TEXAS INSTRUMENTS

ADS1293

Low Power, 3-Channel, 24-Bit Analog Front End for Biopotential Measurements

1.0 General Description

The ADS1293 incorporates all features commonly required in portable, low-power medical electrocardiogram (ECG), sports, and fitness applications. With high levels of integration and exceptional performance, the ADS1293 enables the creation of scalable medical instrumentation systems at significantly reduced size, power, and overall cost.

The ADS1293 features three high resolution channels capable of operating up to 26.5 kSPS. Each channel can be independently programmed for a specific sample rate and bandwidth allowing users' to optimize the configuration for performance and power. All input pins incorporate an EMI filter and can be routed to any channel via a flexible routing switch. Flexible routing also allows independent lead-off detection, right leg drive, and Wilson/Goldberger reference terminal generation without needing to reconnect leads externally. A fourth channel allows external analog pace detection for applications that do not utilize digital pace detection.

The ADS1293 incorporates a self-diagnostics alarm system to detect when the system is out of the operating conditions range. Such events are reported to error flags. The overall status of the error flags is available as a signal on a dedicated ALARMB pin.

The device is packaged in a 5-mm × 5-mm × 0.8-mm , 28-pin LLP. Operating temperature is specified from –20°C to +85° C.

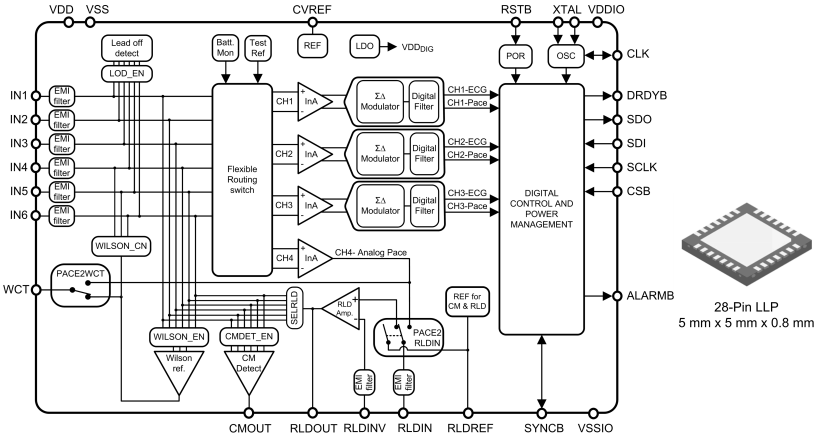
2.0 Applications

- Portable 1/2/3/5/6/7/8/12-Lead ECG Applications
- Patient vital sign monitoring: holter, event, stress, and telemedicine
- Automated External Defibrillator
- Sports and fitness (heart rate and ECG)

3.0 Features

- 3 High Resolution Digital ECG Channels with Simultaneous Pace Output
- EMI Hardened Inputs
- Low Power: 0.3 mW/channel
- Input-Referred Noise: 10 µVpp (40Hz BW, G=3.5)
- Input Bias Current: 100 pA
- Data Rate: Up to 25.6kSPS
- CMRR: >100 dB
- Differential Input Voltage Range: ±400mV
- Analog Supply Voltage: +2.7V to +5.5V
- Digital Input/Output Supply Voltage: +1.65V to +3.6V
- Right Leg Driver Amplifier
- AC and DC Lead-Off Detection
- Wilson and Goldberger Terminals
- ALARM Pin for Interrupt Driven Diagnostics
- Battery Voltage Monitoring
- Built-In Oscillator and Reference
- Flexible Power-Down, Standby Modes
- Standard SPI Interface
- Operating Temp Range: -20°C to +85°C
- Package: 5mm x 5mm x 0.8mm, 28-pin LLP

4.0 Typical Application



28-Pin LLP
5 mm x 5 mm x 0.8 mm

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5.0 Block Diagram

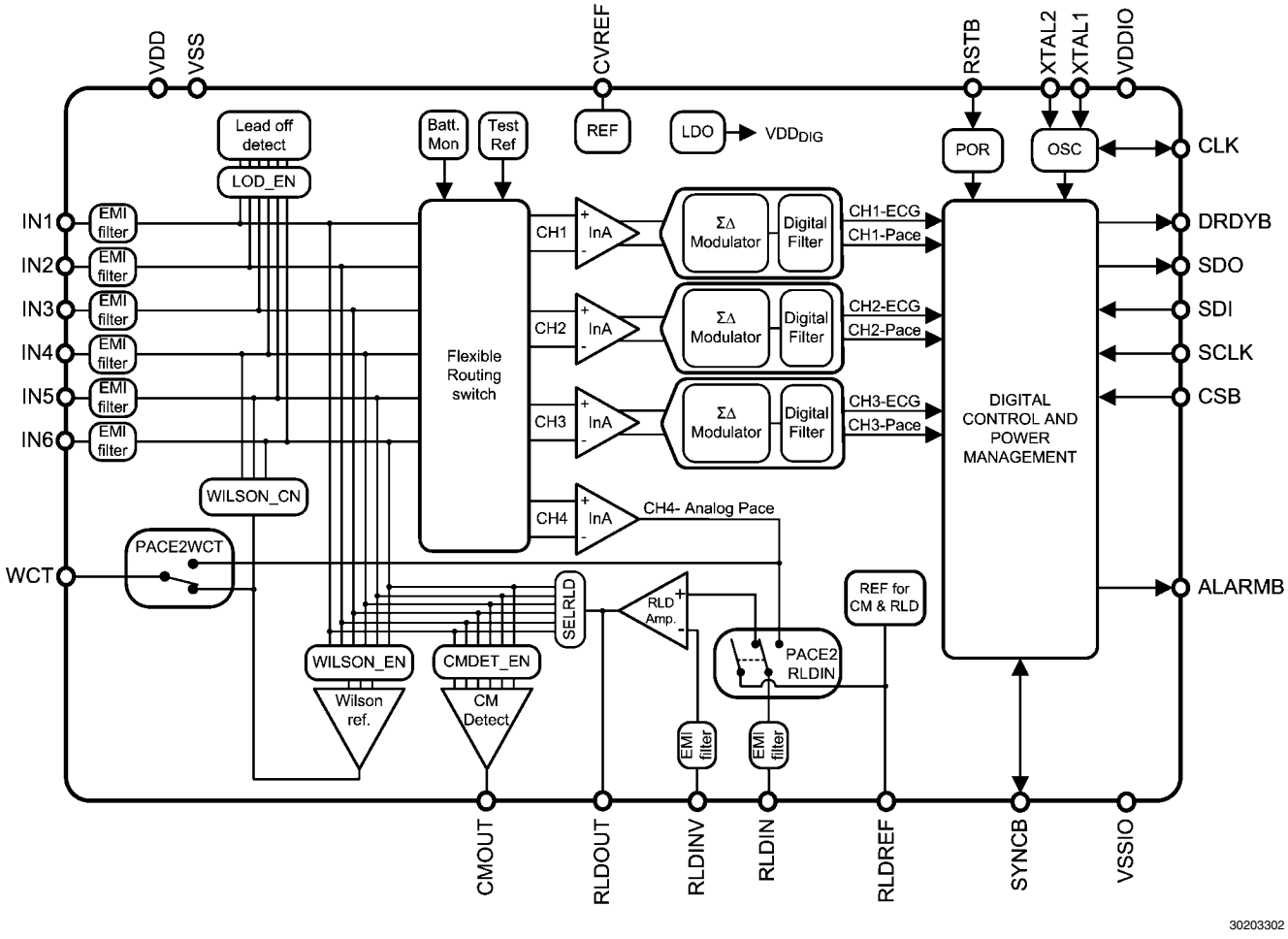


Table of Contents

List of Figures

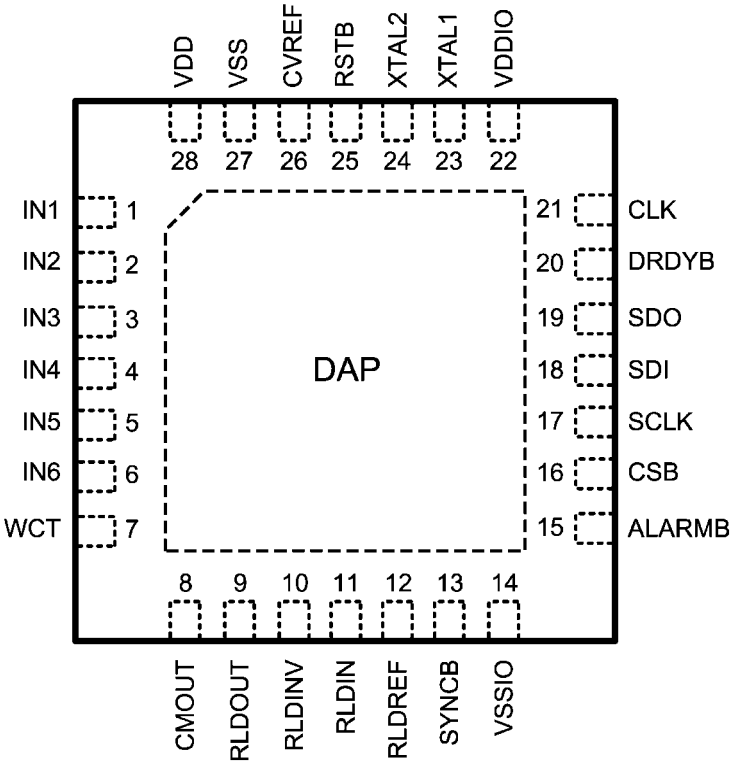
List of Tables

6.0 Ordering Information

Package	Part Number	Package Marking	Transport Media	NSC Drawing
28–Pin LLP	ADS1293	TBD	TBD	SQA28A

7.0 Connection Diagram

28–Pin LLP, Top View



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8.0 Pin Descriptions

Pin #	Pin Name	Type	Function
1 - 6	IN1 - IN6	Analog Input	Electrode input signals
7	WCT	Analog Output	Wilson reference output or analog pace channel output
8	CMOUT	Analog Output	Common mode output
9	RLDOUT	Analog Output	Right-leg drive amplifier output
10	RLDINV	Analog Input	Right-leg drive amplifier negative input
11	RLDIN	Analog I/O	Right-leg drive amplifier positive input or analog pace channel output
12	RLDREF	Analog Output	Internal right-leg drive reference
13	SYNCB	Digital I/O	Multiple-chip synchronization signal input or output
14	VSSIO	Digital Supply	Digital input/output supply ground
15	ALARMB	Digital Output	Alarm bar
16	CSB	Digital Input	Chip select bar
17	SCLK	Digital Input	Serial clock
18	SDI	Digital Input	Serial data input
19	SDO	Digital Output	Serial data output
20	DRDYB	Digital Output	Data ready bar
21	CLK	Digital I/O	Internal clock output or external clock input
22	VDDIO	Digital Supply	Digital input/output supply
23	XTAL2	Digital Input	External crystal for clock
24	XTAL1	Digital Input	External crystal for clock
25	RSTB	Digital Input	Reset bar
26	CVREF	Analog I/O	External cap for internal reference voltage
27	VSS	Analog Supply	Power supply ground
28	VDD	Analog Supply	Positive power supply
	DAP		No connect

9.0 Absolute Maximum Ratings (*Note 1*)

If Military/Aerospace specified devices are required, please contact the Texas instruments Sales Office/Distributors for availability and specifications.

