DALLAS SEMICONDUCTOR

Application Note 58
Crystal Considerations with Dallas Real Time Clocks

Dallas Semiconductor offers a variety of real time clocks (RTCs). The majority of these are available either as integrated circuits or modules. Modules include a real–time clock integrated circuit, crystal, and lithium energy source encapsulated in one package.

This application note is intended to help those customers who choose to use Dallas Semiconductor real time clock chips rather than modules and therefore need to attach their own crystal. The information contained in this article will be beneficial in maximizing accuracy and insuring proper operation of Dallas real time clocks by helping the customer to select the correct crystal to use and by providing a few basic guidelines that should be followed when placing the crystal on a PCB layout. This application note will also include an elementary discussion of the effect of temperature on the accuracy of real time clocks.

CRYSTAL SELECTION

In any crystal based oscillator circuit, the oscillator frequency is based almost entirely on the characteristics of the crystal that is used. It is important to select a crystal that meets the design requirements. In particular, the specified load capacitance (C_L) is a critical crystal parameter that is often overlooked. This parameter specifies the capacitive load that must be placed across the crystal pins in order for the crystal to oscillate at its specified frequency. The crystal manufacturer actually "trims" the crystal to oscillate at its nominal frequency for the given specified load capacitance. Note that the C_L is the capacitance that the crystal needs to "see" from the oscillator circuit, it is **not** the capacitance of the crystal itself.

As previously stated, the load capacitance that the crystal "sees" is due to the capacitance of the oscillator circuit itself. Any change in the load capacitance of the oscillator circuit will therefore have an affect on the frequency of that oscillator. Likewise, using a crystal that has a C_L that is different than the actual load capacitance of the circuit will also affect the frequency of the oscillator.

In general, using a crystal with a C_L that is larger than the load capacitance of the oscillator circuit will cause the oscillator to run faster than the specified nominal frequency of the crystal. Conversely, using a crystal with a C_L that is smaller than the load capacitance of the oscillator circuit will cause the oscillator to run slower than the specified nominal frequency of the crystal.

The majority of Dallas Semiconductor RTCs have an internal capacitance of 6 pF across the crystal input pins. Recent RTC offerings from Dallas Semiconductor have 12.5 pF capacitance or are software configurable for 6 pF or 12.5 pF. For proper operation and accuracy, a crystal that meets the parts requirements should be used. As mentioned above, using a crystal with the wrong C_L will cause the oscillator to run fast or slow. Limited characterization at Dallas Semiconductor has confirmed this. For example, limited characterization on the DS1485, which is designed for a 6 pF crystal, has revealed that the device will run approximately 4 minutes/month fast at room temperature (25°C) when a 12 pF crystal is used. The device had an accuracy within ±30 seconds/month when a 6 pF crystal was used.

Several vendors offer crystals that can be used with Dallas Semiconductor real time clocks. These vendors include Epson and KDS/Daiwa. Equivalent crystals from other crystal manufacturers can also be used. As a reference, see Table 1 for recommended crystal characteristics.

CRYSTAL SPECIFICATIONS Table 1

PARAMETER	SYMBOL	MIN	TYP	MAX	UNITS	NOTES
Nominal Frequency	F_0		32.768		kHz	
Load Capacitance	C_L		6		pF	
Temperature Turnover Point	T_0	20	25	30	°C	
Parabolic Curvature Constant	k			0.042	ppm/°C	
Quality Factor	Q	40,000	70,000			
Series Resistance	R1			45	KΩ	
Shunt Capacitance	C_0		1.1	1.8	pF	
Capacitance Ratio	C_0/C_1		430	600		
Drive Level	D_L			1	μW	

