# Multi-Frequency Range and Tunable DCO on MSP432P4xx Microcontrollers

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**ABSTRACT**

Many families of the ultra-low-power MSP microcontrollers use a DCO-based system to generate an internal high-frequency source for the Clock System. In the earlier implementations found on some MSP430 families, the DCO is calibrated only for a few common clock frequencies over the full operating frequency range. This might not provide sufficient clock flexibility for certain applications with nonstandard but stringent clock requirements. Some more flexible DCO variants such as on MSP430F2xx families offer some calibration capability to tune to a frequency different from the preset ones. But it is a big challenge to meet this requirement without losing the DCO clock accuracy, and the calibration procedure needs to be done at production which can be costly both in resources and test time. Inability to easily tune to any desirable frequency is the main drawback of the traditional DCO approach when compared to an FLL-based approach. Taking the best of both worlds to combine the benefits of traditional DCO and FLL, the DCO on MSP432P4xx family of devices offers features like multiple frequency ranges and frequency tuning that meet the diverse clocking requirements of application without losing the clock accuracy.

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## 1 Comparison between DCO and FLL

The DCO used on MSP430 family of devices is factory calibrated to only a few common frequencies that may not take care of diverse clock frequency requirements by the application. Also it could be challenging to get the desired clock accuracy even when the DCO is calibrated to the target frequency by the application. The DCO clock frequency drifts significantly with change in temperature and supply voltage but the DCO clock will have low clock jitter.

The FLL used on MSP430 family of devices on the other hand offers flexibility to achieve any desired frequency over the full operating frequency range but will have significant clock cycle to cycle period jitter. Since the FLL is a self-regulating frequency loop based on the accurate reference clock its output is stable and tolerant to any change in temperature or supply voltage.

The DCO available on MSP432P4xx family of devices combines the best of both worlds and offers accurate clock through tuning the DCO to any desired frequency over the entire 1-48MHz operating frequency range. This DCO also shows very low clock jitter and very low clock frequency drift upon varying temperature or supply voltage conditions in the application.

## 2 Overview of DCO on MSP432P4xx Microcontrollers

DCO stands for Digitally Controlled Oscillator. It is an R-C type internal oscillator that can operate with an internal or external resistor. The maximum operating frequency of MSP432P4xx family of devices is 48 MHz. The DCO on MSP432P4xx family of devices can generate clock frequencies in the range of 0.98 MHz to 52 MHz. This full range is divided into six individual frequency ranges, and the DCO is factory calibrated to the center value of each of these frequency ranges. It is possible to tune the DCO to achieve a frequency that is different than the center frequency in any of the frequency ranges. Figure 1 shows the high-level functional block diagram of the DCO, and the following sections explain the different features of the DCO.

