Application Report
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Power Reduction Techniques for the FDC2214/2212/2114/2112 in Capacitive Sensing Applications

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ABSTRACT

Capacitive sensing is an effective technique for applications ranging from proximity detection and gesture recognition to liquid level sensing. Depending on the specific application, there will be different system requirements regarding sensitivity, responsiveness, and power. Power consumption is a key parameter for many applications, including wearables, consumer electronics, and some automotive applications. This application note covers techniques to reduce power consumption for TI's FDC2x1x capacitive-to-digital converters and various experiments to verify the effectiveness of these power-reducing techniques.

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Trademarks

1 Duty-Cycling

The FDC2x1x devices utilize an LC tank architecture to determine the change in capacitance by measuring (sampling) the change in oscillation frequency of the tank. The tank oscillation frequency (f_{OSC}) is compared to an independent reference clock (f_{REF}) to produce an output sample that represents f_{OSC} as a fraction of f_{REF}. The power consumption of the FDC2x1x devices is typically on the order of a few milliamps for continuous sampling modes. For low power applications, duty-cycling the FDC2x1x using sleep mode is a technique that can be used to reduce the power consumption. When the FDC2x1x can sample much faster than the application requires, the device can be put into a lower power sleep mode while it is not in the data conversion process. The device is only active when it is performing a measurement conversion to minimize the total amount of current flowing through the device and therefore reduce overall power consumption.

One of the main tradeoffs associated with this duty-cycling technique is responsiveness. The higher the sampling rate, the faster the system responsiveness is, but at the cost of higher average power. However, for applications that do not need an extraordinarily fast response time, a lower sampling rate can be used to achieve lower power consumption. For example, many human-machine interfaces (HMI) only need to run at sampling rates of 40 SPS or lower. The total conversion time of a measurement for a given sampling rate can also affect power consumption depending on the resolution requirements. This concept corresponds to the duty cycle of the device at a particular sampling rate.

1.1 FDC2x1x Operational Parameters That Affect Duty Cycling

The FDC family of devices are either 2 or 4 channel devices. When configured to sample on more than one channel, the FDC sequentially samples the channels. Figure 1 and Figure 2 show both single channel and multichannel mode sequencing in continuous conversion of the FDC2x1x, representing a non-duty cycled mode of operation. The normal sequence of tasks on each channel include sensor activation, conversion, channel switching (multi-mode only), and data readback.