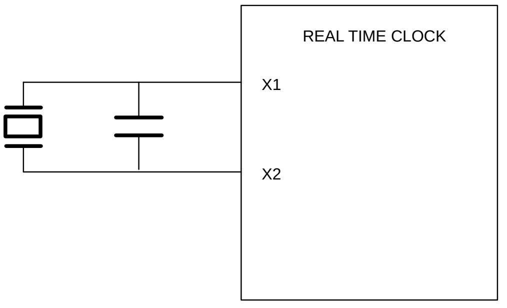
RTC CRYSTAL SUPPLIERS

MANUFACTURER	MODEL	C_L	PACKAGE
KDS/Daiwa Crystal Corp.	DT–38 DT–381 DT–26S DT–261S DT–14 DT–26S 32.768 Hz DMX–2632.768 KHz DS–VT–200	6pF	Cylinder Cylinder Cylinder Cylinder Cylinder Cylinder Cylinder Cylinder
Epson Crystal Corp.	C–001R C–002RX C–004R C–005R MC–306 MC–405 MC–406	6 pF, 12.5 pF 6 pF, 12.5 pF 6 pF, 12.5 pF 6 pF, 12.5 pF 6 pF, 12.5 pF 6 pF, 12.5 pF 6 pF, 12.5 pF	Cylinder Cylinder Cylinder Cylinder SMT SMT SMT
Hooray Electronics	MMTF–32	6pF	Cylinder

CRYSTAL LOAD COMPENSATION

Dallas Semiconductor does not recommend using crystals that do not have a C_L that matches the RTCs specification because this will decrease the accuracy of the clock. We find however that customers sometimes choose to use 12.5 pF crystals with our 6 pF RTCs. For this situation it is possible to improve the decreased accuracy caused by the C_L mismatch. This can be accomplished by increasing the load capacitance that the crystal "sees" by connecting a capacitor in parallel with the crystal as shown in Figure 1. As a rule of thumb, the approximate capacitor value is equal to the specified load capacitance (C_L) of the crystal minus 6 pF (the approximate load capacitance of the real time clock oscillator circuit). For example, if a 12 pF crystal is being used, a 6 pF capacitor should be placed in parallel with it to improve the accuracy of the oscillator. A 12 pF crystal is adjusted by the crystal manufacturer to oscillate at its specified nominal frequency when a 12 pF load is present. A 6 pF capacitor is therefore added to the 6 pF load of the oscillator circuit to compensate for the additional load that the crystal needs in order to oscillate at its specified nominal frequency.

CRYSTAL CONFIGURATION WHEN 6 PF CRYSTAL IS NOT USED Figure 1



As mentioned, a crystal with a C_L of greater than 6 pF can be compensated with an external capacitor to improve the accuracy. However, it should be noted that the oscillator start–up time (the time it takes during initial power up for the oscillator to stabilize) will increase due to the increased capacitance in the feedback path of the oscillator. This capacitance decreases the loop gain of the oscillator which in turn increases the start–up time. For example, limited characterization has shown that the start–up time for a 6 pF crystal is typically less than a couple hundred milliseconds, but can increase to one or two seconds when a 12 pF crystal with a 6 pF capacitor in parallel are used.

NOISE AND CRYSTAL LAYOUT GUIDELINES

Since the crystal inputs of the Dallas Semiconductor real time clocks have a very high impedance (about 10^9 ohms), the leads to the crystal act like a very good antennae, coupling high frequency signals from the rest of the system. If a signal is coupled onto the crystal pins, it can either cancel out or add pulses. Since most of the signals on a board are much higher frequency than the 32.768 KHz crystal, it is more likely to add pulses where none are wanted. These noise pulses get counted as extra clock "ticks" and make the clock appear to run fast.

It is very simple to determine if noise is the cause of the inaccuracy of a real time clock. The following steps illustrate how this can be done.

1. Power the system up and synchronize the real time clock to a known accurate clock.
2. Turn system power off.
3. Wait for a period of time (two hours, 24 hours, etc.). The longer the time period, the easier it will be to measure the accuracy of the clock.
4. Turn system on again, read clock, and compare to the known accurate clock.
5. Re–synchronize the real time clock to the known accurate clock.
6. Keep system powered up and wait for a period of time equal to the period in step 3.
7. Read clock after waiting for the above period of time and compare to the known accurate clock.

