5.95–7.15 GHz**

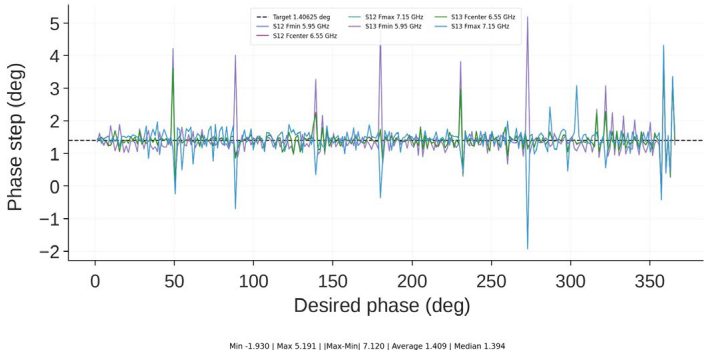


*Figure 50. Average step 1.409° (target 1.406°); minimum step −1.930° (non-monotonic step present)*

Figure 51 shows the external LUT phase step size at 25 °C, Full band: 4.9–7.15 GHz. S12 and S13 traces at $F_{MIN}$, $F_{CENTER}$, and $F_{MAX}$. SN13/SN1_3, 25 °C, TF-TAWS LUT.

**Full band: 4.9–7.15 GHz**

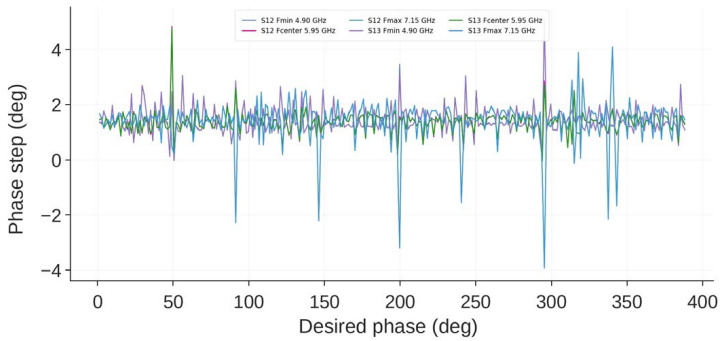


*Figure 51. Average step 1.397° (target 1.406°); minimum step −3.937° (non-monotonic step present)*

## Change in group delay vs. target phase

Figures 52 and 53 show the external LUT change in group delay vs. the target phase: ΔGD = GD(target phase) − GD(0° entry), S12; S13 tracks within ~3 ps.

### Narrow-band LUTs

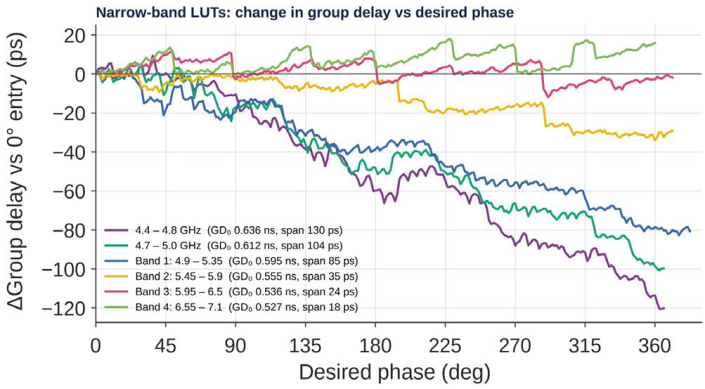


*Figure 52. Narrow-band LUTs*

### Combined and full-band LUTs

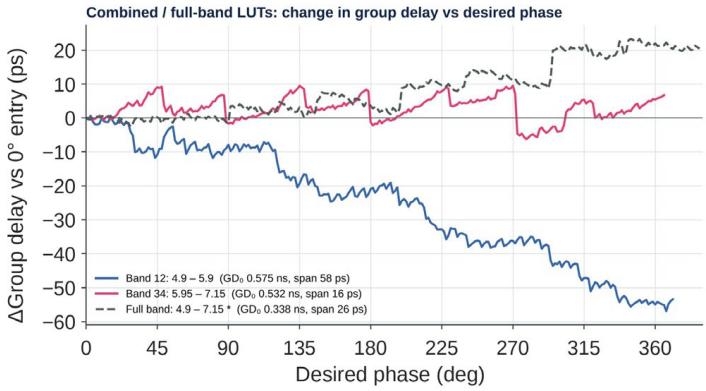


*Figure 53. Combined and full-band LUTs*

$GD_0$ is the absolute group delay at the 0° entry; span = max−min across the LUT. Narrow bands show the smallest group-delay change over the full phase range (Band 4: 18 ps, Band 3: 24 ps); the lowest bands and Band 12 show a steady decrease as phase increases (up to 130 ps at 4.4–4.8 GHz).

Curves digitized from the per-band LUT report plots and calibrated to each report's group-delay min/max. Full-band group delay is reported as negative in its source data; magnitude shown.