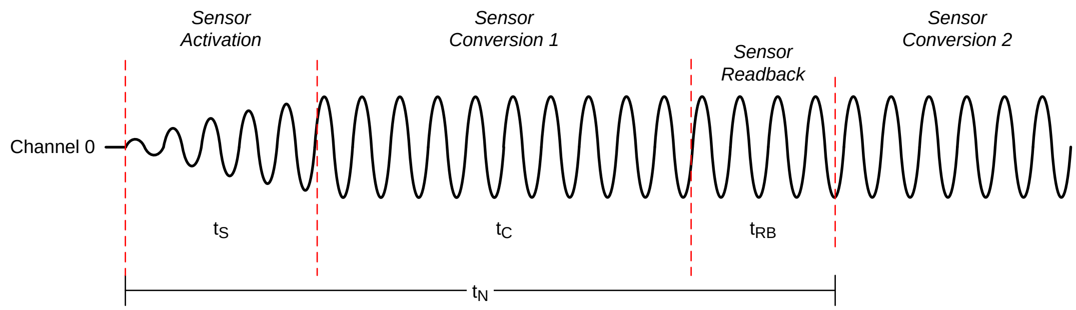

Figure 1. Single Channel Mode Sequencing in Continuous Conversion

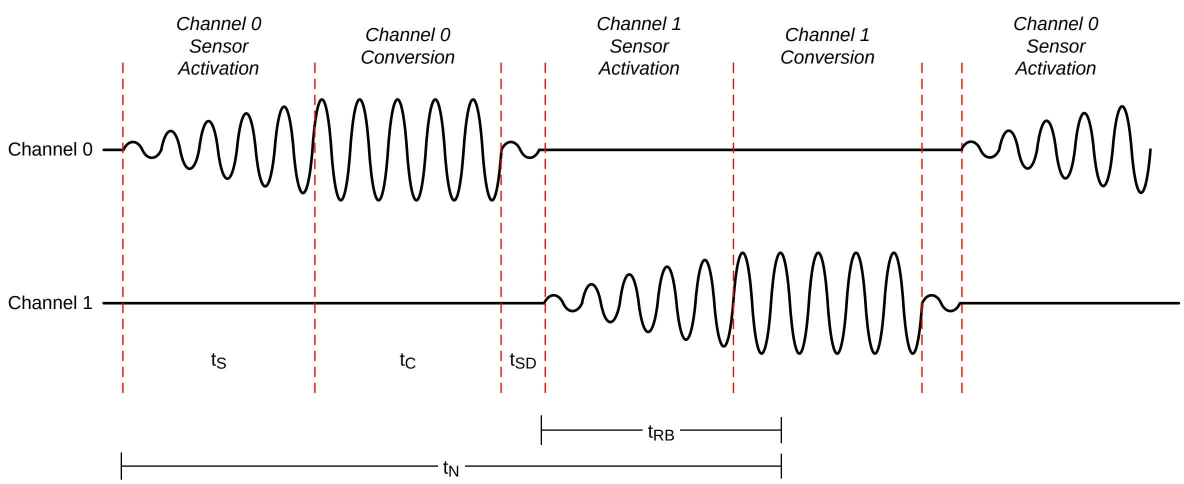

Figure 2. Multi-Channel Mode Sequencing in Continuous Conversion

The sum of the times it takes for each task to complete is equivalent to a sample time, during which the device needs to be actively running. In the data sheet, this is referred to as normal mode, but throughout this application note this will be referred to as active mode. We will also distinguish between sampling period (T_S) and sampling time (t_N). The former is defined as the time between consecutive samples on the same channel, and the latter is defined as the time required to obtain a single sample. The latter is expressed in Equation 1.

$$t_N = t_S + t_C + t_{SD} + t_{RB}$$

where

- t_N is the time the device spends sampling in active mode
- t_S is the sensor activation time
- t_C is the sensor conversion time
- t_{SD} is the channel switch delay
- t_{RB} is the data readback time (1)

In general, $t_{SD} < t_S << t_C$. Consequently, t_C has the most impact on sampling time and hence, duty cycle.

The sensor activation time, t_S, refers to the amount of time needed for the sensor oscillation to startup and stabilize. This activation time (t_S) is programmable through the SETTLECOUNT register for each channel and given by Equation 2 where f_{REF} is the reference clock frequency.

$$t_S = \frac{(16 \times \text{SETTLECOUNT})}{f_{REF}} \quad (2)$$

The sensor conversion time, t_C, is the largest part of this sequence. It represents the number of reference clock cycles (RCOUNT*16) used to perform a measurement conversion. As seen in Equation 3, the sensor conversion time can be set by the RCOUNT register value for each channel.

$$t_C = \frac{(16 \times \text{RCOUNT}) + 4}{f_{REF}} \quad (3)$$

The choice of RCOUNT value is driven by the resolution required by the application. If the required resolution is N bits, then the following equation can be used to calculate an initial value for RCOUNT.

$$\text{RCOUNT} = 2^{(N-4)} \quad (4)$$

See section 9.3.2 of the data sheet (SNOSCZ5) for more explanation of RCOUNT and sample resolution.

When the FDC2x1x is in multichannel mode, the channel switch delay needs to be included in the total sampling time. This is the delay time between the end of a sensor conversion on one channel and the beginning of sensor activation on a subsequent channel. This delay time is relatively minimal and is given by Equation 5.

$$t_{SD} = 692\text{ ns} + \frac{5}{f_{REF}} \quad (5)$$

In addition to the time required to complete the three tasks discussed above, the microprocessor takes some time to read back the channel measurement. This data readback time, t_{RB}, is a function of the data resolution, the number of data registers being read, the number of clocking cycles to read or write to each register, and the I^2C data rate.