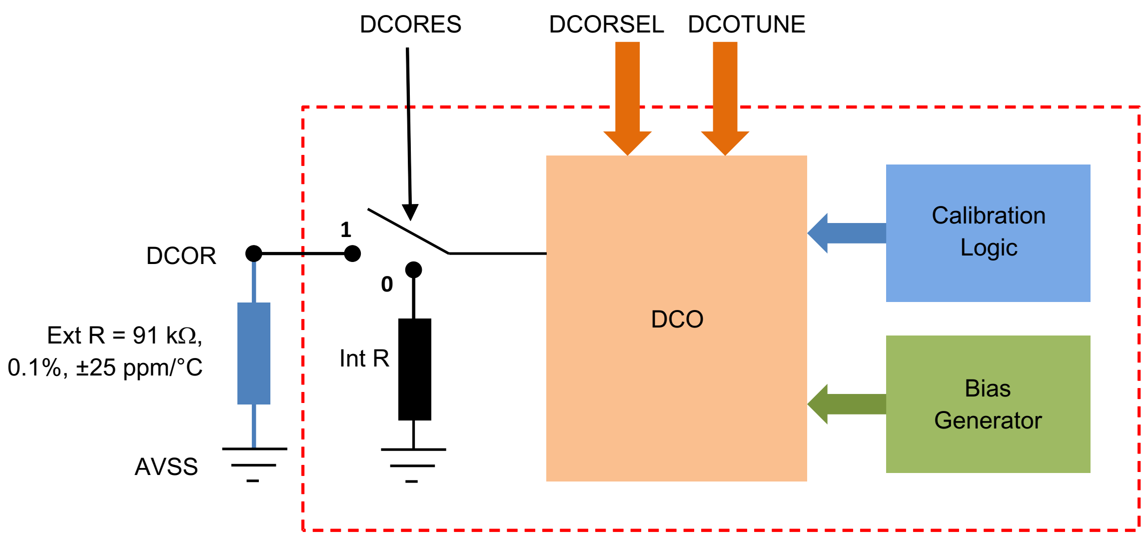


**Figure 1. DCO High-Level Functional Block Diagram**

## 3 DCO Operating Modes

The DCO can be configured to operate either in Internal Resistor mode or in External Resistor mode. This configuration is selected through DCORES bit in CSCTL0 register of the Clock System. After power up or any hard reset the DCO is configured by default in Internal Resistor mode. In Internal Resistor mode, the DCO operates based on a resistor that is implemented internal to the microcontroller. No external components are required to operate the DCO in Internal Resistor mode.

The DCO can be configured in External Resistor mode by programming DCORES bit to 1. The application must change the DCO configuration between Internal Resistor and External Resistor modes only when the DCO is in the default frequency range (DCORSEL = 1). It is necessary to have a 91-kΩ, 0.1%, ±25-ppm/°C resistor connected at the DCOR pin to AVSS of the microcontroller to operate the DCO in External Resistor mode.

The DCO clock stability is high during temperature variations when the DCO operates in External Resistor mode as compared to Internal Resistor mode. The maximum DCO clock frequency drift with temperature in External Resistor mode is ±35 ppm/°C and for Internal Resistor mode is ±250 ppm/°C. Therefore, it is recommended to use the DCO in External Resistor mode for embedded applications that operate under varying temperature conditions. Refer to the DCO electrical specification in the device-specific data sheet for all DCO performance parameters.

## 4 DCO Faults in External Resistor Mode

There can be certain types of faults when DCO operates in the external resistor mode. Open circuit fault is the one in which the external resistor gets detached from the DCOR pin of the device and the DCOR pin is left open. Short circuit fault is the one in which the DCOR pin comes in contact or shorted with the ground supply. Static fault means the DCO encounters open circuit or short circuit fault at the time of switching into external resistor mode. Dynamic fault means the DCO encounters open circuit or short circuit fault while already operating in the external resistor mode.

When there is any static or dynamic, open circuit or short circuit fault detected by the DCO it switches to internal resistor mode as a fail-safe mechanism to keep the system operations alive. The DCO clock frequency settings will be retained during the fail-safe mode of operation. This means the DCO clock frequency with internal resistor mode during fail-safe operation will be same as the DCO clock frequency in external resistor mode prior to fault detection.

## 5 DCO Frequency Ranges

The DCO can generate clock frequencies in the range of 0.98 MHz to 52 MHz. This full frequency range is divided into six individual frequency ranges represented by DCORSEL setting in CSCTL0 register of the Clock System (CS). DCORSEL0 implies that DCO is configured in frequency range 0 and DCORSEL5 implies that DCO is configured in frequency range 5. Each frequency range overlaps with its adjacent frequency ranges thereby constructing one solid continuous range of frequencies from 1MHz to 48MHz available for use in the application.

Table 1 lists the minimum and maximum frequencies attainable in each of the DCO frequency ranges over the full supply voltage and temperature range.

**Table 1. DCO Frequency Ranges**

| PARAMETER | | TEST CONDITIONS | MIN | MAX | UNIT |
|---|---|---|---|---|---|
| $f_{RSEL0}$ | DCO Frequency Range 0 | DCORSEL = 0 | 0.98 | 2.26 | MHz |
| $f_{RSEL1}$ | DCO Frequency Range 1 | DCORSEL = 1 | 1.96 | 4.51 | MHz |
| $f_{RSEL2}$ | DCO Frequency Range 2 | DCORSEL = 2 | 3.92 | 9.02 | MHz |
| $f_{RSEL3}$ | DCO Frequency Range 3 | DCORSEL = 3 | 7.84 | 18.04 | MHz |
| $f_{RSEL4}$ | DCO Frequency Range 4 | DCORSEL = 4 | 15.68 | 36.07 | MHz |
| $f_{RSEL5}$ | DCO Frequency Range 5 | DCORSEL = 5 | 31.36 | 52 | MHz |

From the values in Table 1, it can be observed that the maximum frequency for each frequency range has 15% overlap with the minimum frequency in the next higher frequency range. For example, the maximum frequency of 2.26 MHz in DCORSEL0 has 15% overlap with the minimum frequency of 1.96 MHz in DCORSEL1.