			Units
ESD Tolerance (*Note 4*)	Human Body Model (HBM) /For input pins only	TBD	V
	Human Body Model (HBM) For all other pins	TBD	V
	Charge Device Model (CDM)	TBD	V
Analog Supply Voltage, VDD		-0.3 to 6.0	V
Digital Supply Voltage, VDDIO		-0.3 to 6.0	V
Voltage on any Input Pin		-0.3 to (VDD + 0.3)	V
Input Current at Any Pin		±10	mA
Storage Temperature Range		-65 to +150	°C
Junction Temperature (*Note 3*)		TBD	°C
For soldering specifications see: www.national.com/ms/MS/MS-SOLDERING.pdf			

10.0 Operating Ratings

			Units
Analog Supply Voltage, VDD		+2.7 to +5.5	V
Digital I/O Supply Voltage	VDD > +3.6V	+1.65 to +3.6	V
	VDD ≤ +3.6V	+1.65 to VDD	V
Supply Ground		VSS = VSSIO	
Full Scale Input Range, ΔVIN		±400	mV
Temperature Range (*Note 3*)		-20 to +85	°C
Package Thermal Resistance (*Note 3*), 28-Pin LLP (θ_{JA})		TBD	°C/W

11.0 Electrical Characteristics (*Note 2*)

Unless otherwise noted, all limits guaranteed at T_A = +25°C, +2.7V ≤ VDD ≤ +5.5V, +1.65 ≤ VDDIO ≤ MIN(+3.6V, VDD), VREF = +2.4V, f_{OSC} = 409.6 kHz, 1µF low ESR capacitor between CVREF and GND, 0.1µF capacitor between RLDREF and GND. **Boldface** limits apply for $T_{MIN} \le T_A \le T_{MAX}$.

Symbol	Parameter	Conditions	Min (*Note 6*)	Typ (*Note 5*)	Max (*Note 6*)	Units
Power Supply (VDD, VDDIO)						
VDD	Analog Supply Voltage		2.7		5.5	V
IVDD	Analog Supply Current	Power-down mode		80		µA
		Stand-by mode		105		µA
		1 chan, WILSON OFF, RLD OFF, CMDET OFF, LOD OFF, low power	TBD	165		µA
		1 chan, WILSON OFF, RLD OFF, CMDET OFF, LOD OFF, high-res	TBD	235		µA
		3 chan, WILSON OFF, RLD OFF, CMDET OFF, LOD OFF, low power	TBD	300		µA
		3 chan, WILSON ON, RLD ON, CMDET ON, LOD ON, low power	TBD	390		µA
		3 chan, WILSON ON, RLD ON, CMDET ON, LOD ON, high-res, low cap-drive	TBD	700		µA
		3 chan, WILSON ON, RLD ON, CMDET ON, LOD ON, high-res, high cap-drive	TBD	825		µA

Symbol	Parameter	Conditions	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
VDDIO	IO Supply Voltage	VDD > 3.6V	1.65		3.6	V
		VDD ≤ 3.6V	1.65		VDD	V
IVDDIO	Quiescent Current IO Supply			10		pA
Analog Inputs (IN1 - IN6)						
I_B	Input Bias Current	T_A=25°C, LOD OFF			±100	pA
		T_A=85°C, LOD OFF			±800	pA
		LOD ON	8		2040	nA
CIN	Input Capacitance			TBD		pF
RIN	Differential Input Resistance			10		MΩ
Analog Front End						
DIVR	Differential Input Voltage Range		-400		400	mV
CMVR	Common Mode Voltage Range for full DIVR		0.95		VDD-0.95	V
V_{OS}	Input Referred Offset Voltage			±100	1000	µV
CMRR	Common Mode Rejection Ratio	50 / 60 Hz, VCM = TBD	100			dB
V_e-ECG	Input Referred Voltage Noise for ECG	0.1 - 200Hz, low power mode		21	30	μV_{PP}
		0.1 - 200Hz, high resolution mode		15	18	μV_{PP}
		0.1 - 40Hz, low power mode		10	14	μV_{PP}
		0.1 - 40Hz, high resolution mode		7	8	μV_{PP}
V_e-PACE	Input Referred Voltage Noise for Pace	0.1 - 2.5kHz, high resolution mode		100	200	μV_{PP}
SNR	Signal to Noise Ratio	0.1 - 200Hz, low power mode	104			dB
		0.1 - 200Hz, high resolution mode	108			dB
N_e	Noise Density	0.1 - 200Hz, low power mode		180	350	nV/√Hz
		0.1 - 200Hz, high resolution mode		110	210	nV/√Hz
PSRR	Power Supply Rejection Ratio	50 / 60 Hz	80			dB
XTLK	Crosstalk between channels	Crosstalk from driven channel to zero input channel			-105	dB
THD	Total Harmonic Distortion	VIN_{PP} = 10mV, 10Hz		TBD		dB
ENOB-ECG	Effective Number of Bits for ECG	200 Hz bandwidth, low power mode	17.3			bits
		200 Hz bandwidth, high resolution mode	18.1			bits
ENOB-PACE	Effective Number of Bits for Pace	2.5 kHz bandwidth, high resolution mode	12.7			bits
RS-ECG	Sample Rate ECG Channel	See *Table 3*, *Table 4*, *Table 5* and *Table 6*		1000		sps
RS-PACE	Sample Rate PACE Channel	See *Table 3*, *Table 4*, *Table 5* and *Table 6*		10	25	ksps
TSKEW	Sample Time Skew Between Channels			0	1	µs
RF Immunity Filters						
EMIRR	EMI Rejection Ratio	f = 400 MHz		55		dB
		f = 900 MHz		57		dB
		f = 1800 MHz		60		dB
		f = 2400 MHz		63		dB
Internal Reference (REF)						
V_{REF}	Internal Reference Voltage			2.4		V
	Internal Reference Accuracy			1		%
	Internal Reference Drift			25		ppm/°C
	Internal Reference Start-up Time			10		ms

Symbol	Parameter	Conditions	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
Battery Monitor						
Division	(VDD-V_{REF})/factor			1.656		V/V
	Division Accuracy			0.2		%
Test Reference						
	(V_{REF}-VSS)/factor			12		V/V
	Division Accuracy			0.2		%
	Current Consumption				20	µA
Right-Leg Drive Amplifier (RLD Amp)						
V_{OS}	Input Referred Offset Voltage			±3		mV
CMVR	Common Mode Voltage Range		0		VDD	V
CMRR	Common Mode Rejection Ratio		70			dB
GBW	Programmable Gain Bandwidth	Low bandwidth mode		50		kHz
		High bandwidth mode		200		kHz
SR	Slew Rate	Low bandwidth mode		15		mV/µs
		High bandwidth mode		60		mV/µs
V_e-RLD	Input Referred Noise for Right Leg Drive Amp	0.1 - 200Hz		60		$µV_{PP}$
CI_{MAX}	Programmable Capacitive Load Driving Capability	High bandwidth, Low cap-drive mode (see *Table 9*)		400		pF
		Low bandwidth, High cap-drive mode (see *Table 9*)		8		nF
IVDD	Quiescent Power Consumption	Low cap-drive mode			16	µA
		High cap-drive mode			66	µA
Right-Leg Drive Reference						
RLD_{REF}	Output Voltage	Unloaded		(VDD-VSS)/2.2		V
Common Mode Detector Amplifier (CMDET Amp)						
CMVR	Common Mode Voltage Range		0		VDD	V
BW	Programmable Bandwidth	Low bandwidth mode		50		kHz
		High bandwidth mode		125		kHz
SW	Slew Rate	Low bandwidth mode		15		mV/µs
		High bandwidth mode		60		mV/µs
V_e-CMDET	Input Referred Noise for Common Mode Detect Amp			60		$µV_{PP}$
CI_{MAX}	Programmable Capacitive Load Driving Capability	High bandwidth mode, Low cap-drive mode (see *Table 8*)		400		pF
		Low bandwidth mode, High cap-drive mode (see *Table 8*)		8		nF
IVDD	Power Consumption for Selected Leads	N leads, low bandwidth mode, low cap-drive mode		20+3*N		µA
		N leads, high bandwidth mode, high cap-drive mode		66+3*N		µA
Wilson Reference Circuit						
IVR	Input Voltage Range		0		VDD	V
BW	Bandwidth			100		kHz
SR	Slew Rate			30		mV/µs
N_e	Noise Density	At 10 Hz		250		nV/√Hz
V_e	Input Referred Noise for Wilson Reference Amp	0.1 - 200 Hz		20		$µV_{PP}$

Symbol	Parameter	Conditions	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
IVDD	Power Consumption for Selected Leads	N leads, low power mode		6*N		µA
		N leads, high resolution mode		21*N		µA
Lead Off Detection						
IEXC	Excitation Current	Programmable 8 bit DAC, 8 nA increments (See *Section 14.7 LEAD-OFF DETECTION (LOD)*)	0		2040	nA
$IEXC_{TOL}$	Excitation Current Accuracy			25		%
FEXC	Excitation Frequency	AC LOD mode, programmable (see *Section 14.7.2 Analog AC Lead-Off Detect*)	6.10		12500	Hz
VTH_{DC}	DC Lead Off Comparator Threshold			VDD-0.5		V
VTH_{AC}	Analog AC Lead Off Comparator Threshold	Programmable 2 bit (see *Section 14.7.2 Analog AC Lead-Off Detect*)	0.60*VDD		0.85*VDD	V
V_{HYST}	Comparator Hysteresis	DC lead off mode		100		mV
IVDD	Current Consumption	Programmed excl. excitation current			10	µA
Analog Pace Channel						
	Gain			3.5		V/V
BW	-3dB Bandwidth			28		kHz
	Output Reference			RLD_{REF}		V
V_{OS}	Input Referred Offset Voltage				7	mV
CMVR	Common Mode Voltage Range		0.95		VDD-0.95	V
CMRR	Common Mode Rejection Ratio	0.95V ≤ VCM ≤ VDD-1.5V		90		dB
PSRR	Power Supply Rejection Ratio	3V ≤ VDD ≤ 5V, VCM=VDD/2.2		76		dB
R_{IN}	Differential Input Impedance			1		GΩ
I_B	Input Bias Current				1	pA
SR	Slew Rate			18		mV/µs
	Overload Recovery			300		µs
V_e-APACE	Input Referred Noise for Analog Pace	0.95V ≤ VCM ≤ VDD-1.5V 0.1kHz - 20kHz		120		$µV_{PP}$
		VDD-1.5V ≤ VCM ≤ VDD-0.95 0.1kHz - 20kHz		420		$µV_{PP}$
IVDD	Current Consumption				TBD	µA
Clock						
f_{OSC}	Internal Clock Frequency	$f_{CRYSTAL}$ = 4.096 MHz		409.6		kHz
	Internal Clock Duty Cycle			50		%
T_{START}	Internal Clock Start up Time	$f_{CRYSTAL}$ = 4.096 MHz		25		ms
IVDD	Internal Clock Power Consumption			8		µA
f_{EXT}	External Clock Frequency		330	409.6	500	kHz
	External Clock Duty Cycle		30	50	70	%
Digital Input/Output Characteristics						
VIH	Logical “1” Input Voltage		0.8x VDDIO			V
VIL	Logical “0” Input Voltage				0.2x VDDIO	V
VOH	Logical “1” Output Voltage	I_{SOURCE} = 400 µA Digital output high drive mode	VDDIO -0.075			V
		I_{SOURCE} = 400 µA Digital output low drive mode	VDDIO -0.150			V

Symbol	Parameter	Conditions	Min (Note 6)	Typ (Note 5)	Max (Note 6)	Units
VOL	Logical “0” Output Voltage	I_{SINK} = 400 µA Digital output high drive mode			VSSIO +0.075	V
		I_{SINK} = 400 µA Digital output low drive mode			VSSIO +0.150	V

Note 1: “Absolute Maximum Ratings” indicate limits beyond which damage to the device may occur, including inoperability and degradation of the device reliability and/or performance. Functional operation of the device and/or non-degradation at the Absolute Maximum Ratings or other conditions beyond those indicated in the Recommended Operating Conditions is not implied. The Recommended Operating Conditions indicate conditions at which the device is functional and the device should not be beyond such conditions. All voltages are measured with respect to the ground pin, unless otherwise specified.

