

Precision measurement circuit with 8 differential channels and SPI

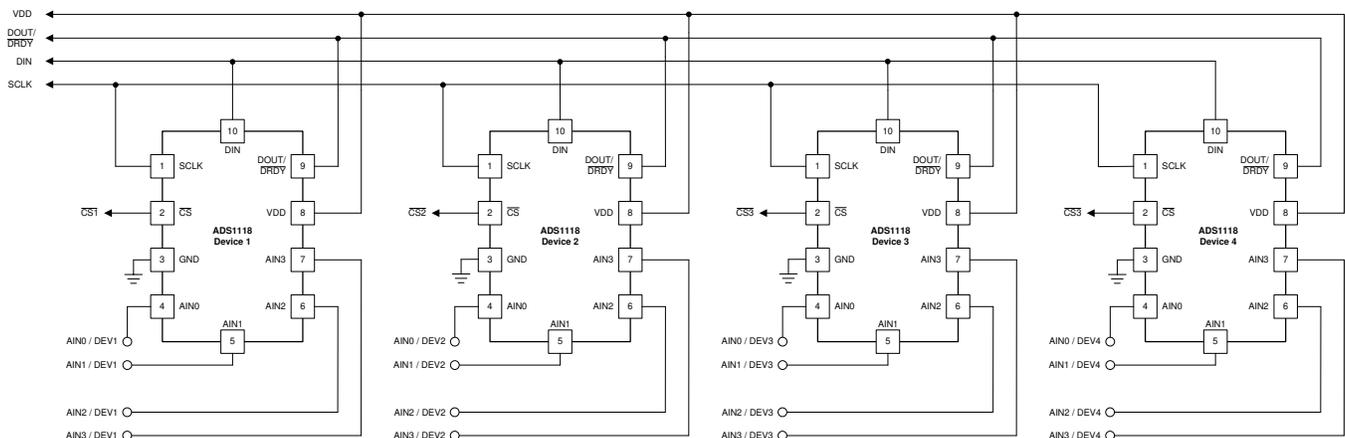
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Input Measurement	AIN _P and AIN _N Inputs	Digital Output ADS1118
PGA[2:0] = 000, FSR = ±6.144V	0V to 5V	–26667 to 26667 97D5h to 682Bh

Power Supplies	
VDD	GND
5V	0V

Design Description

Many applications require a large array of measurements using a minimal amount of space. This circuit document describes an 8-channel measurement system using four ultra-small [ADS1118](#) devices with Serial Peripheral Interface (SPI). These devices have an accurate internal voltage reference, and can be programmed for multiple input ranges as 16-bit differential analog-to-digital converters (ADCs). The ADCs in system are highly configurable for different data rates and voltage ranges and can even be used for alert functions. Additionally, all analog inputs can be configured individually to make a 16-channel measurement system with single-ended input measurements. The ADS1118 is available in an ultra-small 1.5mm × 2.0mm X2QFN that takes up very little space on a board. This circuit can be used in applications such as [analog input modules](#) for PLCs, [lab instrumentation](#), and [factory automation](#).



Design Notes

1. The ADS1118 has a differential ADC. Negative measurements are made when AIN_N is higher than AIN_P and are reported in two's complement notation.
2. The operating range of the ADC analog inputs is between ground and VDD, even with the full-scale range (FSR) set to voltages larger than the VDD. For example, with the FSR set to $\pm 6.144V$ and VDD set to 5V, all analog inputs are limited from 0V to 5V. An FSR larger than the supply prevents over-ranging the ADC for any measurement within the operating range.
3. With the internal reference, the ADS1118 device can conveniently measure its own supply using the internal reference without the need of a voltage divider.
4. Use supply decoupling capacitors for the power supplies. VDD must be decoupled with at least a 0.1- μF capacitor to GND. See the [ADS1118 Ultra-Small, Low-Power, SPI-Compatible, 16-Bit ADCs With Internal Reference, and Temperature Sensor](#) data sheet for details on power-supply recommendations.
5. When possible, use C0G (NPO) ceramic capacitors for input filtering. The dielectric used in these capacitors provides the most stable electrical properties over voltage, frequency, and temperature changes. Because of size, this may not always be practical and X7R capacitors are the next best alternative.
6. If lower resolution is acceptable, the [ADS1018](#) ADC may be set up in a similar system. These 12-bit ADCs allow for a faster data rate and lower cost.
7. The ADS1118 device uses SPI communications. If an I2C interface is required, the [ADS1115](#) ADC has similar functions and may be used. Additionally, the [ADS1015](#) or the [TLA2024](#) devices may be substituted if an ADC with less resolution can be used. See [Precision measurement circuit with 16 singled-ended channels and I2C interface](#) for more details
8. This measurement system may be constructed with 16 single-ended channels instead of 8 differential channels, or with different combinations of differential and single-ended channels. This system is also scalable with fewer devices and channels.
9. The ADS1118 ADC is used in single-shot conversion mode. In this mode of operation, devices are enabled for each conversion and then powered down. The total power of using all four devices individually is the same as using a single device in continuous conversion.
10. The ADS1118 ADC has an accurate internal temperature sensor that may also be used for an additional measurement. For more details about this measurement, see the [ADS1118](#) data sheet.