## 6 DCO Calibrated Frequencies

The DCO is factory calibrated to the center value of each of the frequency ranges when DCOTUNE is 0. The calibrated center frequency tolerance is ±0.5% at 3 V and 25°C conditions for both DCO internal and external resistor modes. Table 2 lists the calibrated frequency and tolerance details for each of the DCO frequency ranges.

**Table 2. DCO Calibrated Frequency and Tolerance**

| PARAMETER | | TEST CONDITIONS | MIN | TYP | MAX | UNIT |
|---|---|---|---|---|---|---|
| $f_{RSEL0\_CTR}$ | Center Frequency for DCORSEL0 | DCORES = 0 or 1, DCORSEL = 0, DCOTUNE = 0 | 1.492 | 1.5 | 1.508 | MHz |
| $f_{RSEL1\_CTR}$ | Center Frequency for DCORSEL1 | DCORES = 0 or 1, DCORSEL = 1, DCOTUNE = 0 | 2.985 | 3 | 3.015 | MHz |
| $f_{RSEL2\_CTR}$ | Center Frequency for DCORSEL2 | DCORES = 0 or 1,DCORSEL = 2, DCOTUNE = 0 | 5.97 | 6 | 6.03 | MHz |
| $f_{RSEL3\_CTR}$ | Center Frequency for DCORSEL3 | DCORES = 0 or 1, DCORSEL = 3, DCOTUNE = 0 | 11.94 | 12 | 12.06 | MHz |
| $f_{RSEL4\_CTR}$ | Center Frequency for DCORSEL4 | DCORES = 0 or 1, DCORSEL = 4, DCOTUNE = 0 | 23.88 | 24 | 24.12 | MHz |
| $f_{RSEL5\_CTR}$ | Center Frequency for DCORSEL5 | DCORES = 0 or 1, DCORSEL = 5, DCOTUNE = 0 | 47.76 | 48 | 48.24 | MHz |

## 7 Tuning the DCO

The DCO can be adjusted or tuned to any specific frequency in a given frequency range through the use of DCOTUNE bits in CSCTL0 register of Clock System. DCOTUNE is a 13-bit register field and it is represented in two's complement form. DCOTUNE value is 0 after device power up or any hard reset.

When the DCOTUNE value is 0 the DCO frequency is at the center value of the selected frequency range. When DCOTUNE value is changed the DCO frequency moves up or down from the center frequency based on the sign of the DCOTUNE value. When DCOTUNE is a positive value the DCO frequency moves upwards from the center frequency. When the DCOTUNE is a negative value the DCO frequency moves downwards from the center frequency. The DCO clock period change for DCOTUNE variation by one step is 0.2% typical.

However, instead of tuning by varying the step count, refer to the next section on the tuning formula for the recommended and much easier method to tune the DCO to any desirable frequency.

### *7.1 Maximum Allowed DCO Tune Values*

It is not allowed to program the DCOTUNE register field up to the highest or down to the lowest values. The maximum allowed positive and negative tune values are identified on per device basis during production for the DCO in Internal and External Resistor modes and the same are recorded in the Device TLV. These maximum positive and negative DCOTUNE values correspond to the maximum and minimum frequencies for each of the DCO frequency ranges given in Table-1. Refer to the TLV in device-specific datasheet for maximum allowed DCO tune values. It is necessary not to violate the maximum allowed tune values while changing the DCO frequency for deterministic behavior.

The maximum allowed positive tune value for DCORSEL 0 to 4 in TLV implies that the DCOTUNE value programmed in the CSCTL0 register must not be higher than the value provided in TLV when the DCO frequency needs to be increased in any of the frequency ranges from DCORSEL0 to DCORSEL4.

The maximum allowed negative tune value for DCORSEL 0 to 4 in TLV implies that the DCOTUNE value programmed in the CSCTL0 register must not be lower than the value provided in TLV when the DCO frequency needs to be decreased in any of the frequency ranges from DCORSEL0 to DCORSEL4.

The maximum allowed positive and negative tune values are recorded separately for DCORSEL5. But the same guidelines apply when the DCO frequency is to be increased or decreased than the center frequency in DCORSEL5 setting. The above set of maximum allowed tune values is available for DCO Internal and External Resistor modes separately in the Device TLV. Refer to TLV section in the device-specific data sheet for complete details.