Note 2: The Electrical Characteristics table lists guaranteed specifications under the listed Recommended Operating Conditions except as otherwise modified or specified by the Electrical Characteristics Conditions and/or Notes. Typical specifications are estimations only and are not guaranteed.

Note 3: The maximum power dissipation must be derated at elevated temperatures and is dictated by $T_{J(MAX)}$, θ_{JA}, and the ambient temperature, T_A. The maximum allowable power dissipation $P_{DMAX} = (T_{J(MAX)} - T_A)/ \theta_{JA}$ or the number given in Absolute Maximum Ratings, whichever is lower.

Note 4: Human Body Model per MIL-STD-883, Method 3015.7. Machine Model, per JESD22-A115-A. Field-Induced Charge-Device Model, per JESD22-C101-C.

Note 5: Typical values represent the most likely parameter norms at T_A = +25°C and at the Recommended Operation Conditions at the time of product characterization and are not guaranteed.

Note 6: Datasheet min/max specification limits are guaranteed by test, unless otherwise noted.

Note 7: Positive current corresponds to current flowing into the device.

12.0 Timing Diagrams

Unless otherwise noted, all limits guaranteed at T_A = +25°C, +2.7V ≤ VDD ≤ +5.5V, +1.65 ≤ VDDIO ≤ VDD, VREF = +2.4V, f_{OSC} = 409.6 kHz and a 10pF capacitive load in parallel with a 10kΩ load on SDO.

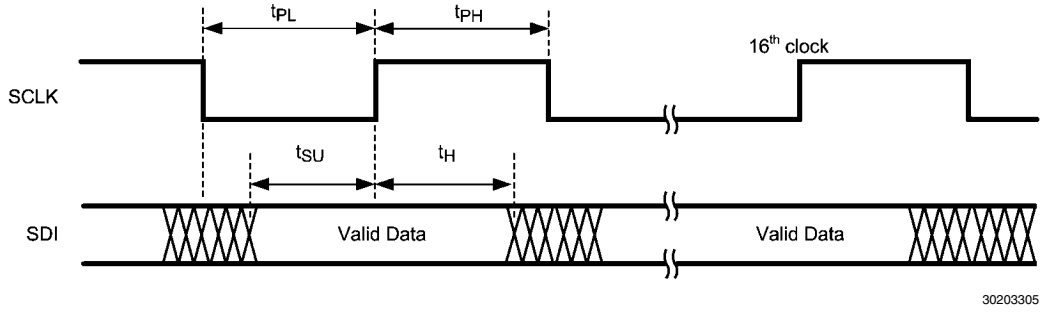
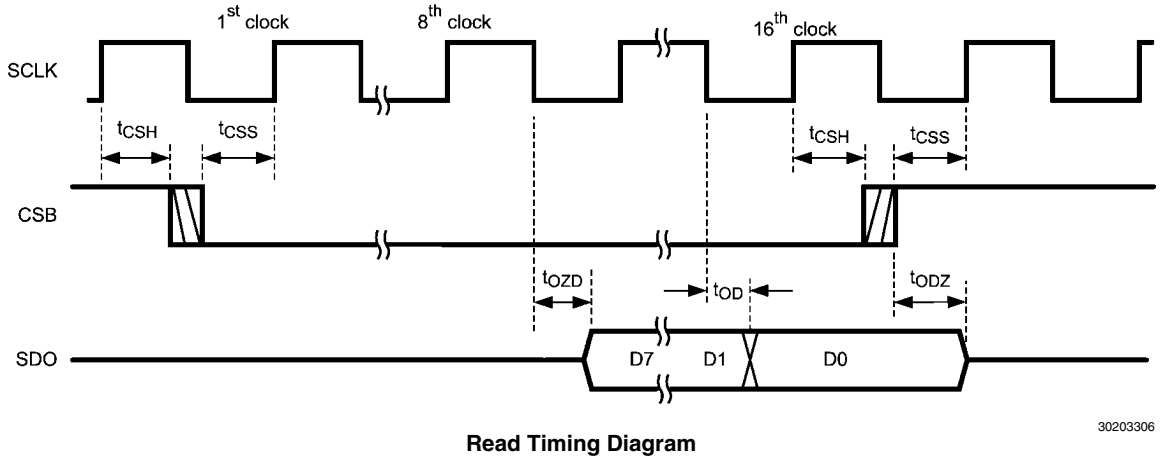


FIGURE 1. Write Timing Diagram

Symbol	Parameter	Conditions	Min	Typ	Max	Units
F_{SCLK}	Serial Clock Frequency				20	MHz
		Clock may be stopped	0			MHz
t_{PH}	SCLK Pulse Width - High		0.4/ F_{SCLK}			s
t_{PL}	SCLK Pulse Width - Low		0.4/ F_{SCLK}			s
t_{SU}	SDI Setup Time		5			ns
t_H	SDI Hold Time		5			ns



Read Timing Diagram

Symbol	Parameter	Conditions	Min	Typ	Max	Units
t_{ODZ}	SDO Driven-to-Tristate Time	Measured at 10% / 90% point			tbd	ns
t_{OZD}	SDO Tristate-to-Driven Time	Measured at 10% / 90% point			tbd	ns
t_{OD}	SDO Output Delay Time		5		15	ns
t_{CSS}	CSB Setup Time		5			ns
t_{CSH}	CSB Hold Time		5			ns
t_{IAG}	Inter-Access Gap		30			ns
t_{DRDYB}	Data Ready Bar at every 1/ODR second, see *Figure 14*			$4/f_{OSC}$		s

13.0 Typical Performance Characteristics

Unless otherwise specified, measurements taken at T_A = +25°C, +2.7V ≤ VDD ≤ +5.5V, VDDIO = +3.3V.

14.0 Functional Description

The ADS1293 is a fully integrated signal chain for ECG applications. It includes three low-power and low-noise analog front-ends followed by three synchronized high-performance 24-bit analog-to-digital converters. In addition, the ADS1293 features lead-off detection, right-leg drive capability, and Wilson and Goldberger terminals.

The ADS1293 features three high-resolution signal paths for ECG monitoring, each of which offers a programmable signal bandwidth from 5 Hz to 1280 Hz. In addition, a lower resolution output with a signal bandwidth of 3.2kHz to 25.6 kHz is optionally provided for each signal channel. These output signals are ideal for sensing a pace-maker signal. Each channel provides enough dynamic range to handle electrode offset and motion artifacts without sacrificing resolution. Each input has a built in EMI filter that eliminates noise from RF transmitters.

14.1 FLEXIBLE ROUTING SWITCH

The flexible routing switch can connect the inputs of the three analog front end channels as well as the inputs of the analog pace channel to any of the 6 input pins. This allows system flexibility and even on-the-fly reconfiguration of the ECG monitoring system. For calibration purposes, the flexible routing switch can short the differential input pins of a channel or connect a differential reference signal to the input of a channel. This reference voltage can be applied with both positive and negative polarity. This feature allows to measure relative mismatches between channels, such as offset and gain mismatches. Additionally, there is an option to route the battery voltage (the voltage source connected to the VDD pin) to an input channel. This allows the ADS1293 to monitor the state of charge of the battery.

The switch path inside the flexible routing switch is illustrated in *Figure 2*. The figure shows only the switch path for the first channel. The other channels are completely identical. The switches are controlled by the registers *FLEX_CH1_CN*, *FLEX_CH2_CN*, *FLEX_CH3_CN*, and *FLEX_VBAT_CN*, which are described in *Section 16.3 Input Channel Selection Registers*.

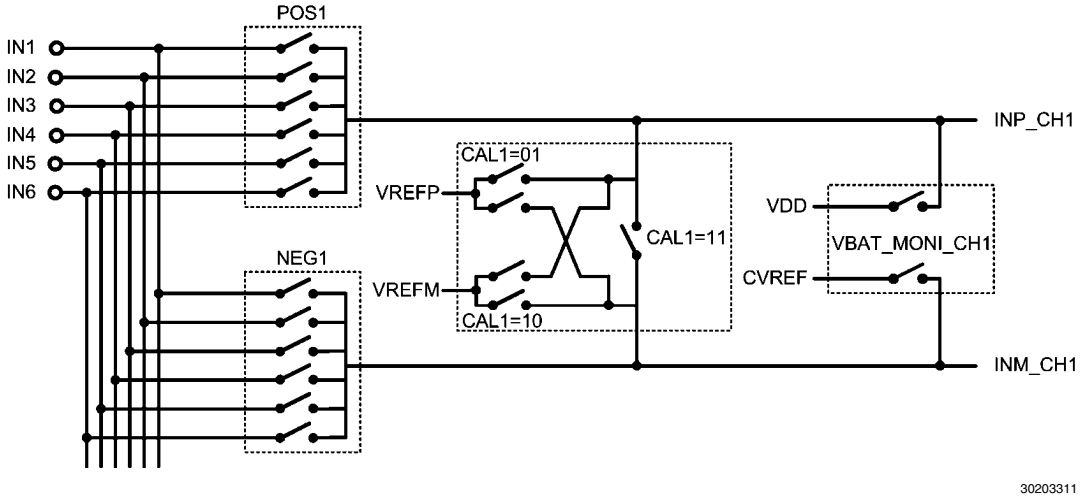


FIGURE 2. Flexible routing switch for channel 1

It should be noted that the switches that control the input selection for the analog front end channels have a certain priority. If the battery voltage monitoring mode is enabled by programming the VBAT_MONI_CHx bit in the *FLEX_VBAT_CN: Flex Routing Switch for Battery Monitoring* register, then the POSx and NEGx bits programmed in the FLEX_CHx_CN register no longer have any effect. The battery voltage monitoring mode thus takes priority; this is shown in the first row of *Table 1*. Furthermore, the calibration features take second priority over the input pin selection. If the CALx bit of the FLEX_CHx_CN register are not zero, then the POSx and NEGx bits are essentially ignored, and the calibration features will take priority as seen in *Table 1*. The CALx, POSx, and NEGx bits are described in *Section 16.3 Input Channel Selection Registers*.