# Band plans and applications

## RF band and sub-band tree for the 4.4–5.925 GHz band

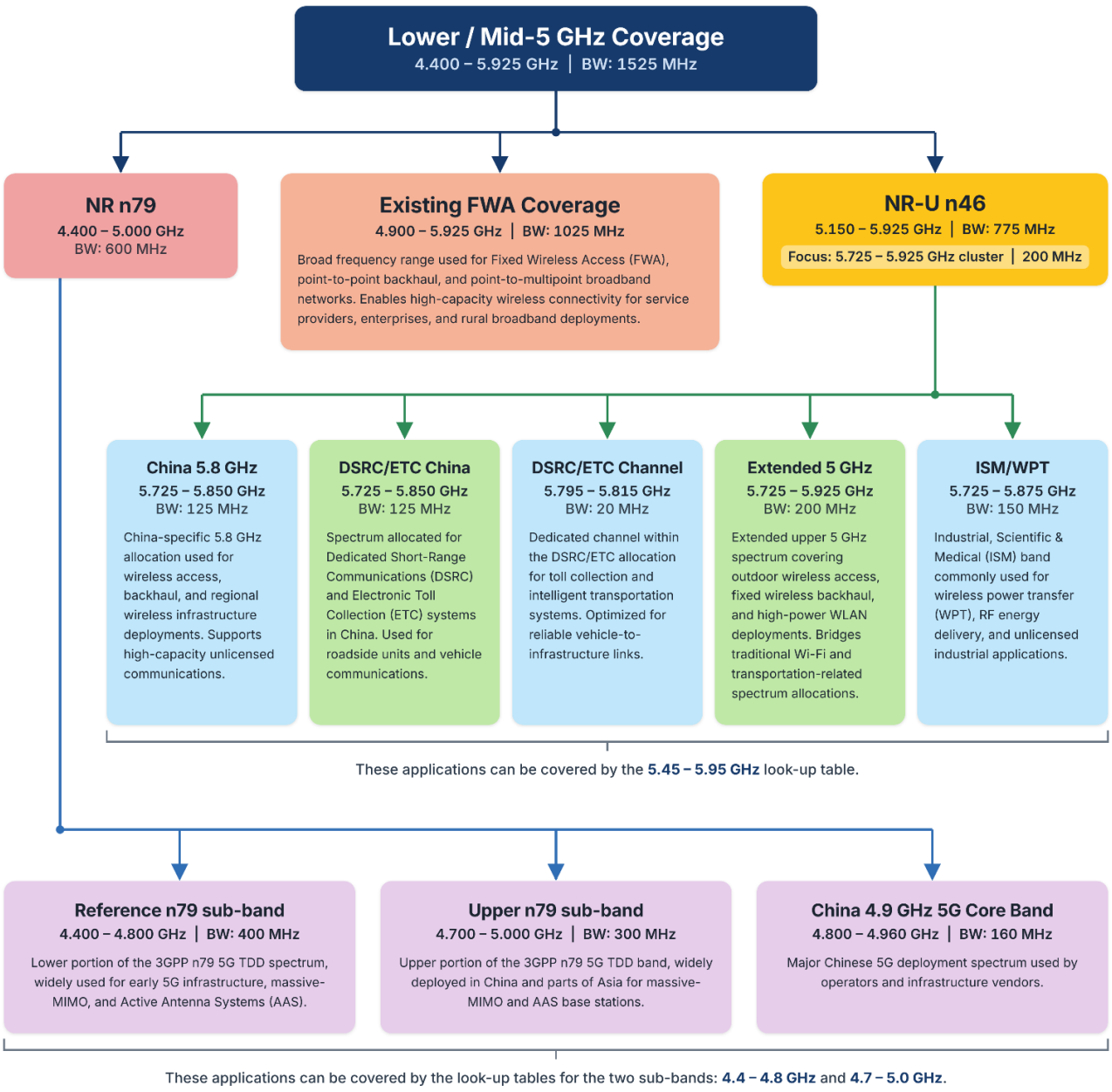


*Figure 54. RF band and sub-band tree, 4.4–5.925 GHz (lower/mid-5-GHz coverage) and the PE44951 LUTs that cover each application*

- NR n79 applications (reference n79 sub-band 4.4–4.8 GHz, 3GPP NR n79 4.7–5.0 GHz, China 4.9 GHz 5G core band 4.8–4.96 GHz) are covered by the look-up tables provided for the two sub-bands, 4.4–4.8 GHz and 4.7–5.0 GHz.
- The 5.725–5.925 GHz applications (China 5.8 GHz, DSRC/ETC, extended 5 GHz, ISM/WPT) are covered by the 5.45–5.95 GHz look-up table.

## RF band and sub-band tree (6G and beyond): 5.925–9.5 GHz

Some of these sub-bands are already covered by PE44951 internal or external look-up tables. pSemi can provide look-up tables for the remaining sub-bands up to 8.5 GHz, as needed.