Configuring the Device

1. Setup the SPI with four \overline{CS} lines to individually select the devices.

This circuit uses four ADS1118 ADCs multiplexed to measure eight different channels. To do this, the four devices must use different \overline{CS} lines, one for the \overline{CS} line for each device. The remaining SPI lines (DIN, DOUT/ \overline{DRDY} , and SCLK) are shared with all devices.

2. Use the multiplexer to cycle through each analog input.

The ADS1118 ADC has a multiplexer for measuring multiple channels. In this design, the system cycles through each of the analog inputs of each device. While single-ended measurements are available, this system is shown by cycling through all of the analog inputs to make differential measurements.

Devices are configured through the configuration register shown in the following table. Within the configuration register, the MUX[2:0] selects the AIN_P and AIN_N nodes for the ADC and sets the input channel for each device. The settings in the following table show settings for differential measurements. As shown in the [ADS1118](#) data sheet, single-ended measurements can be made with settings MUX[2:0] = 100 to 111.

Input Measurement	ADC Input	Device Input Selection
Channel 1	MUX[2:0] = 000	$AIN_P = AIN_0$ and $AIN_N = AIN_1$
Channel 2	MUX[2:0] = 011	$AIN_P = AIN_2$ and $AIN_N = AIN_3$

After cycling through all four channels of the device, the system selects the next device and repeats the cycle.

3. Identify the range of operation for each analog input measurement.

The ADS1118 device has an internal reference for accurate measurements and a scalable gain for the measurement. In this circuit document, the measurements shown are all differential. Negative measurements occur when AIN_N is higher than AIN_P . Single-ended measurements may be selected. However, because the ADS1118 device is a 16-bit ADC as a differential measurement, a single-ended measurement has only 15 bits of resolution.

The ADS1118 ADC can be set to one of 6 settings for the FSR (full-scale range). This is the equivalent to having a programmable gain amplifier on the front end of the ADC. The FSR[2:0] bits of the configuration register have settings from $\pm 0.256V$ up to $\pm 6.144V$. As mentioned previously, the operating range of the ADC analog inputs is between ground and VDD, even with the FSR set to voltages larger than the VDD. For example, with the FSR set to $\pm 6.144V$ and VDD set to 5V, the analog inputs are limited to 0 to 5V.

The FSR settings allow for a variety of different measurements from small voltage measurements such as temperature sensors or current shunt resistors, to larger voltage measurements ADC measuring its own supply without the need for a voltage divider. Settings for the ADS1118 FSR are shown in the following table.

Input Measurement	AIN_N and AIN_P Inputs	Digital Output ADS1118
PGA[2:0] = 000, FSR = $\pm 6.144V$	0V to 5V	97D5h to 682Bh
PGA[2:0] = 001, FSR = $\pm 4.096V$	0V to 4.096V	8000h to 7FFFh
PGA[2:0] = 010, FSR = $\pm 2.048V$	0V to 2.048V	8000h to 7FFFh
PGA[2:0] = 011, FSR = $\pm 1.024V$	0V to 1.024V	8000h to 7FFFh
PGA[2:0] = 100, FSR = $\pm 0.512V$	0V to 0.512V	8000h to 7FFFh
PGA[2:0] = 101–111, FSR = $\pm 0.256V$	0V to 0.256V	8000h to 7FFFh

As a differential measurement, the ADC reports a negative value when the AIN_N input is higher than the AIN_P input. Negative results are reported in two's complement notation.

