A Simple 1-Wire® DAC

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Abstract: Connecting the outputs of a 1-Wire addressable switch (DS2408) to a resistor network allows the 1-Wire interface to control a simple DAC. This idea is illustrated by the presentation of an LED-brightness controller.

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Among devices available with a 1-Wire interface, the best known are memories, temperature sensors, battery monitors, and addressable switches. One-Wire ADCs are also available, but no 1-Wire DACs. You can, however, build a simple 1-Wire DAC using addressable switches.

The circuit (Figure 1) consists of a multi-channel 1-Wire addressable switch (DS2408, U1), a current mirror (Q1, Q2), and a resistor network (Rα, Rβ, Rγ, Rδ, RX). U1’s open-drain output transistors (P0-P3) either conduct (logic 0) or present a high impedance (logic 1). If the logic state of an output port is 0, then current flows to ground through the resistor connected to that port.

Figure 1. This 4-bit DAC is controlled by a 1-Wire interface. (DS2408 outputs P4 to P7 are not used.)

IREF is calculated as follows:

\[
I_{REF} = \frac{V_{CC} - V_{BE(Q1)}}{1/(P0/Rα + P1/Rβ + P2/Rγ + P3/Rδ + 1/RX)} \tag{Eq. 1}
\]

As explained in the Reference¹, the current I₀ is described by equation (2):
where \( V_A \) represents the early voltage of Q2 and \( \beta \) is the current gain, assuming Q1 and Q2 have identical characteristics. For \( V_{CB} \) values from 4.3V to 0.2V and typical values for \( V_A \) (20) and \( \beta \) (180), the mirror ratio \( MR \) ranges from 1.20 (high \( V_{CB} \), low current) to 1.00 (low \( V_{CB} \), high current).

The DAC’s analog output voltage (\( VX \)) is
\[
VX = I_O \times RL = MR \times I_{REF} \times RL \quad \text{(Eq. 3)}
\]

When none of the output ports are asserting logic 0, \( I_{REF} \) is determined by \( RX \):
\[
I_{REF0} = \frac{(V_{CC} - V_{BE(Q1)})}{RX} \quad \text{(Eq. 4)}
\]

\( I_{REF0} \) generates the offset voltage \( VX_0 \):
\[
VX_0 = MR \times I_{REF0} \times RL \quad \text{(Eq. 5)}
\]

Inserting (4) in (5) and solving for \( RX \) yields (6), which lets you calculate the \( RX \) value corresponding to a desired offset voltage:
\[
RX = RL \times MR \times \frac{(V_{CC} - V_{BE(Q1)})}{VX_0} \quad \text{(Eq. 6)}
\]

With \( P_0 \) assigned to the DAC’s least-significant bit (LSB), the resistor \( R_\alpha \) determines \( \Delta VX \), which is the voltage increment between steps. Substituting \( \Delta VX \) for \( VX_0 \) in equation (6) yields (7), which lets you calculate \( R_\alpha \):
\[
R_\alpha = RL \times MR \times \frac{(V_{CC} - V_{BE(Q1)})}{\Delta VX} \quad \text{(Eq. 7)}
\]

Because \( P_1 \) has twice the weight of \( P_0 \) in a binary system, \( R_\beta \) must conduct twice as much current. Consequently, \( R_\beta = R_\alpha/2 \). For the same reasons, \( R_\gamma = R_\alpha/4 \) and \( R_\delta = R_\alpha/8 \). For these conditions the maximum value of \( VX \) is
\[
VX_{MAX} = VX_0 + 15 \times \frac{(V_{CC} - V_{BE(Q1)})}{R_\alpha \times RL \times MR} \quad \text{(Eq. 8)}
\]

**Example 1: Full-Range DAC**

Table 1 explains the choices for input values. Inserting these values in equations (6) and (7) yields \( RX = 94.6k\Omega \) and \( R_\alpha = 18.92k\Omega \). Given the value \( R_\alpha = 18.92k\Omega \), the other (non-standard) values are \( R_\beta = 9.46k\Omega \), \( R_\gamma = 4.73k\Omega \), and \( R_\delta = 2.365k\Omega \). To get closer to E24 standard values (5% tolerance), multiply each one with a factor \( \sim 1.05 \), yielding \( RX = 100k\Omega \), \( R_\alpha = 20k\Omega \), \( R_\beta = 10k\Omega \), \( R_\gamma = 5k\Omega \), and \( R_\delta = 2.5k\Omega \). Changing all resistors by the same factor has little effect on the result, and the reduction in \( I_{REF} \) is compensated by the increased value of \( RL \), leaving \( VX \) unaffected.

**Table 1. Input Values for the Full-Range DAC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( VCC = 5V )</td>
<td>Maximum voltage for the DS2408</td>
</tr>
<tr>
<td>( VX_0 = 0.05V )</td>
<td>Design objective</td>
</tr>
<tr>
<td>( \Delta VX = 0.25V )</td>
<td>Design objective</td>
</tr>
</tbody>
</table>
Example 2: LED-Brightness Control

In Figure 1, the analog output voltage VX controls the light intensity of an LED. Q3 functions as an emitter follower that minimizes the load on VX, and R1 limits the LED current. Assume that the LED voltage drop is 1.9V when ON, and that V_{BE} of Q3 is 0.7V. To keep the LED OFF, VX must be less than 2.6V, i.e., VX_0 = 2.5V. To avoid Q2's V_{CE} saturation range, the voltage swing at VX must remain below 2V. This condition demands that \( \Delta V_X \leq 2V/15 \), i.e., \( \Delta V_X = 0.125V \). Otherwise, the input values of Table 1 apply.

Repeating the calculations of equations (6) and (7) yields \( R_X = 1.892k\Omega \), \( R_\alpha = 37.84k\Omega \), \( R_\beta = 18.92k\Omega \), \( R_\gamma = 9.46k\Omega \), and \( R_\delta = 4.73k\Omega \). Increasing these resistor values by ≈5% gets you closer to the standard values: \( R_X = 2k\Omega \), \( R_\alpha = 40k\Omega \), \( R_\beta = 20k\Omega \), \( R_\gamma = 10k\Omega \), and \( R_\delta = 5k\Omega \).

The circuit of Figure 1 is simple and efficient, but its weak spot is the current mirror. The mirror ratio varies with V_{CB}(Q2), and both the Early voltage V_A and the current gain \( \beta \) change with the collector current. Discrete transistors introduce further imprecision. Using 5% resistors, the actual measurements of VX were within ±10% of the calculated values.

You can improve the current mirror by replacing Q1 and Q2 with a transistor array, or a dual transistor such as the BCV62. (The improved current-mirror designs described in Reference [1] require a third transistor.) Though shown for four switches, this concept can be extended to use all eight ports of U1. Note that this approach increases only the resolution, and not the accuracy or the output-voltage range.


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<td>DS2408</td>
<td>1-Wire 8-Channel Addressable Switch</td>
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