TABLE 1. Channel 1 switch configuration

VBAT_MONI_CH1	CAL1	POS1	NEG1	Mode
1	X	X	X	CH1 is in battery voltage monitoring mode
0	11	X	X	CH1 input shorted
0	01	X	X	CH1 input connected to positive reference
0	10	X	X	CH1 input connected to negative reference
0	00	M	N	CH1 positive input connected to input pin M and negative input connected to input pin N

14.1.1 Battery Monitoring

The battery voltage monitoring mode is enabled by setting bit VBAT_MONI_CHx = 1 in the *FLEX_VBAT_CN: Flex Routing Switch for Battery Monitoring* register. Also, the instrumentation amplifier of this channel must be shut down by setting SHDN_INA_CHx = 1 in the *AFE_SHDN_CN: Analog Front-End Shutdown Control* register. In this mode, the positive input, POSx, of the sigma delta modulator will sample the voltage supplied on the VDD pin. At the same time, the negative input, NEGx, of the sigma delta modulator will sample the reference voltage, V_{REF}, generated on or provided to the CVREF pin. As a result, the output signal of the sigma delta modulator is a measure for (V_{BAT}-V_{REF}). In this operation, the sigma delta modulator works with a modified gain factor, and the battery voltage,V_{BAT}, can be calculated from the ADC output code equation (see section *Section 14.2.4 ADC Ouput Code (ADC_{DOUT})*):

$$V_{BAT} = V_{REF} \left[1 + 2\,(1.656) \left(\frac{ADC_{OUT}}{ADC_{MAX}} - \frac{1}{2} \right) \right] \quad (1)$$

In this equation, V_{REF} equals 2.4V if the internal reference voltage generator is used, and ADC_{MAX} represents the maximum output code of the ADC, which would correspond to a 2.4V signal at the input of the sigma delta modulator. The value of ADC_{MAX} is dependent on the configuration of the digital filters, and the corresponding ADC_{MAX} values are listed in *Table 3* through *Table 6*.

The battery monitoring mode is targeted for battery operated systems within a voltage range of 2.4V to 4.8V. The battery monitoring mode cannot be used when the ADS1293 is powered from a regulated 5V supply because it risks saturating the sigma delta modulator. There is a also a low battery alarm that is implemented independently from the battery monitoring mode, and it will trigger a battery alarm when the supplied voltage is below 2.7V (see the BATLOW description in *Section 14.12 ALARM FUNCTIONS*).

14.1.2 Calibration Mode

If the battery voltage monitoring function is not enabled, and if bit CALx = 01 (see the *Section 16.3 Input Channel Selection Registers* registers), then a positive DC test signal is provided to the input of the instrumentation amplifier. If CALx = 10, then the same test signal is provided but with negative polarity. The expected ADC output code can be calculated as follows:

$$ADC_{OUT} = \left[\pm \frac{3.5\,V_{TEST}}{2\,V_{REF}} + \frac{1}{2} \right] ADC_{MAX} \quad (2)$$

In the above equation, the positive or negative DC test signal $V_{TEST} = V_{REF}/12$. Note that this test mode is not a gain calibration since V_{TEST} and V_{REF} are generated by the same reference; however, it can be used as a self-test or to measure gain mismatches between channels.

When CALx = 11, the inputs of the instrumentation amplifier in the channel can be shorted to provide a zero test signal. The expected ADC output code equation can be simplified to:

$$ADC_{OUT} = \frac{1}{2} ADC_{MAX} \quad (3)$$

For both equations, the value of ADC_{MAX} corresponding to a given decimation configuration can be obtained from the *Table 3* through *Table 6*.

14.2 ANALOG FRONT END

The ADS1293 contains three analog front ends that convert a differential analog voltage into a digital signal. Each analog front end consists of an instrumentation amplifier (INA), a sigma-delta modulator (SDM), and a digital filter.

14.2.1 Instrumentation Amplifier (INA)

The instrumentation amplifier provides a high input impedance to interface with signal sources that may have relatively high output impedance, such as ECG electrodes. The maximum differential input voltage range of the Sigma-Delta Modulator (SDM) behind the INA is ±1.4V, and the gain of the INA is 3.5x. Therefore, the maximum differential input voltage of the INA is ±400mV.

The input common mode voltage range (CMVR) of the INA is 0.95V to VDD-0.95V. If the input differential voltage range is limited to smaller values, then the CMVR can be somewhat extended. If the differential input signal is limited to VIN_{MAX}, then the CMVR ranges from 1.75*VIN_{MAX}+0.25V to VDD-1.75*VIN_{MAX}-0.25V.

The INA can be configured to operate in a low-power mode or in a high-resolution mode. The low-power mode consumes about 4 times less power than the high-resolution mode. However, the high-resolution mode has TBD less noise than the low-power mode. Switching between these two modes is controlled by the EN_HIRES bits in the *AFE_RES: Analog Front-End Frequency and Resolution* register.

When a channel is not in use, its INA can be shut down by programming the SHDN_INA_CHx bit in the *AFE_SHDN_CN: Analog Front-End Shutdown Control* register, and its SDM can be shut down by programming the SHDN_SDM_CHx bit in the same *AFE_SHDN_CN: Analog Front-End Shutdown Control* register.

14.2.1.1 Instrumentation Amplifier Fault Detection

The output signal of the instrumentation amplifier can be monitored to ensure its output signal is within an appropriate range. The out of range error flags for the INAs can be observed in the *ERROR_RANGE1: Channel 1 AFE Out of Range Status*, and *ERROR_RANGE3: Channel 3 AFE Out of Range Status* registers.

The output signal is present at two points: OUTP and OUTN. If the input common mode voltage or differential voltage is such that the instrumentation amplifier would have to drive the voltages at these points above the positive or below the negative supply rail, then the signal accuracy would be lost. These two points are monitored and a warning flag is raised if the voltage on these pins approaches the supply rails. If the OUTP_HIGH flag is raised, then the voltage at OUTP is close to the positive rail. This indicates the differential input signal is too large or the input common mode voltage is too high. If the OUTP_LOW flag is raised, then the voltage at OUTP is close to the negative rail. This happens at low input common mode voltages and large negative differential input voltages. Similar reasoning holds for the OUTN_HIGH and OUTN_LOW flags.

The differential output voltage of the INA is monitored and reported to the DIF_HIGH bit. This error flag indicates that the differential signal is out of range and is no longer an accurate representation of the input signal. The DIF_HIGH error flag is raised if the differential output voltage of the INA exceeds ±1.4V, which is the input range of the Delta-Sigma Modulator. When this happens, the SDM will no longer sample the output of the INA, but instead will sample 0V. The sign of the input signal can still be observed in the SIGN bit of the *ERROR_RANGEx* registers.

The fault detection circuitry for OUTP_HIGH, OUTP_LOW, OUTN_HIGH and OUTN_LOW can be shut down by programming the SHDN_FAULTDET_CHx bits in the *AFE_FAULT_CN: Analog Front-End Fault Detection Control* register. These shutdown bits do not affect the operation of DIF_HIGH and SIGN because the instrumentation amplifier should always provide these signals to the sigma delta modulator. The circuitry that generates DIF_HIGH and SIGN only gets shut down when the corresponding SDM is shut down.

14.2.2 Sigma Delta Modulator (SDM)

The Sigma Delta Modulator (SDM) takes the output signal of the INA and converts this signal into a high resolution bit stream that is further processed by the digital filters.

The SDM can operate at a clock frequency of 102.4kHz or 204.8kHz; these frequencies are generated internally. Running the SDM at 204.8kHz results in a larger oversampling ratio, which improves the resolution of the signal recovered by the digital filters behind the SDM. However, running the SDM at this 204.8 kHz will increase its power consumption, resulting in a trade-off between resolution and power consumption.

The 102.4 kHz or 204.8 kHz clock frequency can be selected for each channel individually by programming the FS_HIGH_CHx bits in the *AFE_RES: Analog Front-End Frequency and Resolution* register.

The SDM also features dithering to reduce tones in the system, a known by-product of Sigma Delta converters. The dithering circuit is active by default and is automatically turned OFF when the input signal is larger than 40mV.

14.2.2.1 Sigma Delta Modulator Fault Detection

The state of the integrators in the Sigma Delta Modulator (SDM) are monitored to detect over-range signals that cause the SDM to become unstable. When an over-range event is detected in the SDM, the state of its integrators is reset, and the over-range error is reported to the SDM_OR_CHx bits of the *ERROR_RANGE1: Channel 1 AFE Out of Range Status*, , and *ERROR_RANGE3: Channel 3 AFE Out of Range Status* registers.

14.2.3 Programmable Digital Filters

A programmable digital filter behind the Sigma Delta Modulator (SDM) reconstructs the signal from the SDM output bit stream. The filter consist of three programmable SINC filters as shown in *Figure 3*. Each stage is a fifth order SINC filters

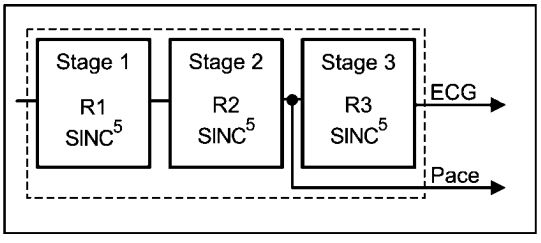


FIGURE 3. SINC Filters

The decimation rates (R1, R2, and R3) of the SINC filters are programmable as described in *Table 2*. Each of the three stages further filters and decimates the bit stream so that the output data rate (ODR) and bandwidth (BW) of the signal is reduced, and at the same time, the resolution is enhanced. A 16-bit digital signal with relatively high ODR and BW, but with somewhat limited resolution, is available after the second stage; this signal can be used for PACE pulse detection. That signal is further decimated by the third stage and results in a very high resolution filtered 24-bit digital signal that is an accurate representation of the ECG signal.

TABLE 2. Programmable digital filter coefficients

Stage 1	Stage 2	Stage 3
R1 = 4 Standard PACE Data Rate	R2 = 4,5,6,8	R3 = 4,6,8,12,16,32,64,128
R1 = 2 Double PACE Data Rate	R2 = 4,5,6,8	R3 = 4,6,8,12,16,32,64,128

The first stage sets the Standard PACE Data Rate (where the decimation rate R1 = 4) or the Double PACE Data Rate (where R1 = 2). Operating the device in the Double PACE Data Rate will double the ODR for the first stage (and therefore also for the subsequent stages). However, the BW of the first stage does not change in this mode; only the ODR is programmable. By operating the device in the Double PACE Data Rate, the ODR of the PACE data is doubled, and thus, more accurate PACE pulse detection is possible. However, operating the device in the Double PACE Data Rate will increase its power consumption. The R1 decimation rate can be programmed for each of the three channels separately by using the *R1_RATE: R1 Decimation Rate* register.

The second stage has a programmable decimation rate R2 of 4, 5, 6, or 8. Programming a low decimation rate sets a relatively high ODR and BW, but doing so will also increase the noise of each channel. When detecting a PACE pulse, a lower R2 is recommended. The R2 decimation rate can be programmed using the *R2_RATE: R2 Decimation Rate* register.