4. Set the data rate.

The ADS1118 ADC can be configured to one of eight data rates, based on the internal oscillator of the device. This data rate has a tolerance of $\pm 10\%$. The data rate is set by the DR[2:0] bits shown in the following table.

Data Rate Setting	Data Rate
DR[2:0] = 000	8SPS
DR[2:0] = 001	16SPS
DR[2:0] = 010	32SPS
DR[2:0] = 011	64SPS
DR[2:0] = 100	128SPS
DR[2:0] = 101	250SPS
DR[2:0] = 110	475SPS
DR[2:0] = 111	860SPS

The data rate is selected to be 128SPS, which is the default setting of the ADS1118 ADC. This data rate is the fastest available that gives a noise performance better than one LSB for all FSR settings.

Configuration Register Settings

The configuration register sets the mode of operation and configuration of the ADC. Configurations include all of the settings described in the previous sections. Nine fields across 16 bits are used to configure the device. Configuration register field descriptions are shown with bit names and positions, read and write usage, and reset values in the following table.

15	14	13	12	11	10	9	8
SS	MUX[2:0]			PGA[2:0]			MODE
R/W-1h	R/W-0h			R/W-2h			R/W-1h
7	6	5	4	3	2	1	0
DR[2:0]			TS_MODE	PULL_UP_EN	NOP[1:0]		RESERVED
R/W-4h			R/W-0h	R/W-0h	R/W-0h		R-1h

The SS bit starts a single conversion. The MUX[2:0] bits set the input multiplexer to cycle through different measurements. The MODE bit sets the device to single-shot conversion mode. The DR[2:0] bits set the data rate of the device. The remaining fields are used for the ADC comparator settings which are not used in this design. See the [ADS1118 Ultra-Small, Low-Power, SPI-Compatible, 16-Bit ADCs With Internal Reference, and Temperature Sensor](#) data sheet for details on the configuration register.

As an example, one ADC is set to measure its own supply to ground, using AIN0 connected to VDD. The FSR is set to $\pm 6.144V$ with a data rate of 128SPS. The following table shows the settings for the configuration register fields.

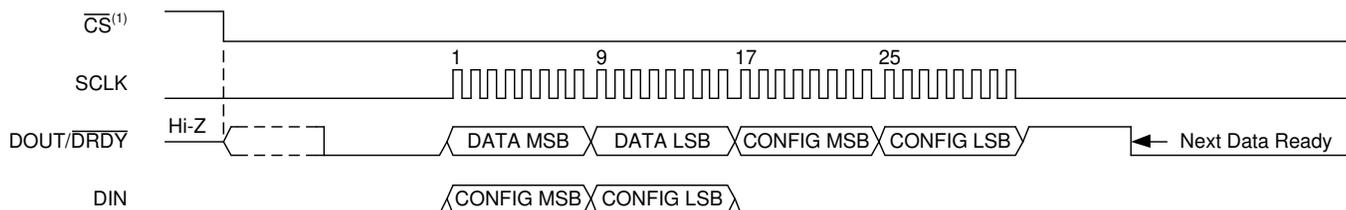
BIT	FIELD	SETTING	DESCRIPTION
15	OS	1	Start conversion
14:12	MUX[2:0]	000	Differential input measurement, AINP – AINN = AIN0 – AIN1, selection of the first channel
11:9	PGA[2:0]	000	FSR = $\pm 6.144V$, sets the ADC to be able to measure the full supply range of 0V to VDD
9	MODE	1	Operation in single-shot conversion mode
7:5	DR[2:0]	100	Data rate = 128SPS
4	TS_MODE	0	Measures analog inputs instead of the temperature sensor
3	PULL_UP_EN	0	Disables the internal pullup resistor on the DOUT/DRDY
2:1	NOP[1:0]	01	Write 01 to these bits to ensure that the device writes to the configuration register
0	RESERVED	1	Always write 1 to this bit

Combining these bits from the field descriptions, the configuration register values is 1000 0001 1000 0011 or 8183h.

Channel Cycling

To cycle through each channel of the system, start each conversion, wait for the conversion to complete, and then read back the data. Then start the conversion for the next channel. Repeat each measurement for both differential input channels before moving on to the next ADC. Repeating this measurement for all four ADCs in the system cycles through all channels.

