designfeature *By A Fox, D Maxwell, and C O'Keeffe, Analog Devices*
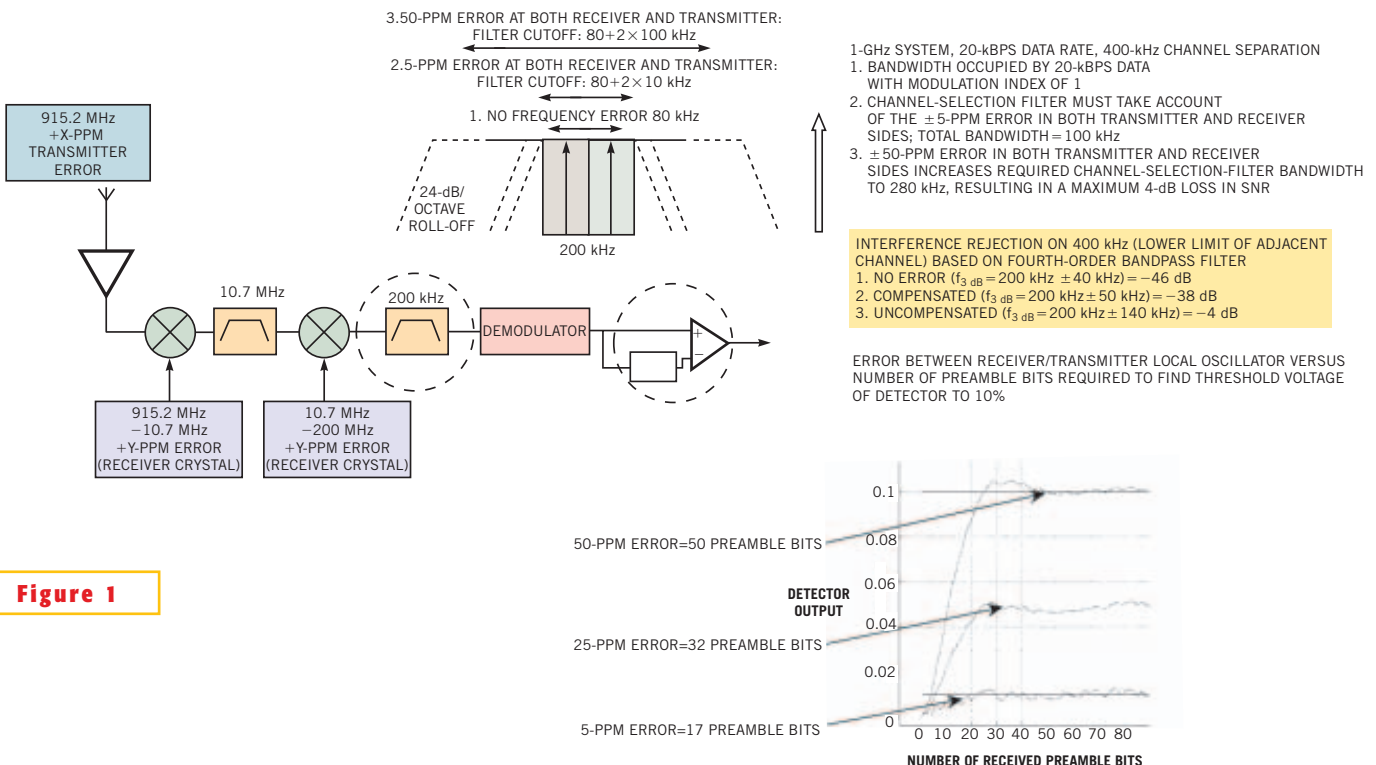
ADVANCES IN FRACTIONAL-N SYNTHESIS AND DIGITAL-
TEMPERATURE-SENSOR ACCURACY IMPROVE FREQUENCY
STABILITY FOR REFERENCE-FREQUENCY IMPLEMENTATIONS
AT A REDUCED COST AND CURRENT CONSUMPTION.