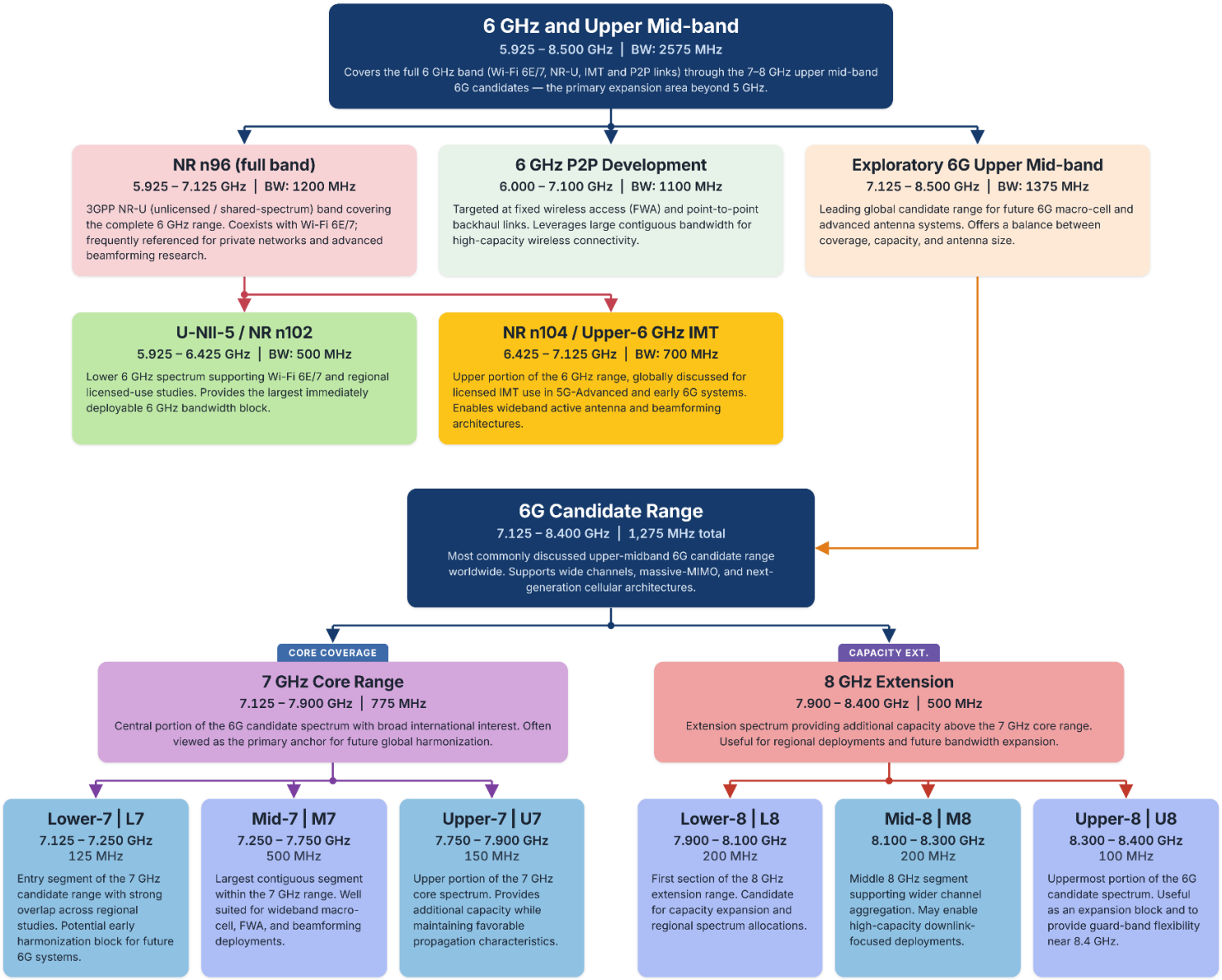


*Figure 55. RF band and sub-band tree (6G and beyond), 5.925–9.5 GHz*

# Array calibration with external LUTs

The host adds steering and calibration in the phase domain, then applies the external LUT for every channel.