Use the associated \overline{CS} line to communicate with the device. Each of the four devices has its own \overline{CS} line to enable the SPI. The 32-bit data transmission cycle with configuration register read back can be used to start conversions. This communication is shown in the following figure.



- (1) \overline{CS} can be held low in systems where the ADS1118 device does not share the serial bus with another device. If \overline{CS} is low, DOUT/DRDY asserts low indicating new data are available.

With this method, 32 SCLKs are used. Communication is full-duplex, meaning that the data is being clocked into the device at the same time as data is being clocked out of the device. The device starts a new conversion after the write of the configuration register.

As the configuration register is being written, 32 SCLKs clock out the data on DOUT/DRDY. The first 16 bits clock out the data from the previous conversion and the second 16 bits clock out contents of the configuration register and verifies the new configuration register write.

The master then waits for the conversion to complete. For this example, the ADS1118 device is set to the default data rate of 128SPS. Because the device uses an internal oscillator, there is some variation in the data rate. To ensure that the device is read after the ADC completes a conversion, the microcontroller waits for the maximum time required for the conversion to complete. This wait time is the nominal data period plus 10% (to compensate for the internal oscillator variation of the device). An additional 20 μ s is added for the wakeup time of the ADC for each single-shot conversion. The total wait time is calculated in the following equation.

$$\text{Wait time} = \text{nominal data period} + 10\% + 20\mu\text{s}$$

As an example, if the device is run at 128SPS, the nominal data period is 7.82ms. The necessary wait time is:

$$\text{Wait time} = (7.82\text{ms} \times 1.1) + 20\mu\text{s} = 8.62\text{ms}$$

Instead of waiting this maximum time as previously calculated, the DOUT/ $\overline{\text{DRDY}}$ line can be monitored to read the data. When the conversion completes, the DOUT/ $\overline{\text{DRDY}}$ transitions from high to low. This transition can be used as an interrupt to indicate that the data is ready, and that it can be clocked out of the device. The 32-bit data transmission cycle makes it easier to monitor the DOUT/ $\overline{\text{DRDY}}$. By reading back the configuration register, DOUT/ $\overline{\text{DRDY}}$ is forced high at the end of the transmission cycle. This makes it easy to find the transition from high to low. If DOUT/ $\overline{\text{DRDY}}$ is low, the data ready indication is a narrow 8- μs pulse.

Measurement Conversion

Conversions for the input voltage are based on the full-scale range (FSR) setting of the ADC. The FSR is set by the PGA[2:0] bits in the configuration register.

$$\text{Output Code} = 2^{15} \times [(V_{\text{AINP}} - V_{\text{AINN}}) / (\text{positive FSR})]$$

$$\text{Input Voltage} = V_{\text{AINP}} - V_{\text{AINN}} = (\text{Output Code}) \times (\text{positive FSR}) / (2^{15})$$

Negative readings are reported in two's complement notation. For example, -1 in decimal is reported as FFFFh and a negative full-scale reading is reported as 8000h.

As previously mentioned, the 16-bit ADS1118 ADC may be replaced with the 12-bit [ADS1018](#) ADC. For these devices, the data format is 12-bits with four bits zero padded on the right. A full scale reading is 7FFh and would be read from DOUT/ $\overline{\text{DRDY}}$ as 7FF0h.

The ADS1118 device also has a onboard precision temperature sensor that can also be measured at any time. For details on the temperature conversion, see the [ADS1118](#) data sheet.

Pseudo Code Example

The following pseudo code sequence shows the required steps to set up conversions from each channel of the four devices and collect the data after each conversion. It also includes setup for the microcontroller that interfaces to the ADC.

For each channel, the microcontroller simultaneously sets up the ADC configuration and starts the conversion. The microcontroller waits for conversion to complete, waiting enough time for the conversion and any variation in the internal oscillator frequency. Then the data is read from the conversion register. The cycle continues through each channel of each device. The setup assumes the previous configuration with the data rate set to 128SPS for the wait time for the conversion.