Fractional-N synthesis improves reference-frequency implementations

PLLs serve as programmable-frequency generators in a long list of RF applications, including cellular-phone base stations and handsets, cable-TV tuners, wireless-LANs, and low-power radios. The reference frequency is a critical element in these systems. It is multiplied up to the PLL RF output and is critical to the frequency accuracy, stability, and overall phase-noise performance of the loop.

Traditional frequency-reference implementations include large, power-hungry OCXOs (oven-controlled crystal oscillators), which base stations favor because of their excellent stability. Space- and power-conscious handset manufacturers use the heavily tested crystal/compensation-circuit combination of TCXOs (temperature-compensated crystal oscillators).

The availability of new ranges of fractional-N synthesizers with system spurious levels approaching those of integer-N PLLs offers an alternative for crystal and oscillator options (**Table 1**). Many fractional-N PLLs support resolution on the order of hundreds of hertz. (Integer-N technology supports the

3.50-PPM ERROR AT BOTH RECEIVER AND TRANSMITTER:
FILTER CUTOFF: 80+2×100 kHz

2.5-PPM ERROR AT BOTH RECEIVER AND TRANSMITTER:
FILTER CUTOFF: 80+2×10 kHz

1. NO FREQUENCY ERROR 80 kHz

24-dB/OCTAVE ROLL-OFF

200 kHz

915.2 MHz +X-PPM TRANSMITTER ERROR

10.7 MHz

200 kHz

DEMODULATOR

915.2 MHz −10.7 MHz +Y-PPM ERROR (RECEIVER CRYSTAL)

10.7 MHz −200 MHz +Y-PPM ERROR (RECEIVER CRYSTAL)

1-GHz SYSTEM, 20-kBPS DATA RATE, 400-kHz CHANNEL SEPARATION
1. BANDWIDTH OCCUPIED BY 20-kBPS DATA WITH MODULATION INDEX OF 1
2. CHANNEL-SELECTION FILTER MUST TAKE ACCOUNT OF THE ±5-PPM ERROR IN BOTH TRANSMITTER AND RECEIVER SIDES; TOTAL BANDWIDTH = 100 kHz
3. ±50-PPM ERROR IN BOTH TRANSMITTER AND RECEIVER SIDES INCREASES REQUIRED CHANNEL-SELECTION-FILTER BANDWIDTH TO 280 kHz, RESULTING IN A MAXIMUM 4-dB LOSS IN SNR

INTERFERENCE REJECTION ON 400 kHz (LOWER LIMIT OF ADJACENT CHANNEL) BASED ON FOURTH-ORDER BANDPASS FILTER
1. NO ERROR ($f_{3 dB}$ = 200 kHz ±40 kHz) = −46 dB
2. COMPENSATED ($f_{3 dB}$ = 200 kHz ±50 kHz) = −38 dB
3. UNCOMPENSATED ($f_{3 dB}$ = 200 kHz ±140 kHz) = −4 dB

ERROR BETWEEN RECEIVER/TRANSMITTER LOCAL OSCILLATOR VERSUS NUMBER OF PREAMBLE BITS REQUIRED TO FIND THRESHOLD VOLTAGE OF DETECTOR TO 10%

50-PPM ERROR=50 PREAMBLE BITS

DETECTOR OUTPUT

25-PPM ERROR=32 PREAMBLE BITS

5-PPM ERROR=17 PREAMBLE BITS

NUMBER OF RECEIVED PREAMBLE BITS

Figure 1

As the crystal reference generates larger frequency errors, receiver performance significantly degrades.

typical minimum of 25 kHz.) This programmable accuracy coupled with improving temperature-sensor technology and the availability of low-cost, predictable crystals allows designers of cost-sensitive RF-links to consider indirectly compensating for temperature effects.

SOURCES OF FREQUENCY ERROR

Temperature plays a major role in the frequency stability of a crystal (see **sidebar** "Quartz crystals and crystal oscilla-

tors"). However, temperature is not the only factor to consider when seeking a stable crystal. Other significant sources of frequency error include initial-crystal-frequency error, mismatching of load capacitance, and crystal aging.