### 7.2 Changing DCO Frequency

The DCO frequency characteristic is given in Equation 1.

$$F_{DCO,nom} = \frac{F_{RSELx\_CTR,nom}}{1 - \dfrac{K_{DCOCONST} \times N_{DCOTUNE}}{8 \times \left(1 + K_{DCOCONST} \times \left(768 - F_{CALCSDCOxRCAL}\right)\right)}} \tag{1}$$

The same equation can be represented for DCO tune value as Equation 2.

$$N_{DCOTUNE} = \frac{\left(F_{DCO,nom} - F_{RSELx\_CTR,nom}\right) \times \left(1 + K_{DCOCONST} \times \left(768 - FCAL_{CSDCOxRCAL}\right)\right) \times 8}{F_{DCO,nom} \times K_{DCOCONST}}$$

where

- $F_{DCO,nom}$ = Target Nominal Frequency
- $F_{RSELx\_CTR,nom}$ = Calibrated Nominal Center Frequency for DCO Frequency Range x
- $K_{DCOCONST}$ = DCO Constant (Floating-point value)
- $N_{DCOTUNE}$ = DCO Tune value in decimal
- $FCAL_{CSDCOxRCAL}$ = DCO Frequency Calibration value for Range x for Internal or External Resistor modes (2)

The DCO frequency calibration value (FCAL) is available in TLV individually for DCO Internal and External Resistor modes. The DCO constant K is also available in TLV individually for frequency ranges DCORSEL 0 to 4 and DCORSEL 5 for Internal and External Resistor modes. Refer to TLV section in the device-specific data sheet for complete details.

To change the DCO nominal frequency to a target value $F_{DCO,nom}$, the DCO tune value N needs to be obtained from the above equation and rounded off to the nearest integer value. This value must be programmed into DCOTUNE field in the CSCTL0 register in twos-compliment form. The error in the DCO target nominal frequency after applying the DCO tune value obtained from the equation will always be less than one DCO tune step. This means the frequency error will be less than the change in frequency caused by varying the DCOTUNE value by one step.

The Driver Library offers intelligent API functions that can be used to calculate the DCO tune value and to set the DCO for the desired target frequency. When using the pre-calibrated frequencies (DCOTUNE = 0), the DriverLib API CS_setCenteredFrequency(value) can be used. On the other hand, to simply tune the DCO as close as possible to any frequency within the 1-48MHz range, the DriverLib API CS_setFrequency(value) can be used. The floating math required to determine the DCO frequency range and the DCOTUNE values leverages the MSP432's built-in floating point engine to efficiently calculate the values for the tuning procedure.

### 7.3 Example Use Case

The following example illustrates how to change the DCO frequency to 2-MHz from the calibrated center frequency of 1.5 MHz in the DCO frequency range 0 when the DCO operates in the Internal Resistor mode.

The following values are obtained from the device TLV.

DCO constant K for DCORSEL0-4 in Internal Resistor mode: 0x3BA2_0147 or 0.004944.

DCO frequency calibration value in Internal Resistor mode: 0x0000_0188 or 392.

DCO maximum allowed positive tune for DCORSEL0-4 in Internal Resistor mode: 0x0000_0600 or 1536

Applying the above values in the DCO tune equation:

$N_{DCOTUNE}$ = [(2 – 1.5) × (1 + 0.004944 × (768 – 392)) × 8] / (2 × 0.004944)

$N_{DCOTUNE}$ = 1156.53, which is rounded off to 1157 or 0x485

The calculated DCO tune value N is 0x485 which is smaller than the maximum allowed positive tune value of 0x600. This value needs to be programmed into the DCOTUNE field in CSCTL0 register to realize the desired target frequency of 2 MHz. Alternatively, one simple DriverLib API call, CS_setFrequency(2000000) would also accomplish every step of the procedure described in the example.

# 8 Summary

The DCO on MSP432P4xx family of devices offer several useful features like operation with internal or external resistor, multiple frequency ranges, and frequency tuning. Especially the frequency tuning feature of the DCO can be useful in embedded applications where nonstandard frequencies or frequencies different than preset calibration frequencies are necessary. The intelligent Driver Library API functions can be used for easy calculation of the DCO tune value to achieve the desired DCO target frequency.

# 9 References

1. *MSP432P4xx Technical Reference Manual* (SLAU356)
2. *MSP432P401xx Mixed-Signal Microcontrollers* (SLAS826)
3. *MSP432P401xx Driver Library:* www.ti.com/tool/mspdriverlib