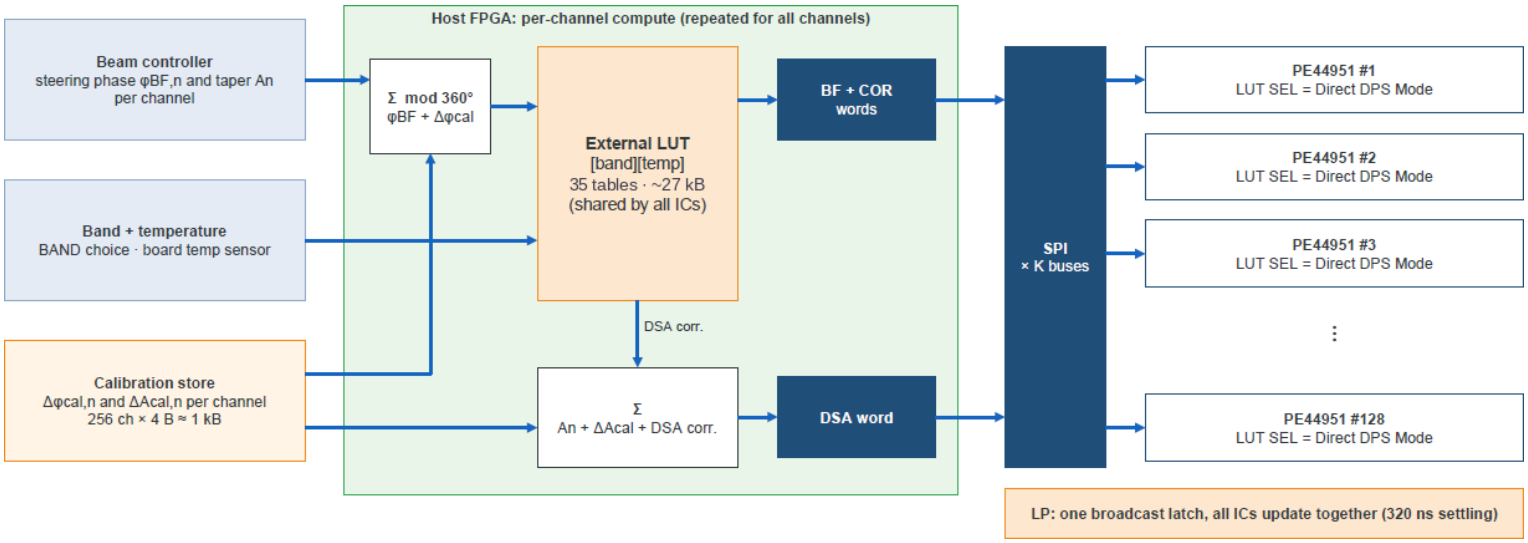


*Figure 56. Array calibration with external LUTs: Per-channel compute in the host FPGA, SPI fan-out to all devices, and one broadcast LP latch (320 ns settling)*

## How array calibration with external LUTs works

In a phased array, every antenna element needs its own phase setting, so the signals add up in the chosen beam direction. For example, to point a beam 20° off center at 7 GHz with λ/2 spacing, each element needs about 62° more phase than its neighbor. A real board does not deliver exactly what is commanded, though, and it causes two kinds of errors. First, every channel has its own fixed phase and gain offset, from differences in PCB trace length, connectors and part-to-part variation, often ±10–30° and ±1 dB. Second, the phase shifter itself is imperfect: each of its states has a slightly different loss and a phase that is not exactly the ideal step, and both change with frequency band and temperature. If neither is corrected, the beam points slightly wrong, loses gain, and has higher sidelobes. The external look-up table (LUT) corrects the phase-shifter errors, and calibration corrects the channel offsets.

The host FPGA repeats the same few steps for every channel and every beam. It takes the steering phase the beam needs (φBF,n), adds that channel's stored calibration offset (Δφcal,n), and wraps the sum into 0–360°. It then looks up that phase in the LUT for the current band and board temperature. The LUT row says which BF and COR words actually produce that phase on the device, and which DSA correction keeps the gain flat for that state. The DSA word sent to the device is the sum of three parts: the intended amplitude taper (An), the channel's gain correction (ΔAcal,n), and the LUT's DSA correction, clipped to the DSA range. The host writes these words to every device over SPI, then sends one broadcast LP pulse so that all devices change at the same instant and no partial beam is ever transmitted.

Calibration is done with the LUT already active, for one reason. With the LUT in place, every phase state of a channel behaves the same, so one phase offset and one gain offset per channel are valid for all beams. Without the LUT, a channel's error would be different in every state (up to ~17° on measured parts), and a single calibration number would be wrong as soon as the beam moved. The calibration is therefore simple: set every channel to the same reference (0° phase, reference DSA), measure each one with a near-field probe, a far-field range, or a built-in coupler, and store the difference. The stored phase offset is the reference minus the measured phase. The stored gain offset is how much stronger the channel is than the weakest one, applied as extra attenuation. Calibration is done once per band. When the temperature changes, the host only switches to the LUT for that temperature; no recalibration is needed.

## Using direct mode for array calibration

Bring-up once, calibrate once per band, then run the beam-update loop.