Every quartz crystal has a significant initial frequency error associated with it. However, once the driving circuit makes the crystal oscillate with parallel capacitors, the initial frequency error often appears much larger. This situation is due

to a mismatch between the crystal's capacitance and the loading capacitors, which causes a shift in the resonance frequency. Because these two errors are constant over temperature, they can be combined and compensated for using an offset calibration at 25°C.

Over time, a crystal's frequency tends to change. This frequency error, or aging, generally occurs due to crystal contamination, excessive drive level, or both. The aging curve is logarithmic in nature, so

QUARTZ CRYSTALS AND CRYSTAL OSCILLATORS

Quartz crystals integrate mechanical and electrical characteristics described by the piezo-electric effect. This integration is the basis for using quartz in crystal manufacturing. Although natural crystals are abundant, they are likely to contain impurities. Alternatively, you can grow flawless synthetic crystals to specific shapes and sizes. Oscillator circuits using a quartz crystal vibrate at the crystal's resonant frequency. The resonant frequency depends on the thickness of the crystal slab; thinner slabs have a higher resonant frequency.

Exposing a quartz crystal to heat expands it, changing the shape and the resonant frequency of the crystal (**Figure A**). Different frequencies and temperature characteristics exist, depending on the way that the crystal is "cut" from the natural crystal.

AT and BT are the most common crystal cuts. BT cuts are

Figure A

Different frequencies and temperature characteristics exist for the AT, BT, and SC crystal cuts.

more often used in low-frequency crystals, whereas AT cuts are common in higher frequency crystals. Because the AT curve is cubic, it offers good temperature stability over the industrial temperature range (−40 to +85°C); however, the AT-cut temperature characteristics depend strongly on the angle deviation from the ideal AT cut. Another frequently used cut is the SC (stress-compensated) cut, which is more precise but deviates less over tem-

perature than the AT cut. A heat source is usually required to operate an SC-cut crystal at its optimum elevated temperature, making it a good candidate for OCXOs (oven-controlled crystal oscillators).

A stand-alone quartz crystal is not an oscillator. External circuitry must drive the quartz crystal to make it oscillate. Noncompensated crystal oscillators employ no correction or control to reduce the frequency variation over tem-

perature beyond the intrinsic crystal stability.

TCXOs (temperature-controlled crystal oscillators) typically consist of a varactor diode in series with a crystal. A thermistor network generates a correction voltage proportional to the frequency error. This correction voltage is usually applied to a varactor diode, altering its capacitance and resulting in a frequency shift approximately equal to and opposite from the frequency error due to temperature (**Figure B**). TCXO stability can approach 0.1 ppm (at a cost). TCXOs are preferable to oven oscillators in low-power applications and when a warm-up period is not applicable.

An OCXO consists of an insulated oven block that houses the quartz crystal, oscillator circuitry, a temperature sensor, and heating elements at a precise and constant elevated temperature. OCXOs allow the use of SC-cut crystals, which offer superior characteristics but are impractical for ordinary TCXOs due to their steep frequency drop at cooler temperatures. OCXOs provide significantly better temperature stability than TCXOs, but the power consumption is much higher—typically, 1 to 2W at 25°C. They also require a few minutes to warm up.

Figure B
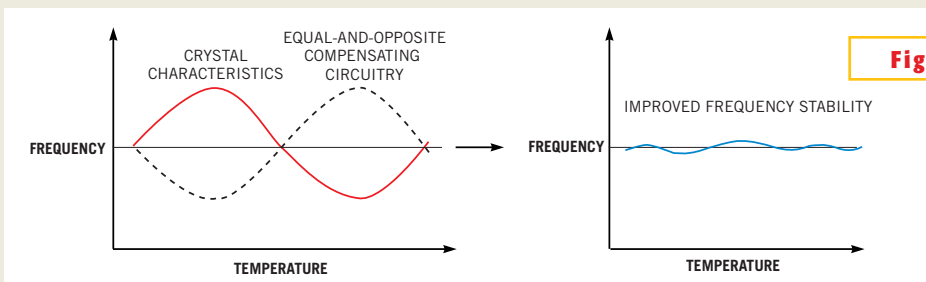
**Performing frequency compensation in TCXOs improves frequency stability.**