The third and final filter stage has a programmable decimation rate R3 of 4, 6, 8, 12, 16, 32, 64 or 128. As R3 increases, the ODR and BW of the ECG decreases. When detecting an ECG signal, a higher R3 is recommended. The R3 decimation rate for each channel can be individually programmed using the *R3_RATE_CH1: R3 Decimation Rate for Channel 1*, *R3_RATE_CH2: R3 Decimation Rate for Channel 2*, and *R3_RATE_CH3: R3 Decimation Rate for Channel 3* registers.

Table 3, *Table 4*, *Table 5*, and *Table 6* illustrate how these decimation rates R1, R2, and R3 affect the ODR, BW, and RMS Noise of the PACE and ECG signals. In addition, the ODR and BW also depend on whether the SDM is running at a low (102.4 kHz) or high (204.8 kHz) clock frequency (set by the FS_HIGH_CHx bits in the *AFE_RES: Analog Front-End Frequency and Resolution* register). The RMS Noise of the PACE and ECG channels also depend on whether the instrumentation amplifier is running in low power or high resolution mode (set by the EN_HIRES bits in the *AFE_RES: Analog Front-End Frequency and Resolution* register).

In summary, the output data rate of an ECG channel can be calculated as follows:

$$ODR_{ECG} = \frac{f_S}{R1\ R2\ R3} \tag{4}$$

And the output data rate of a PACE channel can be calculated as follows:

$$ODR_{PACE} = \frac{f_S}{R1\ R2} \tag{5}$$

Where f_S is the clock frequency of the modulator: 102.4 kHz, or 204.8 kHz.

TABLE 3. Channel Parameters with SDM running at 102.4 kHz and at Standard PACE Data Rate (R1 = 4)

R2	R3	PACE CHANNEL					ECG CHANNEL				
					RMS noise					RMS noise	
		ADC_{MAX}	ODR [Hz]	BW [Hz]	Low Pwr [µV]	High Res [µV]	ADC_{MAX}	ODR [Hz]	BW [Hz]	Low Pwr [µV]	High Res [µV]
4	4	0x8000	6400	1300	tbd	tbd	0x800000	1600	325	3.24	1.98
	6						0xF30000	1067	215	2.64	1.61
	8						0x800000	800	160	2.28	1.39
	12						0xF30000	533	105	1.97	1.20
	16						0x800000	400	80	1.61	0.98
	32						0x800000	200	40	1.14	0.70
	64						0x800000	100	20	0.80	0.49
	128						0x800000	50	10	0.57	0.35
5	4	0xC350	5120	1040	tbd	tbd	0xC35000	1280	260	2.90	1.77
	6						0xB964F0	853	175	2.38	1.46
	8						0xC35000	640	130	2.05	1.25
	12						0xB964F0	427	85	1.80	1.10
	16						0xC35000	320	65	1.45	0.89
	32						0xC35000	160	32	1.02	0.62
	64						0xC35000	80	16	0.72	0.44
	128						0xC35000	40	8	0.51	0.31
6	4	0xF300	4267	870	tbd	tbd	0xF30000	1067	215	2.64	1.61
	6						0xE6A900	711	145	2.17	1.32
	8						0xF30000	533	110	1.89	1.15
	12						0xE6A900	356	70	1.61	0.98
	16						0xF30000	267	55	1.33	0.82
	32						0xF30000	133	27	0.94	0.57
	64						0xF30000	67	13	0.65	0.40
	128						0xF30000	33	7	0.48	0.29
8	4	0x8000	3200	650	tbd	tbd	0x800000	800	160	2.28	1.39
	6						0xF30000	533	110	1.89	1.15
	8						0x800000	400	80	1.61	0.98
	12						0xF30000	267	55	1.39	0.85
	16						0x800000	200	40	1.14	0.70
	32						0x800000	100	20	0.80	0.49
	64						0x800000	50	10	0.57	0.35
	128						0x800000	25	5	0.40	0.25

TABLE 4. Channel Parameters with SDM running at 102.4 kHz and at Double PACE Data Rate (R1 = 2)

R2	R3	PACE CHANNEL					ECG CHANNEL				
					RMS noise					RMS noise	
		ADC_{MAX}	ODR [Hz]	BW [Hz]	Low Pwr [µV]	High Res [µV]	ADC_{MAX}	ODR [Hz]	BW [Hz]	Low Pwr [µV]	High Res [µV]
4	4	0x8000	12800	1280	tbd	tbd	0x800000	3200	640	4.55	2.78
	6						0xF30000	2133	430	3.73	2.28
	8						0x800000	1600	320	3.22	1.97
	12						0xF30000	1067	215	2.64	1.61
	16						0x800000	800	160	2.28	1.39
	32						0x800000	400	80	1.61	0.98
	64						0x800000	200	40	1.14	0.70
	128						0x800000	100	20	0.80	0.49
5	4	0xC350	10240	1030	tbd	tbd	0xC35000	2560	510	4.06	2.48
	6						0xB964F0	1707	340	3.32	2.03
	8						0xC35000	1280	255	2.87	1.76
	12						0xB964F0	853	170	2.35	1.43
	16						0xC35000	640	130	2.05	1.25
	32						0xC35000	320	65	1.45	0.89
	64						0xC35000	160	32	1.02	0.62
	128						0xC35000	80	16	0.72	0.44
6	4	0xF300	8533	860	tbd	tbd	0xF30000	2133	420	3.69	2.25
	6						0xE6A900	1422	285	3.04	1.86
	8						0xF30000	1067	210	2.61	1.59
	12						0xE6A900	711	140	2.13	1.30
	16						0xF30000	533	105	1.84	1.13
	32						0xF30000	267	55	1.33	0.82
	64						0xF30000	133	26	0.92	0.56
	128						0xF30000	67	13	0.65	0.40
8	4	0x8000	6400	650	tbd	tbd	0x800000	1600	320	3.22	1.97
	6						0xF30000	1067	215	2.64	1.61
	8						0x800000	800	160	2.28	1.39
	12						0xF30000	533	110	1.89	1.15
	16						0x800000	400	80	1061	0.98
	32						0x800000	200	40	1.14	0.70
	64						0x800000	100	20	0.80	0.49
	128						0x800000	50	10	0.57	0.35

TABLE 5. Channel Parameters with SDM running at 204.8 kHz and at Standard PACE Data Rate (R1 = 4)

R2	R3	PACE CHANNEL					ECG CHANNEL				
					RMS noise					RMS noise	
		ADC_{MAX}	ODR [Hz]	BW [Hz]	Low Pwr [µV]	High Res [µV]	ADC_{MAX}	ODR [Hz]	BW [Hz]	Low Pwr [µV]	High Res [µV]
4	4	0x8000	12800	2600	tbd	tbd	0x800000	3200	640	4.55	2.78
	6						0xF30000	2133	430	3.73	2.28
	8						0x800000	1600	325	3.24	1.98
	12						0xF30000	1067	215	2.64	1.61
	16						0x800000	800	160	2.28	1.39
	32						0x800000	400	80	1.61	0.98
	64						0x800000	200	40	1.14	0.70
	128						0x800000	100	20	0.80	0.49
5	4	0xC350	10240	2080	tbd	tbd	0xC35000	2560	520	4.10	2.51
	6						0xB964F0	1707	350	3.37	2.06
	8						0xC35000	1280	260	2.90	1.77
	12						0xB964F0	853	170	2.35	1.43
	16						0xC35000	640	130	1.45	0.89
	32						0xC35000	320	65	1.02	0.62
	64						0xC35000	160	32	0.70	0.43
	128						0xC35000	80	15	0.48	0.29
6	4	0xF300	8533	1740	tbd	tbd	0xF30000	2133	430	3.73	2.28
	6						0xE6A900	1422	290	3.07	1.87
	8						0xF30000	1067	215	2.64	1.61
	12						0xE6A900	711	140	2.13	1.30
	16						0xF30000	533	110	1.89	1.15
	32						0xF30000	267	55	1.33	0.82
	64						0xF30000	133	27	0.94	0.57
	128						0xF30000	67	13	0.65	0.40
8	4	0x8000	6400	1300	tbd	tbd	0x800000	1600	325	3.24	1.98
	6						0xF30000	1067	215	2.64	1.61
	8						0x800000	800	160	2.28	1.39
	12						0xF30000	533	105	1.84	1.13
	16						0x800000	400	80	1061	0.98
	32						0x800000	200	40	1.14	0.70
	64						0x800000	100	20	0.80	0.49
	128						0x800000	50	10	0.57	0.35

TABLE 6. Channel Parameters with SDM running at 204.8 kHz and at Double PACE Data Rate (R1 = 2)

R2	R3	PACE CHANNEL					ECG CHANNEL				
		ADC_{MAX}	ODR [Hz]	BW [Hz]	RMS noise		ADC_{MAX}	ODR [Hz]	BW [Hz]	RMS noise	
					Low Pwr [µV]	High Res [µV]				Low Pwr [µV]	High Res [µV]
4	4	0x8000	25600	2550	tbd	tbd	0x800000	6400	1280	6.44	3.94
	6						0xF30000	4267	850	5.25	3.21
	8						0x800000	3200	640	4.55	2.78
	12						0xF30000	2133	430	3.73	2.28
	16						0x800000	1600	325	3.24	1.98
	32						0x800000	800	160	2.28	1.39
	64						0x800000	400	80	1.61	0.98
	128						0x800000	200	40	1.14	0.70
5	4	0xC350	20480	2050	tbd	tbd	0xC35000	5120	1020	5.75	3.51
	6						0xB964F0	3413	680	4.69	2.87
	8						0xC35000	2560	510	4.06	2.48
	12						0xB964F0	1707	340	3.32	2.03
	16						0xC35000	1280	260	2.90	1.77
	32						0xC35000	640	130	2.05	1.25
	64						0xC35000	320	65	1.45	0.89
	128						0xC35000	160	32	1.02	0.62
6	4	0xF300	17067	1720	tbd	tbd	0xF30000	4267	850	5.25	3.21
	6						0xE6A900	2844	570	4.30	2.93
	8						0xF30000	2133	420	3.69	2.25
	12						0xE6A900	1422	285	3.04	1.86
	16						0xF30000	1067	215	2.64	1.61
	32						0xF30000	533	110	1.89	1.15
	64						0xF30000	267	55	1.33	0.82
	128						0xF30000	133	26	0.92	0.56
8	4	0x8000	12800	1300	tbd	tbd	0x800000	3200	640	4.55	2.78
	6						0xF30000	2133	425	3.71	2.27
	8						0x800000	1600	320	3.22	1.97
	12						0xF30000	1067	215	2.64	1.61
	16						0x800000	800	160	2.28	1.39
	32						0x800000	400	80	1.61	0.98
	64						0x800000	200	40	1.14	0.70
	128						0x800000	100	20	0.80	0.49

14.2.4 ADC Ouput Code (ADC_{DOUT})

The ADC_{DOUT} of the ADS1293 is due to a differential voltage applied between the positive and negative input terminals of the instrumentation amplifier and can be calculated with the following equation:

$$ADC_{OUT} = \left[\frac{3.5\left(V_{INP}-V_{INM}\right)}{2\,V_{REF}} + \frac{1}{2} \right] ADC_{MAX} \quad (6)$$

The reference voltage V_{REF}, equals to 2.4V if the on-chip voltage reference is used. ADC_{MAX} represents the maximum output code of the ADC, which corresponds to a +2.4V signal at the input of the SDM. The value of ADC_{MAX} changes with the configuration of the digital filters, and the corresponding value can be found in *Table 3*, *Table 4*, *Table 5*, and *Table 6*. Note that ADC_{OUT} equals $ADC_{MAX}/2$ for a 0V differential input.