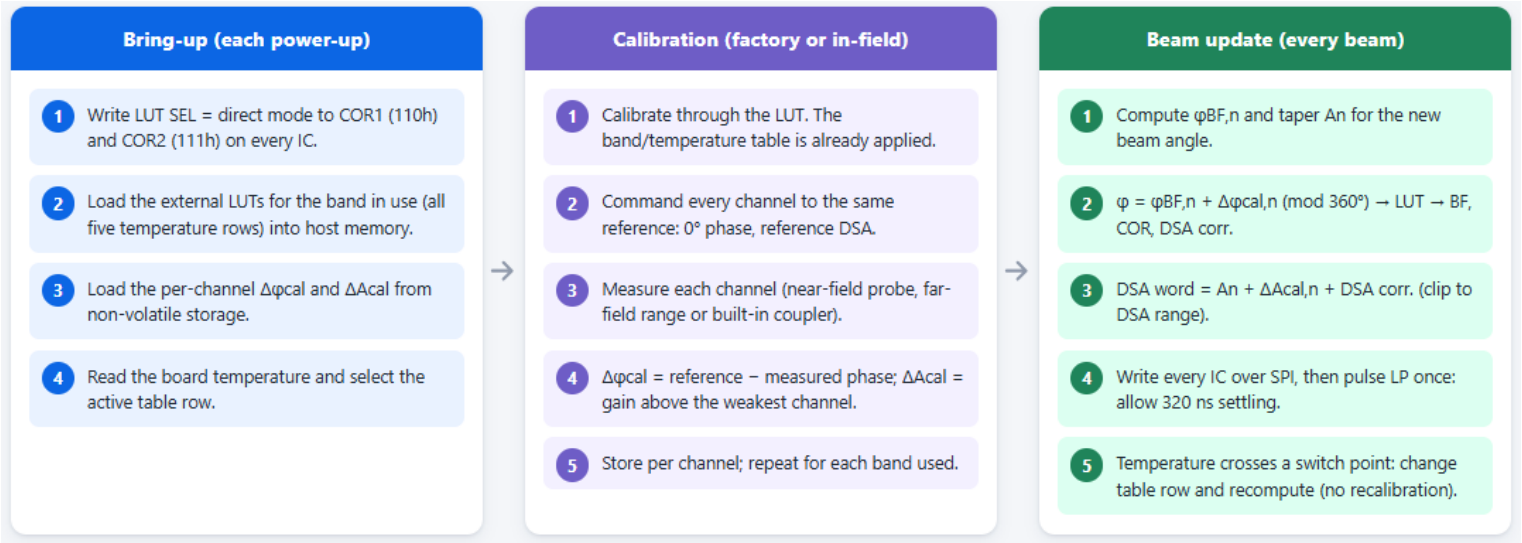


*Figure 57. Array calibration procedure using direct mode*

## Flattening insertion loss across phase states

Each external LUT entry pairs a phase setting with a DSA setting.

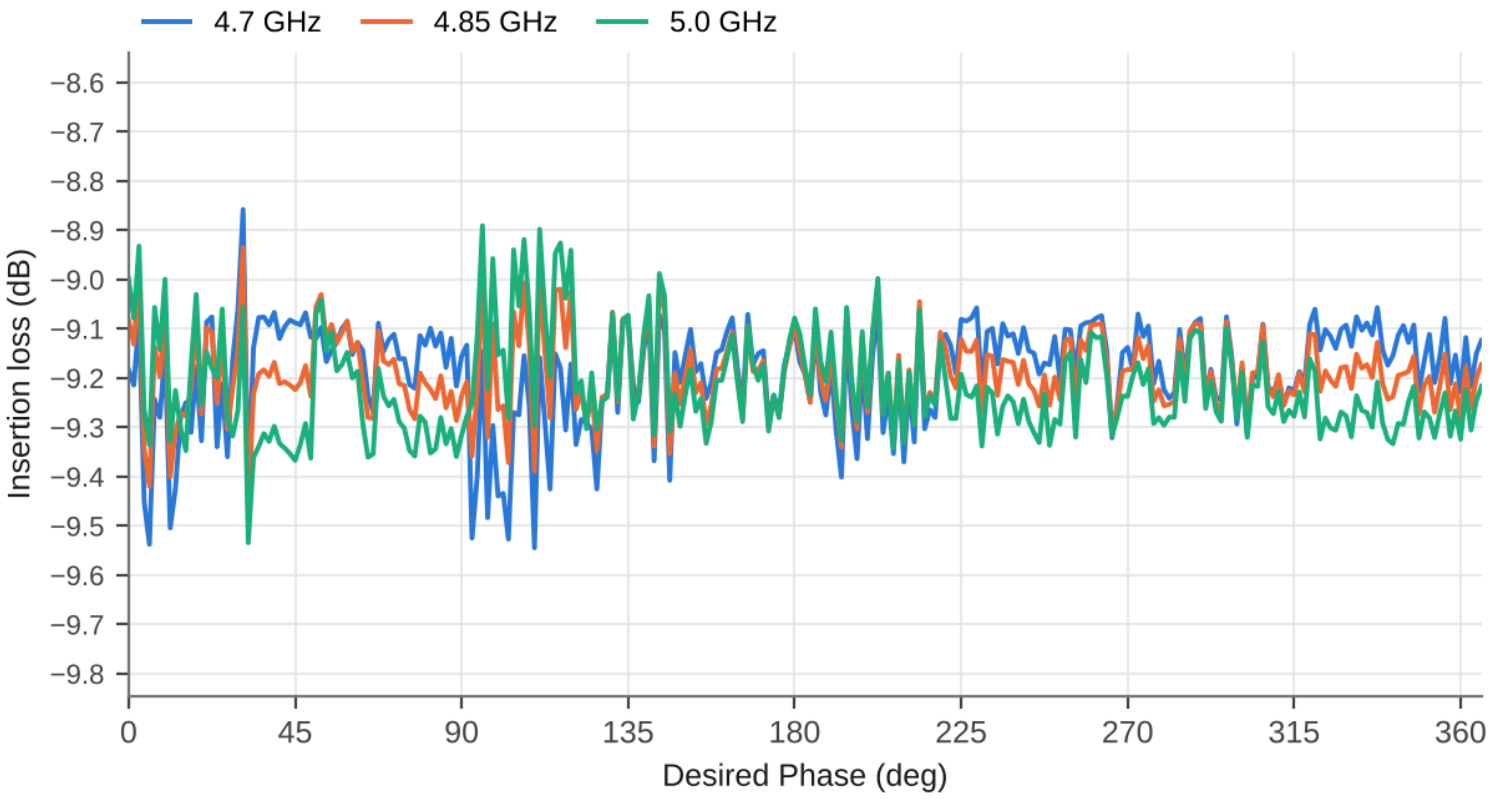


*Figure 58. Measured insertion loss vs. target phase, 4.7–5.0 GHz LUT (RFB): Insertion loss held within 0.69 dB p-p across all 261 phase states*