most of the frequency change occurs in the initial time stages. Crystals are usually preaged at high temperatures to help alleviate this initial steep frequency change. Aging is generally specified as X ppm in the first year and Y ppm/year after that.

The frequency alignment of the transmitter and receiver local oscillators is critical in designing a robust wireless-communication system. Large frequency errors impact the receiver SNR, adjacent-channel rejection, and required preamble length. Often, to compensate for the subsequent reduced sensitivity, a designer must select higher output power on the transmitting side and increased receiver sensitivity. Doing so, however, comes at a cost of higher current consumption to maintain the required link budget.

The data bandwidth, the deviation from the receiver local oscillator of the frequency tone, and the error in the transmitting/receiving crystal set the required bandwidth of the IF or the baseband filters (depending on the receiver architecture). For a low-data-rate system with a low modulation index, the error in the crystal becomes significant. For each doubling of the filter bandwidth, you lose as much as 3 dB of SNR. Reducing the modulation index can improve the SNR.

Controlling the frequency accuracy of both the transmitter and the receiver local oscillators allows more efficient use of available spectrum allocation. By restricting the error, you can place hopping channels in closer proximity and, therefore, use more channels. This higher channel density is particularly important in the congested, unlicensed ISM (industrial, scientific, and medical) bands. As well as reducing unwanted transmission to the adjacent channel, frequency compensation allows designers to reduce the IF-filter bandwidth, and thus achieve

Figure 2
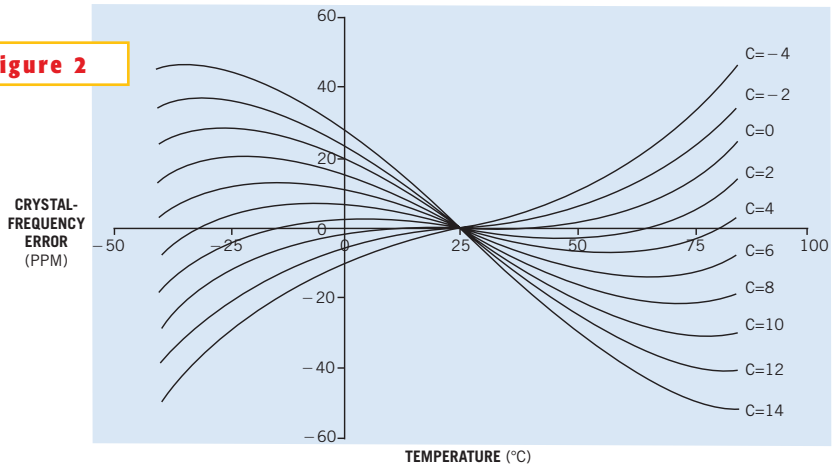
An uncompensated quartz crystal with various randomly chosen angles of cut cannot operate within the desired limits of ±5 ppm.

more attenuation of unwanted large signals in the next band.

The FSK (frequency-shift-keying) demodulator has time to acquire its required threshold voltage during the preamble sequence. The frequency error directly affects the length of time it takes to acquire this threshold. Minimizing the transmitting/receiving error reduces the number of preamble bits that the system requires, allowing for lower duty cycles on both the transmitting and the receiving sides (**Figure 1**).

Receiver performance degrades significantly as the crystal reference generates larger frequency errors, and including a highly accurate oscillator to improve stability can be costly. Any system trade-off must balance the desired frequency stability and the associated cost. For low-power radio applications, a frequency error of ±5 ppm allows the bandwidth of the channel-select filter to be narrow enough to achieve good receiver sensitivity and sufficient rejection of the busy adjacent channels in the ISM bands.