Configure the SPI interface of the microcontroller to SPI mode 1 (CPOL = 0, CPHA =1);
Conversions from two channels of device 1:

```
{
  Set CS1 to the device low;
  Send 32 SCLKs, Write 8183h, 0000h; // start conversion Channel 1, AIN0-AIN1
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 32 SCLKs, Write B183h, 0000h; // start conversion Channel 2, AIN2-AIN3, Read Channel 1
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 16 SCLKs; // read Channel 2
  Set CS1 to the device high;
}
```

Conversions from two channels of device 2:

```
{
  Set CS2 to the device low;
  Send 32 SCLKs, Write 8183h, 0000h; // start conversion Channel 3, AIN0-AIN1
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 32 SCLKs, Write B183h, 0000h; // start conversion Channel 4, AIN2-AIN3, Read Channel 3
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 16 SCLKs; // read Channel 4
  Set CS2 to the device high;
}
```

Conversions from two channels of device 3:

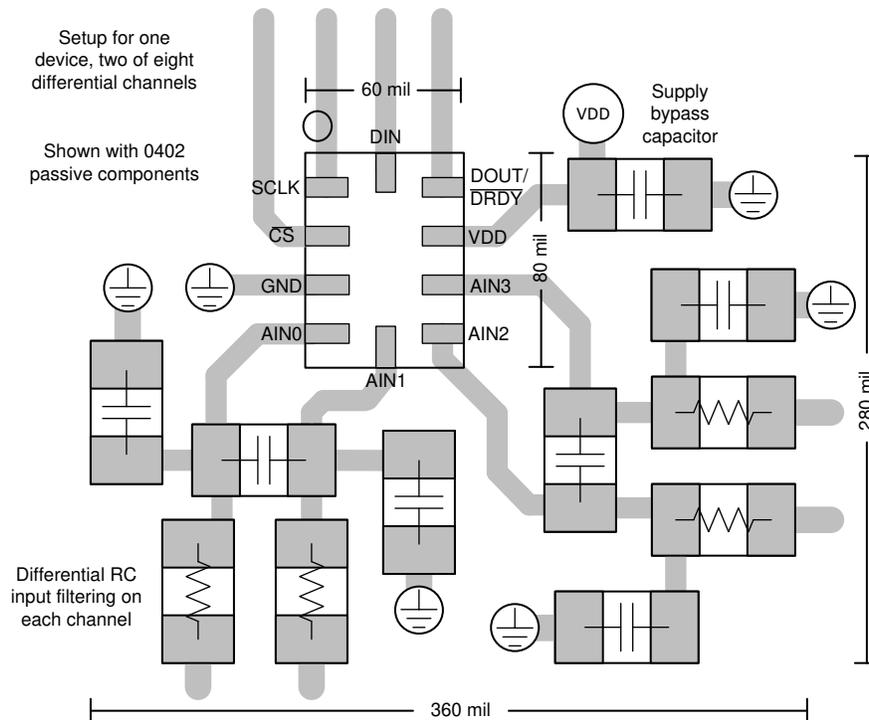
```
{
  Set CS3 to the device low;
  Send 32 SCLKs, Write 8183h, 0000h; // start conversion Channel 5, AIN0-AIN1
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 32 SCLKs, Write B183h, 0000h; // start conversion Channel 6, AIN2-AIN3, Read Channel 5
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 16 SCLKs; // read Channel 6
  Set CS3 to the device high;
}
```

Conversions from two channels of device 4:

```
{
  Set CS4 to the device low;
  Send 32 SCLKs, Write 8183h, 0000h; // start conversion Channel 7, AIN0-AIN1
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 32 SCLKs, Write B183h, 0000h; // start conversion Channel 8, AIN2-AIN3, Read Channel 7
  Wait 8.62ms or for the DOUT/DRDY line to return low
  Send 16 SCLKs; // read Channel 8
  Set CS4 to the device high;
}
```

Layout Example

The following image shows an example layout of one of the four ADS1118 devices. Differential RC input filtering is added using 0402 resistors and capacitors. The resulting layout is about 280 mils by 340 mils.



Example Layout

Design Featured Devices

Device	Key Features	Link	Other Possible Devices
ADS1118	ADS1118 ultra-small, low-power, SPI-compatible, 16-bit ADCs with internal reference, oscillator, and temperature sensor	http://www.ti.com/product/ADS1118	Link to similar devices Link to similar I2C devices

Design References

See the [Analog Engineer's Circuit Cookbooks](#) for TI's comprehensive circuit library.

For direct support from TI Engineers use the E2E community:

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