- Each DPS state has a slightly different insertion loss; uncorrected, amplitude changes as the beam steers and sidelobes rise.
- Each LUT entry chooses BF + COR for phase and a DSA setting that keeps the amplitude inside a set window.
- A tighter window provides flatter amplitude: 1.90 dB p-p with a 1.5 dB window (4.4–4.8 GHz) vs. 0.69 dB p-p with a 0.5 dB window (4.7–5.0 GHz).
- The phase and DSA are chosen together, so the DSA setting's own phase shift is already included.

DSA written to the device = taper An + calibration ΔAcal,n + LUT DSA (phase state).

## Calibration options with external LUTs

Table 8. Calibration options with external LUTs (example: 128 ICs = 256 channels)

| Option | Bands | Where calibration and steering are combined | Phase/amplitude accuracy | SPI traffic per beam | Host storage |
|---|---|---|---|---|---|
| Internal LUT mode (on-chip AC+BF adder) | 6.1–7.55 GHz only | On chip, before the internal LUT | Good: LUT corrects the summed state | BF word per IC (steering differs per element) + one LP latch | Calibration held in chip registers |
| Direct mode, host computes (recommended) | Any band or temperature | Host FPGA, in the phase domain, before the external LUT | Good: same as internal LUT | Full words to every IC (3 × 24 = 72 bits): ~184 µs on 1 SPI bus, ~23 µs on 8 buses | ~1 kB calibration + ~27 kB LUTs (~3.5 MB if per-IC LUTs) |
| Direct mode, precomputed beam tables | Any band or temperature | Offline, stored per beam | Good | Same writes, no compute latency | ~74 kB for 64 beams |

Assumptions: 72 bits per device per beam update (three 24-bit frames: BF, COR, DSA) at 50 MHz SPI; each table ≈ 261 entries (257–277 depending on the band, slightly beyond 360°) × ~19-bit word stored in 3 bytes ≈ 0.8 kB, so 35 tables ≈ 27 kB; precomputed beams: 128 ICs × 9 bytes = 1.15 kB per beam. Broadcasting one identical BF word to every device only steers to boresight: any steered beam needs a different phase per element.

## Beam update time and calibration options

### Why each beam takes time to load, and how long it takes

To steer a beam, every antenna element needs a different phase, so every PE44951 must get its own settings each time the beam moves. In external LUT (direct) mode the host computes three values per channel: the phase word (BF), the fine-trim word (COR) and the attenuator word (DSA). It sends them over SPI as three 24-bit frames per IC. Each frame carries the same register for both channels, so one frame covers BF1 and BF2, the next COR1 and COR2, and the last DSA1 and DSA2. That is 72 bits per IC. At a 50 MHz SPI clock, one bit takes 20 ns, so one IC takes 72 × 20 ns = 1.44 µs. The time grows with the number of ICs: 128 ICs (256 channels) take 128 × 1.44 µs ≈ 184 µs on one SPI bus. Loading new words does not change the RF output yet. The ICs only switch when the host sends one LP (latch) pulse to all of them, so the whole array moves to the new beam at the same instant after about 320 ns of settling. You never transmit a half-old, half-new beam.

### How to make it faster

The SPI clock is fixed, so the practical way to speed up beam changes is to split the devices across several SPI buses that load in parallel. With eight buses, each bus loads only 16 of the 128 devices, so the time drops from 184 µs to about 23 µs (roughly 43,000 beam changes per second instead of ~5,400). A good habit is to load the next beam's words while the current beam is still transmitting, then latch at the moment you want to switch. The times in Table 10 count only the clock bits. Allow about 5–10 % extra for the chip-select gaps between frames.

### Which calibration option to choose in Table 8

The three options differ in where the beam-steering and calibration numbers are combined:

- Internal LUT mode: the device does the addition itself and needs only one frame per device (about 61 µs for 128 devices on one bus). It covers only 6.1–7.55 GHz.
- Direct mode with the host computing (recommended): works for any band and temperature. The host adds the steering phase and calibration offset, looks up the external LUT, and sends the full three frames. It costs more SPI time but provides the same accuracy.
- Precomputed beam tables: the host calculates every beam's words in advance and stores them. Beam changes then involve no calculation at all—only the SPI write—at the cost of memory for each stored beam.

In every option, each element must receive its own phase. Sending the same BF word to every device only points the beam straight ahead.

## Beam-steering update time in external LUT mode

### SPI writes per PE44951 for one beam

A 24-bit SPI frame writes the same register on both channels.