Many systems require high oscillator accuracy but cannot afford to include an expensive TCXO. Digital compensation can minimize the frequency error of a standard quartz crystal to provide a cost-effective option for these systems. To compensate for the frequency error of a crystal, you must first predict the error. Because AT cut crystals are the most common, this discussion will concentrate on them, but the same ideas apply for any crystal. You can characterize the crystal-frequency error of an AT cut crystal over temperature (relative to the error at 25°C) by the following third-order equation:

$Error (ppm) =$
$10^6 \times [-8.585 \times 10^{-8} C(T-25) + (3.9 \times 10^{-10} - 7.833 \times 10^{-11} C)(T-25)^2 + (1.095 \times 10^{-10} - 3.3 \times 10^{-14} C)(T-25)^3]$,
where C is the angle of cut in minutes and T is the temperature in degrees Celsius.

An uncompensated quartz crystal with various randomly chosen angles of cut cannot operate within the desired limits of ±5 ppm (**Figure 2**). Knowing the angle of cut of the crystal allows you to predict and compensate for the frequency error of the crystal. The easy way to learn the angle of cut of the crystal is to buy a crystal with a particular angle of cut directly from the crystal manufacturer. Crystal manufacturers can supply crystals guaranteed to stay within ±2 ppm of a known temperature characteristic. You can typically buy these crystals for less than $1. Alternatively, you can measure the crystal-frequency error (relative to 25°C) at two further temper-

Figure 3
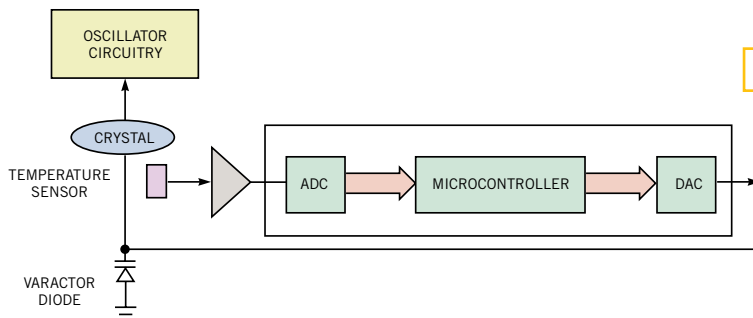
In a typical system, a sensor and ADC measure the temperature, and a DAC and varactor diode pull the oscillator back to its nominal frequency.

atures and predict the angle of cut of crystal based on these values. However, doing so adds to your test cost.

Designs have used direct digital compensation to calculate the estimated frequency error and then attempt to "pull" the crystal frequency back to the nominal frequency. A lower cost and simpler alternative is now possible using indirect frequency compensation. Indirect compensation uses fractional-N technology to correct for the estimated frequency error in the PLL.

In direct-digital compensation, a varactor diode in the feedback network pulls the crystal frequency back to its nominal frequency in a similar way to TCXOs. The key difference is that in direct-digital-frequency compensation, the compensation resides in the digital domain. In a typical system, a temperature sensor close to the crystal measures the crystal temperature (**Figure 3**). The analog output from the sensor is conditioned and scaled to match the input range of the ADC, converting it to the digital domain. Once the microcontroller reads the temperature from the ADC, it uses a look-up table to find out what DAC output is necessary to pull the oscillator back to its nominal frequency. The accuracy of direct-digital-frequency compensation is limited by how closely the crystal follows the estimated temperature-characteristic curve, the accuracy of the ADC and DAC, and the predictability of the capacitance of the varactor diode. With a 12-bit-accurate ADC and DAC, this system typically keeps the frequency error of a well-behaved crystal at ±5 to ±10 ppm over the industrial temperature range (-40 to $+85°C$).