14.2.5 Filter Settling Time

The settling time of the SINC filters in response to a step signal is determined by the filter's order, N, the differential delay, M, and the channel's output data rate (ODR):

$$t_S = {N*M}/{ODR} \quad (7)$$

When operating in the Standard PACE Data Rate (where R1 = 4), then N*M = 5. However, when operating in the Double PACE Data Rate (where R1 = 2), then N*M = 10. The ODR can be found in *Equation 4* and *Equation 5*.

In summary, when an unclamped pace signal is applied to the filter, the output of an ECG channel will go through a transmission time of:

$$t_{S\text{-}ECG} = {5*R1*R2*R3}/{f_S} \quad (8)$$

When operating in the Standard PACE Data Rate, the output of a PACE channel will go through a transmission time of:

$$t_{S\text{-}PACE} = {5*R1*R2}/{f_S}$$

When operating in the Double PACE Data Rate, the output of a PACE channel will go through a transmission time of:

$$t_{S\text{-}PACE} = {10*R1*R2}/{f_S} \quad (9)$$

14.3 ANALOG PACE CHANNEL

The ADS1293 features an additional analog pace channel to process pulses from a pace maker. The analog pace channel is suitable for low power applications where the device can be configured for low data rates in ECG mode only, while an analog channel detects PACE pulses. This channel consists of a traditional three opamp instrumentation amplifier and is designed to amplify an ECG signal in a 28kHz bandwidth, allowing for external circuitry to detect the PACE pulses. The analog pace implementation inside the ADS1293 is depicted in *Figure 4*. The analog pace channel is not limited to PACE detection; it is a full analog channel that could be used to pre amplify signals, for instance, from a respiration sensor.

The output voltage of the analog pace channel is:

$$Vpaceout = 3.5 \times (Vinp - Vinm) + RLDREF \quad (10)$$

Where Vinp and Vinm are the positive and negative inputs of the analog pace channel. The input pins of this channel can be selected in the *FLEX_CH1_CN: Flex Routing Switch Control for Channel 1* register, and can connect to any of the IN1 through IN6 pins. Note there is no battery monitoring option available through this channel. There is, however, the reference voltage calibration mode available as described in *Section 14.1.2 Calibration Mode*, allowing the offset and gain measurement of the channel.

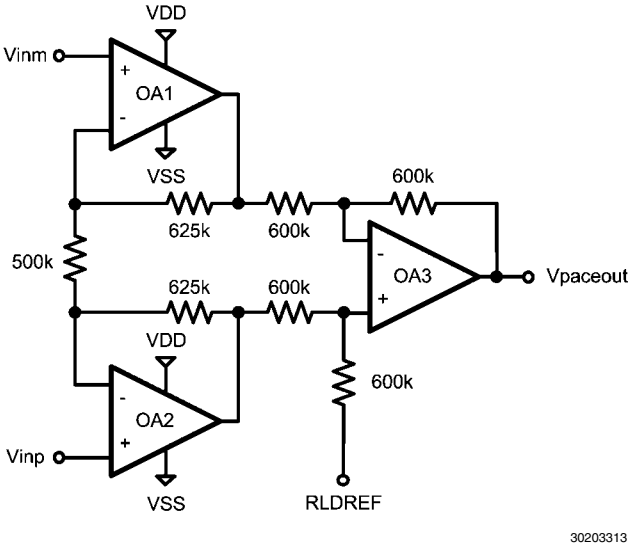


FIGURE 4. Analog pace channel instrumentation amplifier

The output of the analog pace channel can be multiplexed to the WCT or RLDIN pin using the *AFE_PACE_CN: Analog Pace Channel Output Routing Control* register. When PACE2RLDIN = 1, the output is routed to the RLDIN terminal, while internally the positive input of the Right Leg Drive amplifier is connected to the RLDREF pin. When PACE2WCT = 1, the output is routed to the WCT terminal, and the WCT terminal is disconnected from the Wilson output. The Wilson output can still be connected internally to the IN6 pin using the *WILSON_CN: Wilson Reference Control* register. The analog pace channel is disabled when SHDN_PACE = 1 to save power when it is not used.

The analog pace channel is designed to drive a high pass filter and can directly drive a capacitive load of 100pF.

For analog pace detection, it is recommended to have a band pass filter at the output of the analog pace channel, amplify the resulting signal with a relatively high bandwidth amplifier, and compare the amplified pulses with a relatively high speed window comparator. The bandwidth of the band pass filter, gain of the amplification, and the thresholds of the window comparator should be tuned so the comparators trigger on PACE maker pulses, but not to disturb signals present in the ECG environment.

14.4 WILSON REFERENCE

The ADS1293 features a Wilson reference block consisting of three buffer amplifiers and resistors that can generate the voltages for the Wilson Central Terminal or Goldberger terminals. Each of the three buffer amplifiers can be connected to any input pin, IN1 through IN6, by programming the *WILSON_EN1: Wilson Reference Input one Selection*, *WILSON_EN2: Wilson Reference Input two Selection*, and *WILSON_EN3: Wilson Reference Input three Selection* registers. A buffer that is not connected to an input pin is automatically disabled.

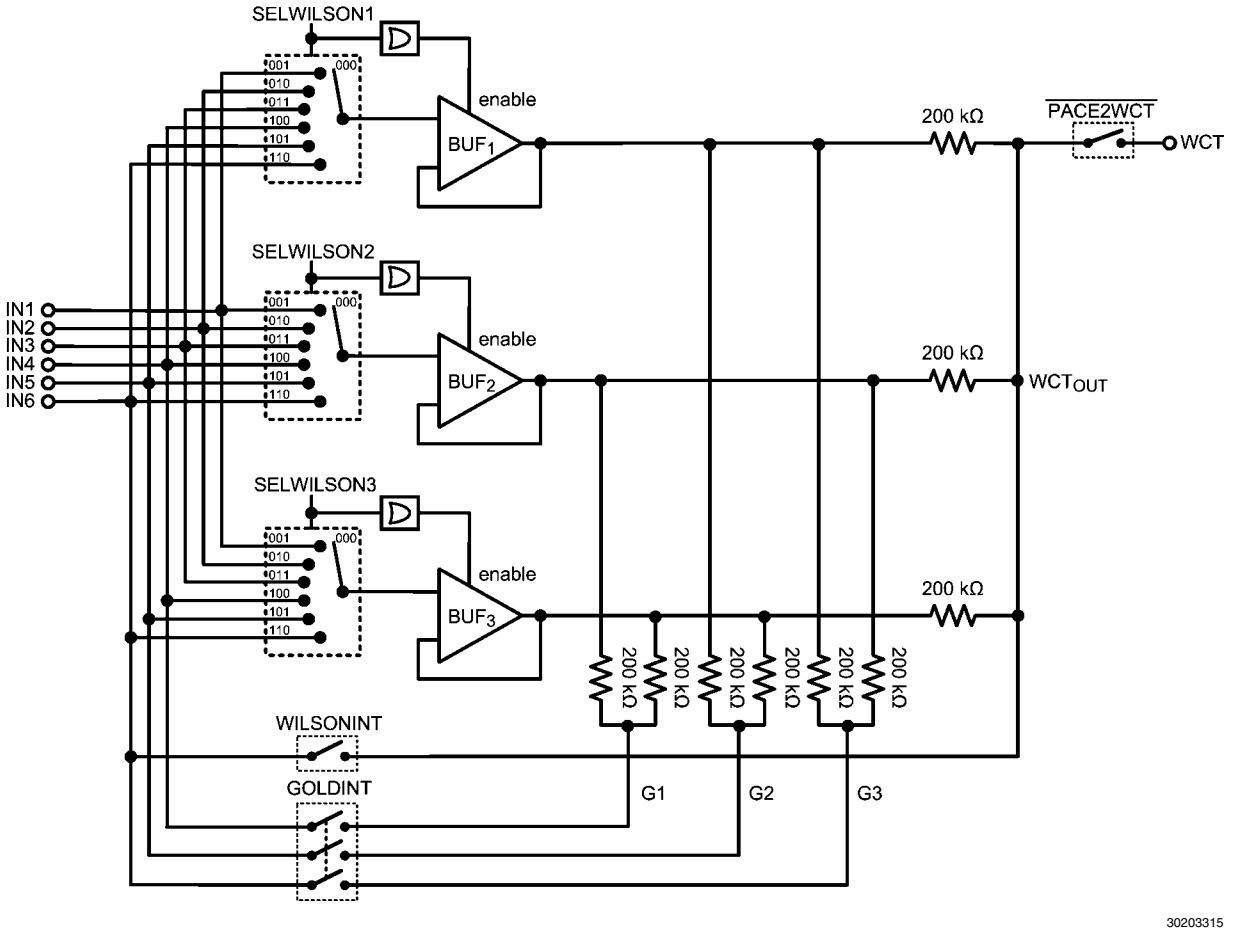


FIGURE 5. Wilson reference generator circuit

The bandwidth of the buffer amplifiers and the internal routing of the output terminals can be configured in the *WILSON_CN: Wilson Reference Control* register. The buffers are configured in a high bandwidth mode when WILSON_MODE = 1; this mode increases the bandwidth by a factor of four, providing better AC PSRR and CMRR.

14.4.1 Wilson Central Terminal

There are three main ECG leads that are measured differentially:

$$\text{Lead I: I} = \text{LA} - \text{RA}$$

$$\text{Lead II: II} = \text{LL} - \text{RA}$$

$$\text{Lead III: III} = \text{LL} - \text{LA}$$

Where LA is the left arm electrode, LL is the left leg electrode, and RA is the right arm electrode.

In a standard 5-lead or 12-lead ECG, the Wilson Central Terminal is used as the reference voltage for the chest electrodes, which are measured differentially against this reference. The Wilson Central Terminal is defined as the average of the three limb electrodes, RA, LA and LL:

$$\text{Wilson Central Terminal} = (\text{RA} + \text{LA} + \text{LL})/3$$

The output of Wilson Central Terminal generated by the ADS1293, as seen in *Figure 5*, is defined as:

$$\text{WCT}_{\text{OUT}} = (\text{BUF}_1 + \text{BUF}_2 + \text{BUF}_3)/3$$

The user must program the *WILSON_EN1* register to connect the RA electrode to BUF_1, program the *WILSON_EN2* register to connect the LA electrode to BUF_2, and program the *WILSON_EN3* register to connect the LL electrode to BUF_3.

When the Wilson reference is enabled, its output is present at the WCT pin, except when the analog pace channel is routed to the WCT pin (see *Section 14.3 ANALOG PACE CHANNEL*. In such a configuration, the Wilson terminal can still be made available at an external pin by programming the WILSONINT bit to 1. Setting this bit connects the output of the Wilson reference internally to the IN6 pin.