The total time to complete this sequence is the total amount of time for which the FDC2x1x must be in active mode (Equation 1). If f_S is the required sampling rate and T_S is the sampling period (T_S=1/f_S), the idea behind the duty-cycling technique is that the device is put into sleep mode when it is not operating in this data conversion process ($T_{SLEEP} = T_S – t_N$). Consequently, the percentage of time the FDC is in a low power sleep mode is given by Equation 6.

$$\frac{T_{SLEEP}}{T_S} \times 100\% = \left(1 - \frac{t_N}{T_S}\right) \times 100\% \quad (6)$$

For more information on how to configure the FDC2x1x, refer to the data sheet (SNOSCZ5).

In summary, given a minimum sampling rate required by the application, the duty cycle only needs to be large enough to meet the minimum resolution requirements of the application. Figure 3 illustrates this graphically.

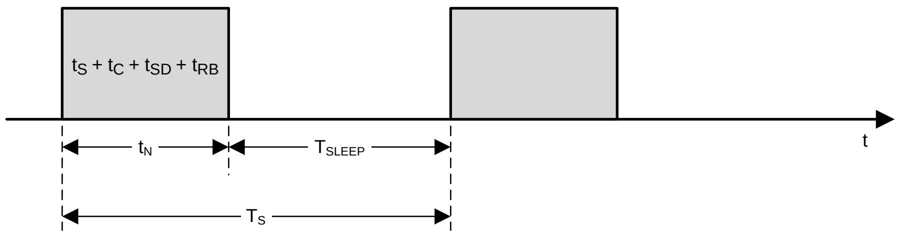

Figure 3. Duty Cycle as a Function of Settling Time, Conversion Time, Switching Time, and Readback Time

To place the FDC in sleep mode, write the value 1 to the CONFIG.SLEEP_MODE_EN register field. While in sleep mode, the FDC retains its register contents except for that in the data registers, which must be read before the device is placed in sleep mode. To exit sleep mode, write the value 0 to the CONFIG.SLEEP_MODE_EN register field.

2 Clock Gating

A second important technique to reduce power consumption in the FDC is gating of the external reference clock. Simply put, the reference clock is also put into a sleep state whenever the FDC is placed into a sleep state. This not only reduces the power consumed by the external clock, but also significantly reduces the leakage current from the FDC.

3 Test Setup

Duty-cycling the FDC2x1x was tested on the Noise-immune Capacitive Proximity Sensor System Reference Design (TIDA-00466) with only one channel (Channel 0, proximity sensor) enabled. The current flowing through the FDC2214 was measured using a digital multi-meter. The test setup is shown in Figure 4 and the testing conditions are given in Figure 4.

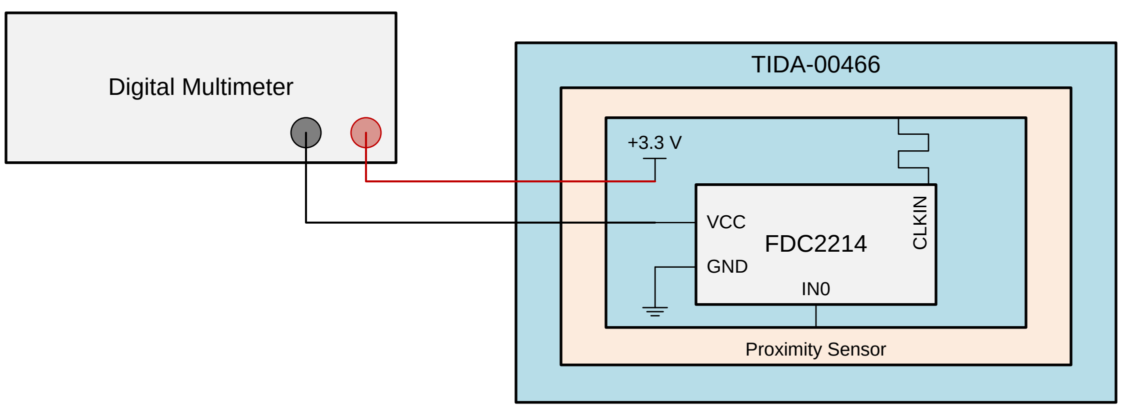

Figure 4. Test Setup

Table 1. Testing Conditions

	CHANNEL 0
Reference Frequency (MHz)	40
Sensor Frequency (MHz)	5.3
Amplitude (V_PP)	1.22
SETTLECOUNT	30
Current Drive Setting (mA)	0.069

The reference frequency was set by an external crystal oscillator and the current drive was set to achieve the recommended voltage amplitude for the oscillation waveform, which is between 1.2 and 1.8 V_{PP}.