DIGITAL-CRYSTAL-FREQUENCY COMPENSATION

Traditionally, with integer-N technology, you can change the output of the VCO (voltage-controlled oscillator)
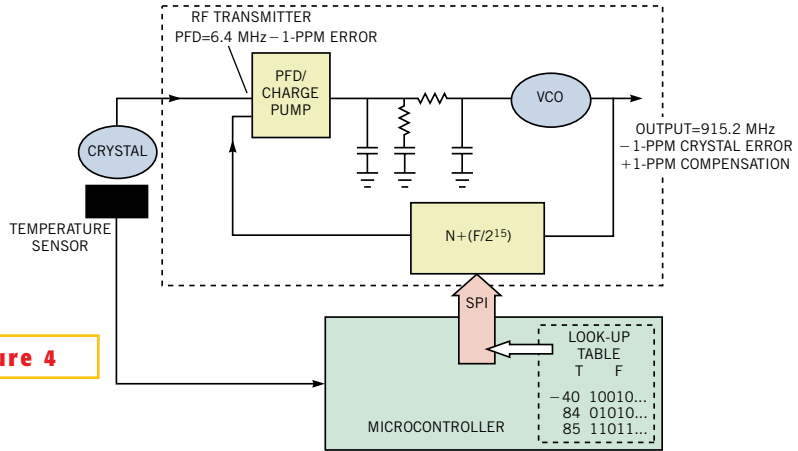
Figure 4

In indirect-digital-frequency compensation, a digital temperature sensor close to the crystal measures the temperature.

only in steps of tens of kilohertz, because you can move the output of an integer-N PLL only in multiples of the comparison PFD (phase-frequency-detector) frequency. Reducing the PFD to 1 kHz to gain sufficient resolution to compensate requires generating a large N-divider value. Because noise is multiplied up to the output by 20logN, using an integer-N PLL results in poor phase noise and long delays in moving frequency due to the narrow loop bandwidth required for the loop to lock.

The recent improvements in fractional-N spurious performance offer an alternative to direct compensation. Traditionally, fractional-N spurious levels have restricted its use to a limited number of applications with limited flexibility in the fractional divider. The small fractions now available on fractional-N synthesizers allow moving the output of the VCO in steps of as little as 0.1 ppm. It is therefore possible to use indirect-digital-frequency compensation to accurately compensate for the frequency error of the crystal over temperature within registers of the PLL itself.

In indirect-digital-frequency compensation, a digital temperature sensor close to the crystal measures the temperature (**Figure 4**). Based on the temperature, a microcontroller predicts the frequency error and writes a corresponding value from its look-up table to the fractional-N register to compensate for the frequency error. The accuracy of indirect-digital-frequency compensation is limited by how closely the crystal follows the estimated temperature-characteristic curve and the accuracy of the temperature sensor. A crystal with a frequency stability following a known temperature-characteristic curve within ±2 ppm in a system with a $\pm1°C$ accurate temperature sensor, guarantees a compensated frequency stability of ±3 ppm. You can keep the frequency error using indirect compensation at less than ±5 ppm over the industrial temperature range, which is better than what you can achieve with the direct method.

One of the key advantages of this approach is that once you assume a particular error, the error correction is guaranteed to be the same on all systems, because

TABLE 1—SUMMARY OF CRYSTAL AND OSCILLATOR OPTIONS

| Type	Stability (ppm over −10 to +70°C)	Typical price (1000) (−10 to +70°C)	Comment
Quartz crystal	±5 to ±100	20 cents (±50 ppm), 70 cents (±5 ppm)	Small and inexpensive but unstable
Crystal oscillator	±10 to ±100	$2 ($\pm50$ ppm), $7 ($\pm10$ ppm)	Inexpensive and relatively small but unstable
VCXO	±10 to ±100	$4 ($\pm20$ ppm)	Relatively small and suited to compensation but expensive
TCXO	±0.1 to ±5	$8 ($\pm2.5$ ppm), $40 ($\pm0.5$ ppm)	Very good stability but expensive
OCXO	±0.0001 to ±5	$80 ($\pm0.3$ ppm), $125 ($\pm0.02$ ppm)	Excellent stability but large, power-hungry, and expensive
Direct-digital-frequency compensation	±5	$3* ($\pm5$ ppm)	Lower cost option than TCXOs but requires significant design
Indirect-digital-frequency compensation	±3	$1 to $2* ($\pm3$ ppm)	Good stability, inexpensive, and easy to implement