14.4.2 Goldberger Terminals

Augmented leads in 3-lead, 5-lead or 12-lead ECG are typically calculated digitally based on the measurement results of Lead I and Lead II. The augmented leads are defined as:

$$\text{aVR} = -(\text{I} + \text{II})/2 = \text{RA} - (\text{LA} + \text{LL})/2 = \text{RA} - \text{G1}$$

$$\text{aVL} = (\text{I} - \text{II})/2 = \text{LA} - (\text{RA} + \text{LL})/2 = \text{LA} - \text{G2}$$

$$\text{aVF} = (\text{II} - \text{I})/2 = \text{LL} - (\text{RA} + \text{LA})/2 = \text{LL} - \text{G3}$$

Augmented leads can also be measured directly with the Goldberger terminals to give the best SNR. The Goldberger terminals generated by the ADS1293, as seen in *Figure 5*, are defined as:

$$\text{G1} = (\text{BUF}_2 + \text{BUF}_3)/2$$

$$\text{G2} = (\text{BUF}_1 + \text{BUF}_3)/2$$

$$\text{G3} = (\text{BUF}_1 + \text{BUF}_2)/2$$

The user must program the *WILSON_EN1* register to connect the RA electrode to BUF_1, program the *WILSON_EN2* register to connect the LA electrode to BUF_2, and program the *WILSON_EN3* register to connect the LL electrode to BUF_3.

The Goldberger output terminals, G1, G2 and G3 can be made available on external pins programming the GOLDINT bit to 1. Setting this bit connects the Goldberger terminals internally to the IN4, IN5 and IN6 pins. Note that more than one ADS1293 are required if both the augmented leads and the three basic leads need to be converted directly.

The WILSONINT and GOLDINT bits must not be programmed to 1 simultaneously because it will short-circuit the Wilson output terminal and the third Goldberger output terminal. The options described in these sections are summarized in *Table 7*.

TABLE 7. Wilson and Goldberger Reference control

GOLDINT	WILSONINT	PACE2WCT	Terminal Outputs			
			WCT pin	IN4 pin	IN5 pin	IN6 pin
0	0	0	WCT_{OUT}	General input	General input	General input
0	1	0	WCT_{OUT}	General input	General input	WCT_{OUT}
1	0	0	WCT_{OUT}	$(BUF_2+BUF_3)/2$	$(BUF_1+BUF_3)/2$	$(BUF_1+BUF_2)/2$
1	1	X	Illegal	Illegal	Illegal	Illegal
0	0	1	Vpaceout	General input	General input	General input
0	1	1	Vpaceout	General input	General input	WCT_{OUT}
1	0	1	Vpaceout	$(BUF_2+BUF_3)/2$	$(BUF_1+BUF_3)/2$	$(BUF_1+BUF_2)/2$

14.5 COMMON MODE (CM) DETECTOR

The Common Mode Detector averages the voltage of up to six input pins and its output can be used in a right leg drive feedback circuit. The selection of the input pins that contribute to the average is configured in the *CMDET_EN: Common Mode Detect Enable* register. The Common Mode Detector is automatically disabled when no input pin is selected.

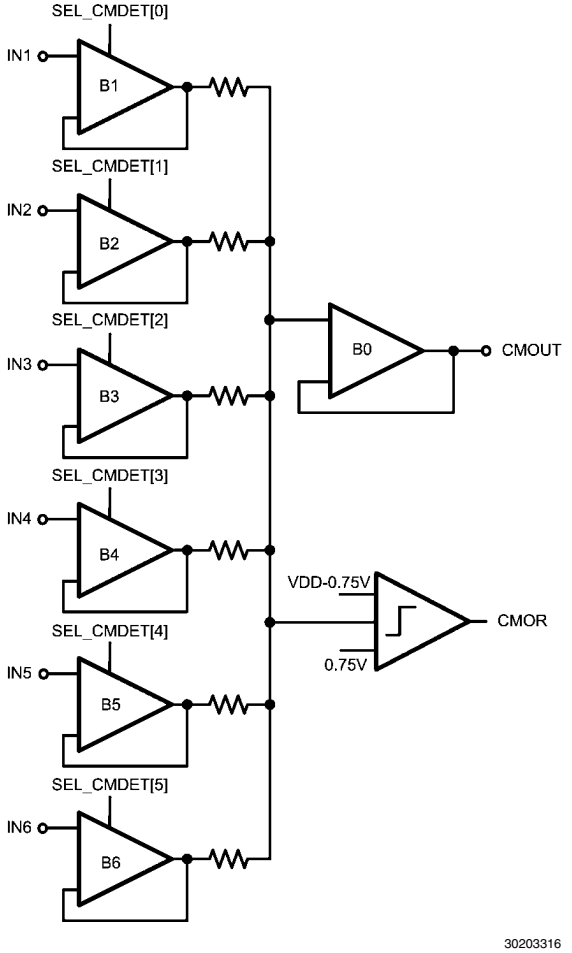


FIGURE 6. Common mode detector circuit

14.5.1 Capacitive Load Driving

The Common Mode Detector also has a programmable capacitive load driving capability of up to 8nF that allows it to drive a cable shield to reduce the common mode signal current through a cable. This effectively increases the common mode filter bandwidth in the cable and decreases cable mismatches at low frequencies that can lead to common mode to differential mode crosstalk. As a result, the CMRR of the overall ECG system is improved.

The bandwidth and capacitive load driving capability of the Common Mode Detector can be configured in the *CMDET_CN: Common Mode Detect Control* register to achieve an optimal tradeoff with power consumption. *Table 8* lists the power consumption corresponding to different configuration scenarios given that all inputs are enabled by setting the *CMDET_EN: Common Mode Detect Enable* register = 0x3F.

The lowest current consumption setting can be used when the Common Mode Detector is only used to drive the Right Leg Driver, and no cable shield is driven. If a cable shield needs to be driven, the power can be increased to drive the cable capacitance depending on the number and type of the driven cable shields. Note that the capacitive driving capability is reduced in the higher bandwidth mode.

TABLE 8. Typical Common Mode Detector Bandwidth, Capacitive Drive and Power Consumption

CMDET_BW	CMDET_CAPDRIVE	CM_BW (kHz)	C_{LOAD} (nF)	CMDET I_{SUPPLY} (µA)
0: Low BW mode	00: Low Cap Drive	50	2	38
0: Low BW mode	01: Medium Low Cap Drive	50	3.3	45
0: Low BW mode	10: Medium High Cap Drive	50	4.5	58
0: Low BW mode	11: High Cap Drive	50	8	80
1: High BW mode	00: Low Cap Drive	125	0.4	42
1: High BW mode	01: Medium Low Cap Drive	125	0.65	49
1: High BW mode	10: Medium High Cap Drive	125	1	62
1: High BW mode	11: High Cap Drive	125	1.6	84

14.5.2 Common Mode Output Range (CMOR)

The Common Mode Detector incorporates an out-of-range alarm to sense if the common mode voltage is in range of the common mode specification of the ADS1293. A Common Mode Out-of-Range Alarm is created in the CMOR bit of the *ERROR_STATUS: Other Error Status* register when the common mode drops below 0.75V or exceeds VDD-0.75V. System alarms are filtered by the digital circuitry (see *Section 14.13 ERROR FILTERING*), and for this reason, the master clock must be active in order to capture an alarm.

14.6 RIGHT-LEG DRIVER (RLD)

The RLD is a programmable operational amplifier that is intended to control the common-mode level of the patient connected through electrodes to the ADS1293 and improve the AC CMRR of the overall ECG system. In a typical ADS1293 application, the common mode level of the patient's body is measured by the Common Mode Detector described in the previous section. The CMOUT is compared by the RLD to the reference voltage present on the RLDREF pin. When used in an inverting amplifier topology, the right leg electrode is driven by the RLD to counter any differences between the reference voltage and the detected common-mode level. This also improves the 50/60Hz common-mode interference.

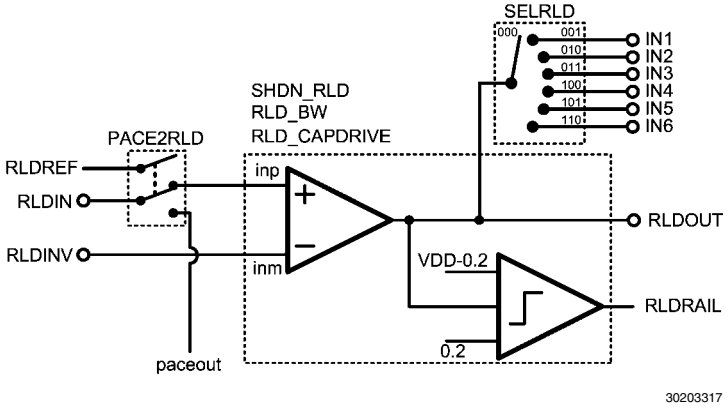


FIGURE 7. Right leg drive circuit

The negative input terminal of the RLD op-amp is always connected to the RLDINV pin. By default, the positive input terminal of the RLD op-amp is routed to the RLDIN pin. However, when bit PACE2RLDIN = 1 in the *AFE_PACE_CN: Analog Pace Channel Output Routing Control* register, the positive input terminal is routed to the internal 2.3V reference for the RLD. This will allow connecting the output of the analog pace instrumentation amplifier to the RLDIN pin. The output of the RLD op-amp is always connected to the RLDOUT pin, and in addition, can be connected to one of the IN1-IN6 terminals by programming the SELRLD bit in the *RLD_CN: Right Leg Drive Control* register. The RLD circuit can be shut down in the same register by setting bit SHDN_RLD = 1.

14.6.1 Capacitive Load Driving

The bandwidth and capacitive load driving capability of the RLD can be configured in the *RLD_CN: Right Leg Drive Control* register to achieve an optimal tradeoff of power consumption. *Table 9* lists the power consumption corresponding to different configuration scenarios.

TABLE 9. Typical Right Leg Drive Bandwidth, Capacitive Drive and Power Consumption

RLD_BW	RLD_CAPDRIVE	BW (kHz)	C_{LOAD} (nF)	RLD I_{SUPPLY} (µA)
0: Low BW Mode	00: Low Cap Drive	50	2	16
0: Low BW Mode	01: Medium Low Cap Drive	50	3.3	25
0: Low BW Mode	10: Medium High Cap Drive	50	4.5	38
0: Low BW Mode	11: High Cap Drive	50	8	63
1: High BW Mode	00: Low Cap Drive	200	0.4	19
1: High BW Mode	01: Medium Low Cap Drive	200	0.65	28
1: High BW Mode	10: Medium High Cap Drive	200	1	40
1: High BW Mode	11: High Cap Drive	200	1.6	66

14.6.2 Error Status: RLD Rail

The RLD amplifier incorporates a near to rail alarm function that is triggered when the output of the op-amp is below 0.2V or above VDD-0.2V. The alarm is reported to the RLDRAIL bit in the *ERROR_STATUS: Other Error Status* register and indicates that the RLD's feedback loop has difficulty maintaining a constant voltage on the patient's body. In this case, the common mode on the patient's body may drift away from its target value, but it may stay within the proper input common mode voltage range of the ADS1293, and the ECG signal data acquisition can continue. When the common mode on the patient's body is outside the operation range of the ADS1293, the CMOR error will be raised, as described in the previous section. System alarms are filtered by the digital circuitry (see *Section 14.13 ERROR FILTERING*), and for this reason, the master clock must be active in order to capture an alarm.