4 Measurement Results

4.1 Measurements with Gated Clock

The TIDA-00466 was programmed so that the FDC2214 was only operating in one of three states: active, sleep, and shutdown. For each state, the current consumption of the device was measured and compared to the expected values given in the data sheet.

Table 2. Current Consumption for Each State: Gated Clock

	MEASURED CURRENT (TIDA-00466)
Active Mode	2.78 mA
Sleep Mode	29.7 µA
Shutdown Mode	0.145 µA

These supply current values are taken with a gated external reference clock. If the clock is not turned off while the FDC2214 is in sleep or shutdown mode, the power consumption in these modes will significantly increase as seen in Table 3. The clocking transitions result in an increase of the FDC2214 input pin leakage currents, which is negligible when compared to the normal mode current, but is significant when added onto the lower power mode currents.

Table 3. Current Consumption in Each State Without Gating the External Reference Clock

	MEASURED CURRENT (TIDA-00466)
Sleep Mode	271.6 µA
Shutdown Mode	26 µA

5 Current Consumption Measurements vs Data Conversion Time

5.1 Data Readback Overhead

The FDC2214 does not retain its conversion results when in sleep mode. Because of this, the device cannot be put into the sleep state until the channel conversion measurements have been read by the microcontroller. Therefore, the data registers must be read while the device is still running in active mode which results in a fixed power consumption overhead. From the data given in Table 4, the data readback time is 0.688 ms. This overhead has a greater impact on conversion times in that order of magnitude, in this instance, at lower RCOUNT values where the data conversion times are less than 10x the data readback time.

Table 4. The Effect of Data Readback Overhead on Device Active Time

RCOUNT	Data Conversion Time (t_S+t_C+t_{SD}) (ms)	Readback Time (t_{RB}) (ms)	Data Conversion Time + Data Readback Time (ms)
500	0.212	0.688	0.9
1000	0.412	0.688	1.1
5000	2.012	0.688	2.7
10000	4.012	0.688	4.7
20000	8.012	0.688	8.7
30000	12.012	0.688	12.7
40000	16.012	0.688	16.7
50000	20.012	0.688	20.7

6 Comparison of Measured and Estimated Current Consumption

6.1 Estimating Current Consumption

The following procedure can be used to estimate the current consumption of the FDC2x1x . First, the active time, or time the device spends in normal mode, should be determined. As expressed in Equation 1, this includes the sensor startup time, t_S, the sensor conversion time, t_C, and the data readback time, t_{RB}. The channel switch delay time, t_{SD}, can be ignored while operating in single channel mode. Once t_N has been calculated, the percentage of time the device spends in active mode, D_N, can be calculated using Equation 7 where T_S is the sampling period. The percentage of time the device spends in sleep mode, D_S, can also be calculated by using Equation 8.

$$D_N = \frac{t_N}{T_S} \quad (7)$$

$$D_S = \frac{(T_S - t_N)}{T_S} \quad (8)$$

Equation 9 then estimates the amount of power the FDC2x1x will burn given the above percentages per period (D_N and D_S) where I_N is the supply current in active mode and I_S is the supply current in sleep mode (given in Table 2).

$$I_{AVG} = D_N I_N + D_S I_S \quad (9)$$

7 Results

Figure 5 and Table 5 show the comparison between the experimental results and analytical results for varying values of RCOUNT.