*Additional cost of implementing compensation in system

all compensation is performed in the digital domain. Compensating in the digital domain avoids problems due to analog layout and grounding, greatly simplifying the design and significantly reducing oscillator current consumption. Using the indirect method saves costs because it requires neither an ADC nor a DAC. Many systems already have a temperature sensor, so including one incurs no additional cost. The receiver synchronizing to the accurate base-station clock during data transmission delivers improved accuracy in cellular communications. The fractional-N resolution allows dynamic correction for Doppler, aging, and temperature effects previously performed directly with a DAC and a VCXO. This indirect method alleviates the stress that regular compensation can place on the crystal of the VCXO, which can result in excessive aging and worsening of in-band phase noise.

Figure 4 depicts an indirect-crystal-frequency-compensation implementation using an 8051 microcontroller, a temperature sensor, an RF transmitter,

Figure 5
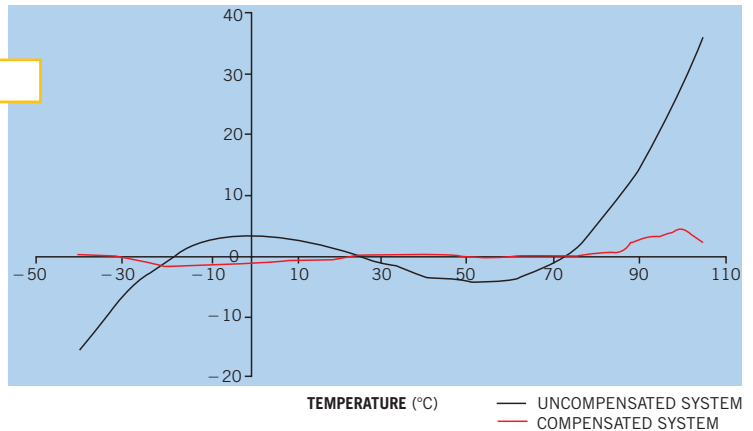
In indirect digital-frequency compensation, the compensation happens indirectly within the fractional-N PLL of the RF transmitter.

and a 19.2-MHz quartz crystal with an angle of cut of C≈3. The output frequency of the VCO was measured from −40 to +85°C in compensated and uncompensated systems (**Figure 5**). The compensated system worked well with a maximum frequency error of −1.52 ppm, which is well within the ±5-ppm limit. Because the crystal had a cut of C≈3, the uncompensated system performed within the ±5-ppm limit from −25 to +80°C. Crystals with different cuts have larger frequency errors over this temperature range. However, the temperature-compensation algorithm compensates for the larger frequency errors

of these crystals. Larger errors start to occur in the compensated system at 85 to 105°C. You may be unable to achieve a frequency stability of ±5 ppm in this range, because the error in crystal frequency changes greatly with temperature (1 to 2.5 ppm/°C), the crystal may not follow the temperature-characteristic curve to within ±2 ppm, and the temperature-sensor accuracy decreases at the increased temperatures. Using a more accurate temperature sensor, such as the ADT7301, can reduce the contribution of the temperature-sensor errors.

Sigma-delta fractional-N synthesizers offer advances in spurious performance, giving you an alternative for generating accurate local-oscillator frequencies in low-cost systems. They improve phase noise and offer a faster lock time than current integer-N parts. They also allow PLLs to output the resolution necessary (0.1 ppm) to compensate for temperature effects in crystals.

Digitally performed indirect compensation offers the benefits of cost reduction, ease of implementation, and improved accuracy. Although the example setup achieved frequency stability within ±5 ppm, improving temperature-sensor and crystal technology will eventually offer less costly and more accurate options.□

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