*Figure 59. 24-bit SPI frame*

Table 9. SPI frames written per PE44951 for one beam

| Frame | Registers | Contents |
|---|---|---|
| 1 | BF1 + BF2 | 8-bit DPS word |
| 2 | COR1 + COR2 | 2.8°/1.4°/0.7° trims (keep LUT SEL = 5) |
| 3 | DSA1 + DSA2 | Taper + cal + LUT DSA correction |

- Per IC: 3 frames × 24 bits = 72 bits → 1.44 µs at 50 MHz.
- Per beam: 3 × N frames, then one LP pulse latches all devices (320 ns settling).

### Time per beam update at 50 MHz SPI

Table 10 lists the bit-clock time to update every device for one beam.

Table 10. Time per beam update at 50 MHz SPI

| ICs (channels) | SPI frames | Bits | 1 bus | 4 buses | 8 buses |
|---|---|---|---|---|---|
| 8 (16) | 24 | 576 | 11.5 µs | 2.9 µs | 1.4 µs |
| 32 (64) | 96 | 2,304 | 46.1 µs | 11.5 µs | 5.8 µs |
| 64 (128) | 192 | 4,608 | 92.2 µs | 23.0 µs | 11.5 µs |
| 128 (256) | 384 | 9,216 | 184.3 µs | 46.1 µs | 23.0 µs |
| +320 ns settling after LP. 128 devices: ~5,400 beams/s on 1 bus, ~43,000 beams/s on 8 buses. Bit-clock time only; allow ~5–10% for chip-select gaps between frames. Internal LUT mode (6.1–7.55 GHz only) needs 1 frame per IC: ~61 µs for 128 devices on 1 bus. | | | | | |

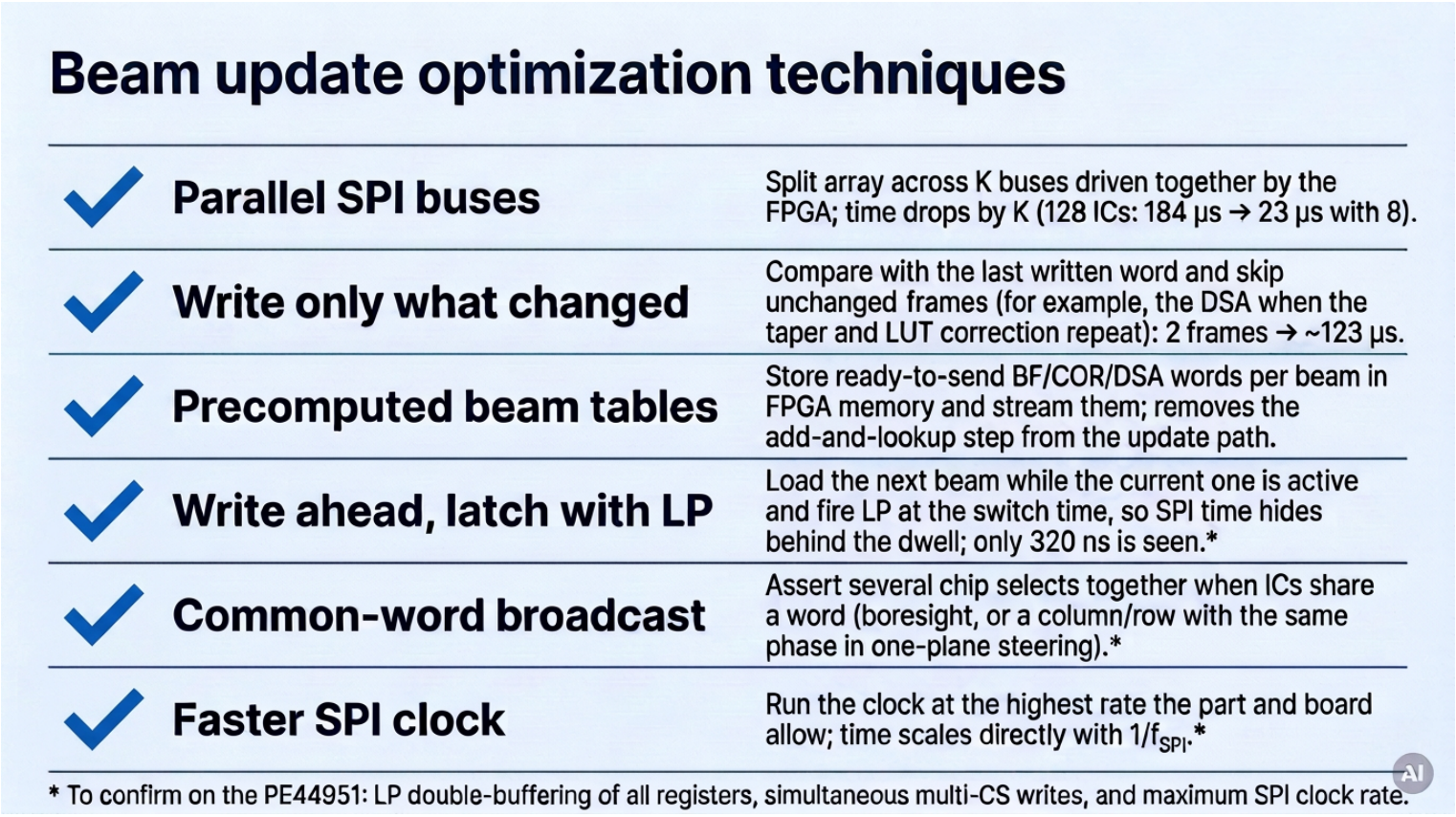


*Figure 60. Speed up beam updates in external LUT mode*

# Temperature-compensated LUTs and direct mode

## Temperature-compensated look-up tables

pSemi can provide an external table per band at five temperatures. The host selects the table by the measured board temperature, with switch points at the midpoints between tables.