By using the above steps, the accuracy of the clock can be determined both when the system is powered up and when the system is powered down. If the clock proves to be inaccurate when the system is powered up, but is accurate when the system is powered down, the problem is most likely due to noise from other signals in the system. However, if the clock is inaccurate both when the system is powered up and when it is powered down, then the problem is not due to noise from the system.

Since it is possible for noise to be coupled onto the crystal pins, care must be taken when placing the external crystal on a PCB layout. It is very important to follow a few basic layout guidelines concerning the placement of the crystal on the PCB layout to insure that extra clock "ticks" do not couple onto the crystal pins.

1. It is important to place the crystal as close as possible to the X1 and X2 pins. Keeping the trace lengths between the crystal and the real time clock as small as possible reduces the probability of noise coupling by reducing the length of the "antennae". Keeping the trace lengths small also decreases the amount of stray capacitance.
2. Keep the crystal bond pads and trace width to the X1 and X2 pins as small as possible. The larger these bond pads and traces are, the more likely it is that noise can couple from adjacent signals.
3. If possible, place a guard ring (tied to ground) around the crystal. This helps to isolate the crystal from noise coupled from adjacent signals. See Figure 2 for an illustration of using a guard ring around a crystal.
4. Try to insure that no signals on other PCB layers run directly below the crystal or below the traces to the X1 and X2 pins. The more the crystal is isolated from other signals on the board, the less likely it is that noise will be coupled into the crystal.
5. It may also be helpful to place a local ground plane on the PCB layer immediately below the crystal guard ring. This helps to isolate the crystal from noise coupling from signals on other PCB layers. Note that the ground plane needs to be in the vicinity of the crystal only and not on the entire board. See Figure 2 for an illustration of a local ground plane. Note that the perimeter of the ground plane does not need to be larger than the outer perimeter of the guard ring.

   Note that care must be taken concerning the use of a local ground plane because of the stray capacitance that it introduces. This capacitance will be added to the crystal pins and if large enough could slow the clock down. Therefore, some factors must be taken into account when considering adding a local ground plane. For example, the capacitance due to the ground plane may be approximated by