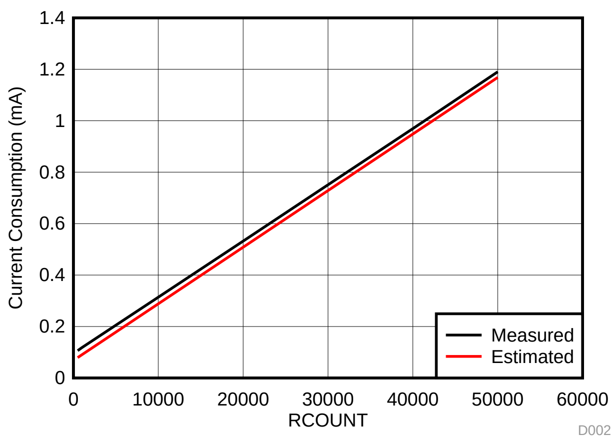

Figure 5. Comparison Between Measured and Estimated Current Consumption

Table 5. Differences in Measured and Estimated Current Consumption

RCOUNT	Duty Cycle	Measured Current, Active State (mA)	Estimated Current, Active State (mA)	Difference (Measured – Estimated) (mA)
500	0.42%	0.106	0.079	0.027
1000	0.82%	0.118	0.090	0.028
5000	4.02%	0.205	0.178	0.027
10000	8.02%	0.314	0.288	0.026
20000	16.02%	0.532	0.508	0.024
30000	24.02%	0.751	0.728	0.023
40000	32.02%	0.969	0.948	0.021
50000	40.02%	1.190	1.168	0.022

Based on the data above, the measured current consumption and estimated current consumption differ by an average of 25 µA, where the estimated current consumption is slightly less than the measured current consumption. This can be attributed to the fact that various other system parameters such as the sensor frequency, sensor amplitude, and sensor current drive were not taken into account in the estimation. TI provides a spreadsheet-based calculator tool, the FDC211x/FDC221x Current Consumption Estimator, which is based on the above equations and also takes into account these other parameters. This calculator tool was designed to estimate a worst-case power consumption scenario so for a real-world system, the current consumption through the device is generally less than what the calculator predicts.

After verifying the current estimation model, a set of experiments varying RCOUNT values at different sampling rates were conducted using the experimental setup shown previously in Figure 4.

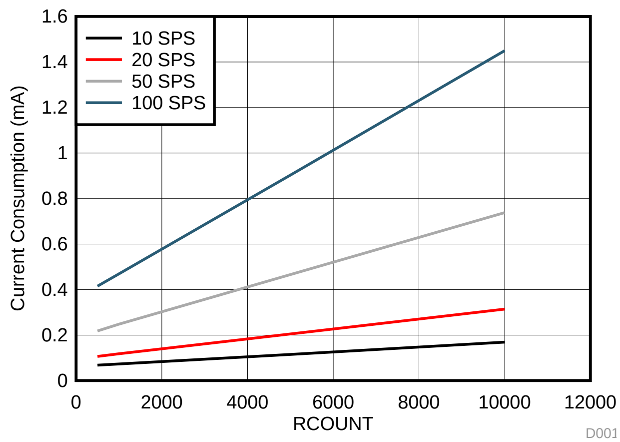

Figure 6. Current Consumption for Varying RCOUNT Values at Specified Sampling Rates

Figure 6 shows an approximately linear relationship between current consumption and RCOUNT. Since RCOUNT is directly related to sensor conversion time (Equation 3), a lower RCOUNT results in a shorter conversion time, t_C, and allows the device to spend less time in normal mode and more time in sleep mode (per sampling period, T_S). For a given sampling rate, a lower RCOUNT consumes less current while a higher RCOUNT consumes more current. Another way to understand the relationship is that if RCOUNT is kept constant but the sampling rate is varied, the FDC2214 sampling at a higher rate consumes more power than a FDC2214 sampling at a lower rate.

8 Summary

Duty-cycling and clock gating are effective techniques that can be implemented in order to minimize power consumption of the FDC2x1x. In order to ensure that there is minimal current flowing through the device, the external oscillator used as the reference clock should be turned off while the device is in either sleep or shutdown mode. It is important to note that the data readback overhead can affect current consumption measurements, especially at lower RCOUNT values. The resulting current values for varying RCOUNT values at different sampling rates follow expected trends and the measured current values are similar to the estimated current values. The FDC211x/FDC221x Current Consumption Estimator provided by TI can be used as a reference tool for estimating a worst-case power consumption scenario.

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