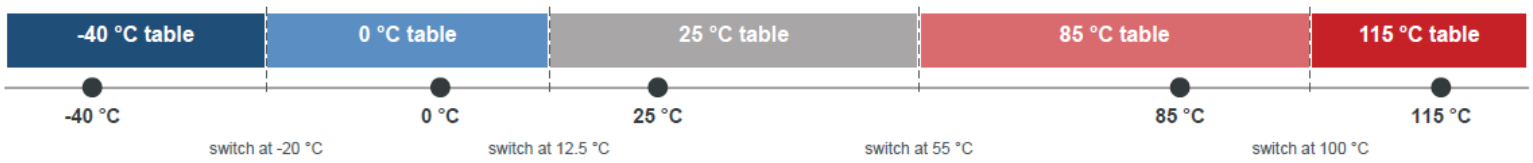


*Figure 61. Table selection by measured board temperature (switch points at the midpoints between tables)*

**How it works**

- The DPS and DSA phase and amplitude drift with temperature, so a table built at 25 °C loses accuracy at the extremes.
- pSemi supplies tables at −40, 0, 25, 85, and 115 °C for each band: 7 bands × 5 temperatures = 35 tables.
- The host reads a board temperature sensor and loads the table for that temperature range, or interpolates between the two nearest tables

**Implementation notes**

- Add a few °C of hysteresis around each switch point so that the table does not toggle on sensor noise.
- Reload the table only when the temperature range changes; beam updates still use the same SPI writes.
- Temperature compensation is done entirely in the host software and tables.

## Direct mode: External multiband + temperature LUTs

In direct DPS mode (LUT SEL = direct DPS mode on every IC), the host holds the external tables for every band and temperature and writes the selected entry to the PE44951 over SPI.

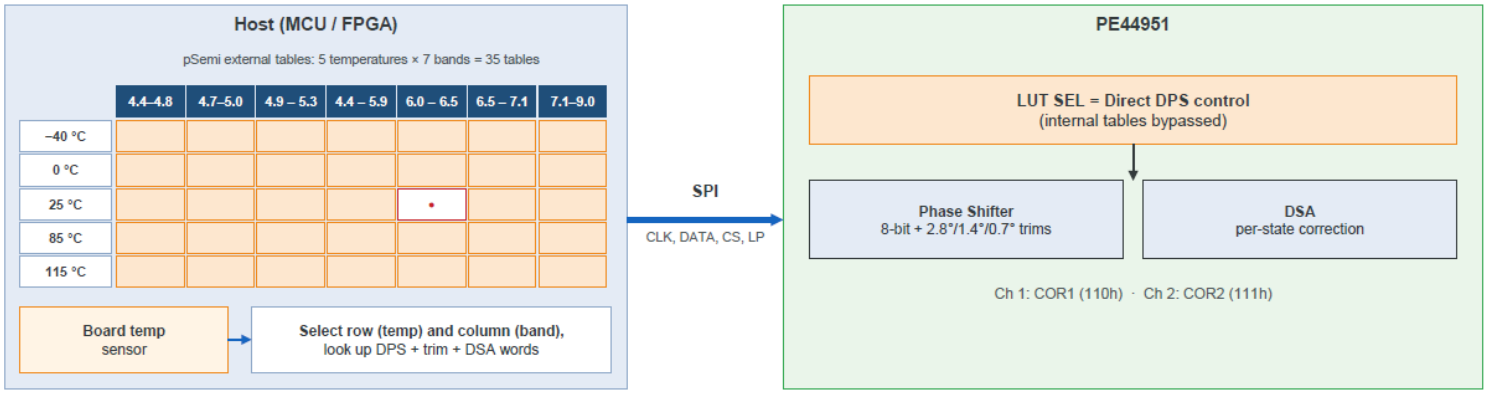


*Figure 62. Direct mode with external multiband and temperature LUTs: Host table store (5 temperatures × 7 bands = 35 tables) and PE44951 in direct DPS control*

### What it provides

- Any band set by the PCB matching, at each of the five temperatures.
- Tables can be updated in software, such as for new sub-band plans.

### What it costs

- The host stores the tables and requires a board temperature sensor.
- Every beam update writes the full DPS + trim + DSA setting over SPI.

## Conclusion

A single PE44951 covers from 4.4 GHz to beyond 8.5 GHz by retuning its RF ports with a few passive components per band and controlling it in direct DPS mode from a band-specific external look-up table. Each table entry sets phase (BF + COR) and amplitude (DSA) together, which keeps the phase error, phase step, and insertion-loss variation small across all phase states. Narrower sub-band tables tighten these further. Temperature-compensated tables, per-channel calibration in the phase domain, and the SPI update-time guidance described in this application note let the same flow scale to large, phased arrays and radar systems.

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