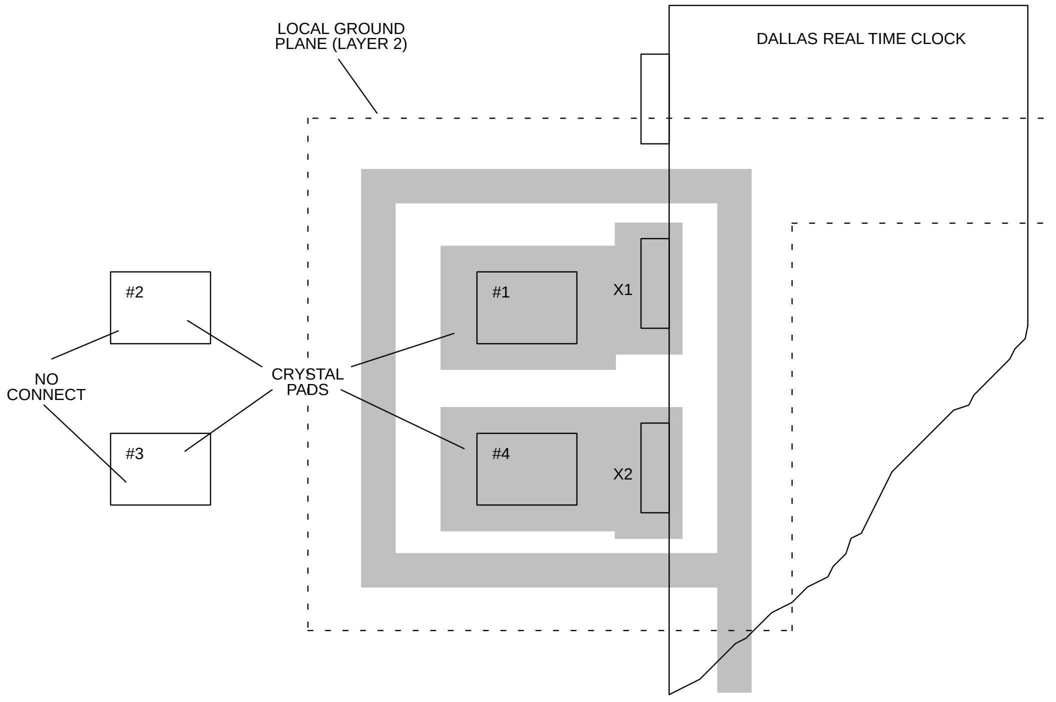
   $$C = \varepsilon A/t$$

   where

   ε = dielectric constant of the PCB
   A = area of the ground plane
   t = thickness of the PCB layer.

Therefore, to determine if a ground plane is appropriate for a given design, the above parameters must be taken into account to insure that the capacitance from the local ground plane is not sufficiently large enough to slow down the clock.

EXAMPLE OF CRYSTAL PLACEMENT ON PCB Figure 2



NOTE: Crystal referred to in this diagram is the Epson MC–406.

CLOCK ACCURACY OVER TEMPERATURE

The accuracy of a real time clock is directly dependent upon the frequency of the crystal. Therefore, since the resonant frequency of a crystal is dependent upon temperature, a real time clock will also be dependent upon temperature. The resonant frequency of a crystal is expressed in the following basic formula:

$$f = f0 + k * (T - T0)^2$$

where

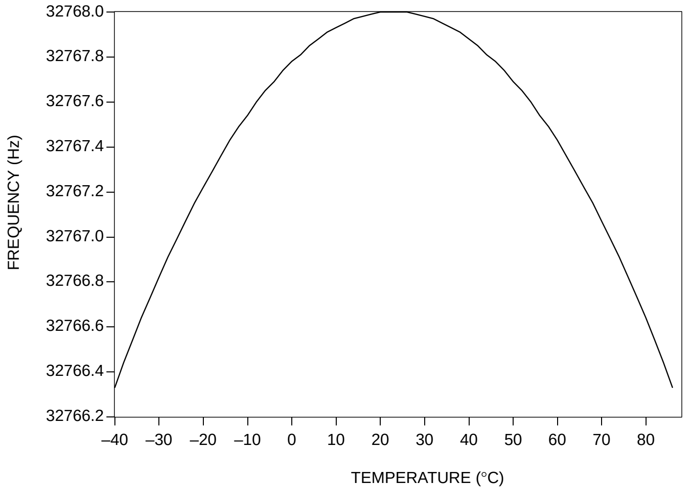
f_0 = nominal frequency
k = parabolic curvature constant
T_0 = turnover temperature
T = temperature

The values of the above parameters can be found in the data sheet of the crystal being used. The temperature characteristic of a nominal Daiwa crystal is illustrated in Figure 3 where f_0 = 32.768 KHz, k = –0.042 ppm/°C, and T_0 = 23°C. As can be seen in this figure, frequency has a parabolic relationship to temperature – as temperature deviates from the ideal 23°C, the crystal frequency becomes increasingly slower.

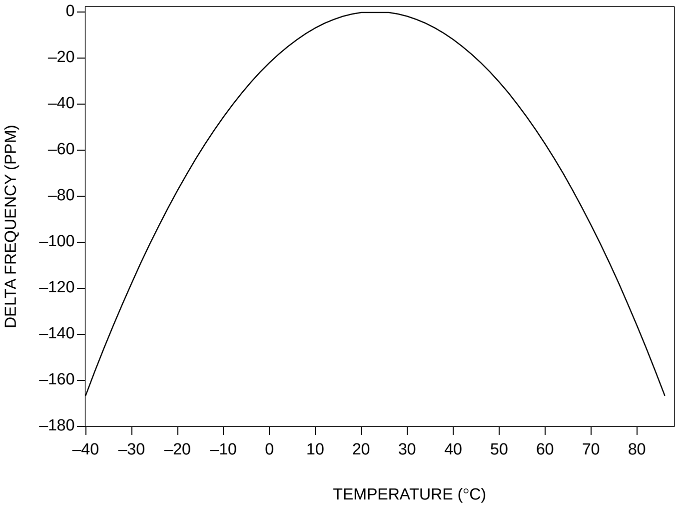
Figure 4 shows the same basic curve, however, the Y axis has been changed to show the frequency deviation (in ppm) from the crystal's nominal frequency at 23°C. This curve illustrates more clearly how the frequency of the crystal will affect the accuracy of the clock. A frequency deviation of 23 ppm translates into an accuracy of approximately ±1 minute per month. With this in mind, a quick glance at Figure 4 will give an approximate expected accuracy at a given temperature.

The above information should help to provide a basic understanding of how temperature will affect Dallas Semiconductor real time clocks.

CRYSTAL FREQUENCY VS. TEMPERATURE Figure 3



FREQUENCY DEVIATION VS. TEMPERATURE Figure 4



TROUBLESHOOTING

This section is provided as a summary of the most frequent causes of real time clock inaccuracies. Most of these problems have been mentioned earlier, but are repeated here as a quick reference. This section has been divided into two parts. The first part will consider the factors that cause a real time clock to run too fast and the second part will consider the factors that cause a real time clock to run too slow.

FAST CLOCKS

The following are the most common scenarios that cause a crystal–based real time clock to run fast.

1. Noise coupling into the crystal from adjacent signals: This problem has been extensively covered above. Noise coupling will usually cause a real time clock to be grossly inaccurate.
2. Wrong crystal: A real time clock will typically run fast if a crystal with a specified load capacitance (C_L) greater than 6 pF is used. The severity of the inaccuracy is dependent on the value of the C_L. For example using a crystal with a C_L of 12 pF will cause the real time clock to be about 3–4 minutes per month fast.

SLOW CLOCKS

The following are the most common scenarios that cause a crystal–based real time clock to run slow.

1. Overshoot on real time clock input pins: It is possible to cause a real time clock to run slow by periodically stopping the oscillator. This can be inadvertently accomplished by noisy input signals to the real time clock. If an input signal rises to a voltage that is greater than a diode drop (∼0.3V) above V_{DD}, the ESD protection diode for the input pin will forward bias, allowing the substrate to be flooded with current. This, in turn, will stop the oscillator until the input signal voltage decreases to below a diode drop above V_{DD}.

   This mechanism can cause the oscillator to stop frequently if input signals are noisy. Therefore, care should be taken to insure that there is no overshoot on input signals.

   Another situation that is common to overshoot problem is having an input to the real time clock at 5V when the real time clock is in battery back–up mode. This can be a problem in systems that systematically shut down certain circuits, but keep others powered up. It is very important to insure that there are no input signals to the real time clock that are greater than the battery voltage when the device is in battery back–up mode.
2. Wrong crystal: A real time clock will typically run slow if a crystal with a specified load capacitance (C_L) less than 6 pF is used. The severity of the inaccuracy is dependent on the value of the C_L.
3. Stray capacitance: Stray capacitance between the crystal pins can slow a real time clock down. Therefore care must be taken when designing the PCB layout to insure that the stray capacitance is kept to a minimum.
4. Temperature: The further the operating temperature is from the crystal turnover temperature, the slower the crystal will oscillate. See Figures 3 and 4.

REFERENCES

1. Eaton, S. S. *Timekeeping Advances Through COS/MOS Technology*, RCA Application Note ICAN–6086.
2. Eaton, S. S. *Micropower Crystal–Controlled Oscillator Design Using RCA COS/MOS Inverters*, RCA Application Note ICAN–6539.
3. Meyer, R. G. “MOS Crystal Oscillator Design,” *IEEE Journal of Solid–State Circuits*, Vol. SC–15, No. 2, pp. 222–227, April 1980.
4. Williamson, T. *Oscillators for Microcontrollers*, Intel Application Note AP–155.