14.7 LEAD-OFF DETECTION (LOD)

The lead-off detect (LOD) block of the ADS1293 can be used to monitor the connectivity of the 6 input pins to electrodes. The LOD block injects a programmable DC or AC excitation current into selected input pins and detects the voltages that appear on the input pins in response to that current. If a lead is not making a proper contact, then the electrode impedance will be high, and as a result, the voltage in response to a small test current will be relatively large, while the voltage for a well-connected lead will be small.

The LOD block can work in one of the three following modes: 1) DC lead-off detect, 2) analog AC lead-off detect and 3) digital AC lead-off detect. All three LOD modes use a common DAC that provides a programmable reference current. This reference current is used to set the magnitude of the test current for lead-off detection. The amplitude of the excitation current used for lead-off detection can be programmed in the *LOD_CURRENT: Lead-Off Detect Current* register, where codes 0 to 255 result in currents ranging from 0 to 2.040µA in steps of 8nA.

The complete LOD block can be shut down by programming the SHDN_LOD bit to 1 in the *LOD_CN: Lead-Off Detect Control* register.

14.7.1 DC Lead-Off Detect

The LOD block can be configured for DC LOD mode by programming a 0 in the SELAC_LOD bit of the *LOD_CN: Lead-Off Detect Control* register. In the DC LOD mode, a DC test current can be injected into any of the six input pins by setting the corresponding bit EN_LOD[x] of the *LOD_EN: Lead-Off Detect Enable* register. Programming a bit to 1 in this register enables a switch that allows a copy of the current programmed into the DAC to be injected into the desired input pins, as shown in the simplified block diagram of *Figure 8*.

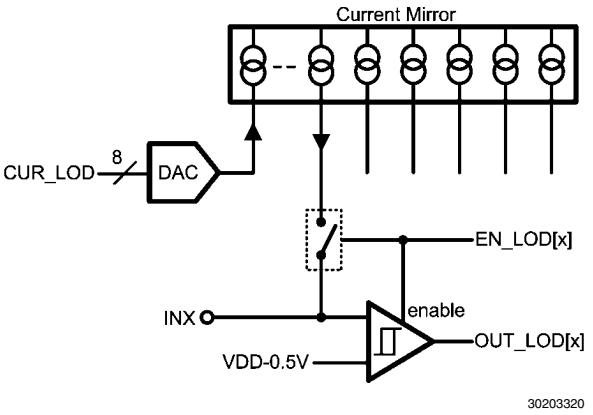


FIGURE 8. Simplified DC lead-off detect block diagram

For the selected input pins, a Schmitt-trigger comparator then compares the voltage that appears on the pin to (VDD-0.5V). The result of this comparison can be accessed through the corresponding OUT_LOD[x] bit of the *ERROR_LOD: Lead Off Detect Error Status* register. If a lead is off, the injected current has no return path to ground, and as a result, the voltage on the associated input pin will rise towards VDD. This is detected by the comparator and used as a signal that indicates the lead is not properly connected.

The lead-off detection circuit requires a low impedance return path from the right leg electrode to ground, such as a voltage reference or the RLD amplifier output. Without a proper low impedance return path for the LOD currents, all enabled LOD pins will report a lead disconnected.

14.7.2 Analog AC Lead-Off Detect

DC lead-off detection cannot be used when using capacitively coupled electrodes, such as dry electrodes, because they have a high DC impedance that will block DC test currents. In this case the analog AC LOD block can be used. Contrary to the DC LOD, the AC LOD injects AC excitation currents with programmable amplitudes and frequencies into the desired lead.

To operate the LOD in analog AC LOD mode, the SELAC_LOD and the ACAD_LOD bit of the *LOD_CN: Lead-Off Detect Control* register must be set to 1.

A simplified block diagram of the analog AC LOD block is shown in figure *Figure 9*. The AC excitation frequency can be programmed by a 7-bit number, ACDIV_LOD, and a division factor, ACDIV_FACTOR, in the *LOD_AC_CN: AC Lead-Off Detect Control* register. The register sets the output frequency of the divider to a rate of:

$$\Phi = 50/(4 * K * (ACDIV\_LOD + 1)) \text{ kHz}$$

Where K is 1 if the ACDIV_FACTOR bit equals 0, and K is 16 if the ACDIV_FACTOR bit equals 1. For instance, ACDIV_LOD = 0 and ACDIV_FACTOR = 0 results in an excitation frequency of 12.5 kHz, which is the maximum excitation frequency.

Complimentary driven switches, enabled by the EN_LOD[x] bits of the *LOD_EN: Lead-Off Detect Enable* register, sink and source the AC excitation currents into the desired input pins. The resulting AC current has a frequency Φ and a peak-to-peak amplitude equal to the current programmed into the DAC. An AC coupled synchronous detector detects the amplitude of the AC voltage appearing on the lead. The detected amplitude is compared to a reference voltage V_{ACLVL_LOD} by means of a Schmitt trigger comparator. The comparator's reference voltage is determined by a 2-bit reference DAC using the ACLVL_LOD bits of the *LOD_CN* register. The reference DAC output voltage is equal to:

$$V_{ACLVL\_LOD} = (VDD/2.2)*(0.1811*ACLVL\_LOD + 1.2943)$$

The comparator outputs can be accessed at the OUT_LOD[x] bit of the *ERROR_LOD: Lead Off Detect Error Status* register. A high comparator output signal indicates that the AC voltage at the excitation frequency is larger than the programmed threshold, which indicates that the lead is not well connected.

The lead-off detection circuit requires a low impedance return path from the right leg electrode to ground, such as a voltage reference or the RLD amplifier output. Without a proper low impedance return path for the LOD currents, all enabled LOD pins will report a lead disconnected.

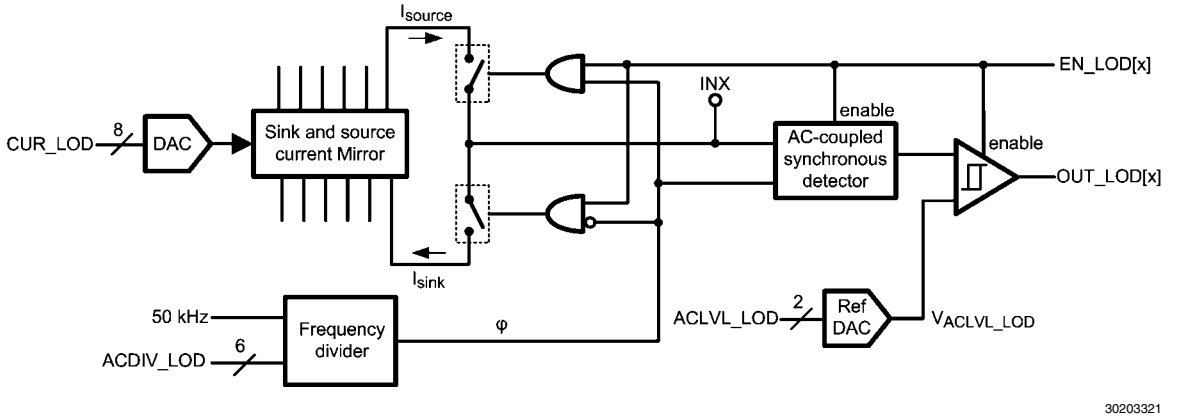


FIGURE 9. Simplified analog AC lead-off detect block diagram

14.7.3 Digital AC Lead-Off Detect

The digital AC lead-off detect (LOD) allows for measurement of the impedance of the two electrodes connected to an AFE channel by measuring a signal through the AFE. In this mode, the lead-off detect current is injected in a balanced manner at the inputs of the AFE behind the flex routing switch. The AC test current is injected into the positive input of the AFE behind the flex routing switch; while at the same time, a similar test current with opposite sign is injected into the negative input of the AFE. Since the AFE has a very high input impedance, the current injected into the positive input pin cannot flow into the AFE. Instead, it will flow through the flex routing switch, via the positive input electrode into the patient, and then back through the negative input electrode and via another path in the flex routing switch towards the negative input of the AFE, where it is cancelled by the current injected at that point. As a result of this test current, an additional AC voltage input will occur at the input of the AFE with a frequency equal to the frequency of the AC LOD test signal frequency. The magnitude of this voltage equals the magnitude of the AC LOD test current (programmed into the CUR_LOD bit in the *LOD_CURRENT: Lead-Off Detect Current* register) multiplied by the impedances of the two electrodes routed to the AFE input in series. This AC voltage will be digitized by the AFE, and the result is available in the digital AFE output signals. The lead connectivity can be determined in the digital domain by applying an FFT to the digital data and by measuring the amplitude of the tone at the AC LOD excitation frequency. It should be noted that the digital AC LOD can only determine the series connectivity of the two leads attached to the inputs of a differential channel, and hence the connectivity of the individual input pins can only be determined by the DC or the analog AC LOD.

Figure 10 shows a simplified block diagram of the digital AC LOD. Follow the procedures below to activate the Digital AC LOD:

1. Select the AC lead-off mode by setting bit SELAC_LOD = 1 in the *LOD_CN: Lead-Off Detect Control* register.
2. Select the Digital AC lead-off mode by setting bit ACAD_LOD = 1 in the *LOD_CN: Lead-Off Detect Control* register.
3. Program the excitation frequency Φ by using the ACDIV_LOD and ACDIV_FACTOR bits in the *LOD_AC_CN: AC Lead-Off Detect Control* register. See equation in *Section 14.7.2 Analog AC Lead-Off Detect*
4. Enable which channel the digital AC LOD will be applied to by selecting the EN_LOD[2:0] bits in the *LOD_EN: Lead-Off Detect Enable* register . These bits correspond to the AFE channels CH3 to CH1 from MSB to LSB, respectively.
5. Determine the phase of the injected current to the AFE channels by programming the EN_LOD[5:3] bits in the *LOD_EN: Lead-Off Detect Enable* register.
   The EN_LOD[5:3] bits determine the phase of the injected current to the AFE channels CH3 to CH1 from MSB to LSB, respectively. A bit set to 1 means that the corresponding channel will receive an anti-phase excitation current in respect to the frequency divider's phase. In some applications, it may be necessary to invert the sign of the digital AC lead-off test current on a channel. Consider an example where the first AFE is configured through the flexible routing switch to measure the voltage between IN1 and IN2, and the second AFE is configured through the flexible routing switch to measure the voltage between IN2 and IN3. In this configuration, if digital AC LOD test currents are applied to the inputs of both AFEs, the test current that is applied to the negative input of the first AFE and the test current that is applied to the positive input of the second AFE are both flowing through IN2. Depending on the sign of the test current in the second AFE, these currents can add up or cancel each other. If the currents add up, the system will correctly measure the differential input impedance on both AFE channels. If the currents on IN2 cancel, the test current will only flow through IN1 and IN3, and the impedance of the electrode connected to IN2 cannot be measured. To apply the digital AC LOD to CH3 and CH2, set EN_LOD[2] = 1 and EN_LOD[1] = 1. Then, by programming EN_LOD[5] = 0 and EN_LOD[4] = 1, CH3 and CH2 will receive excitation currents in-phase and anti-phase, respectively.

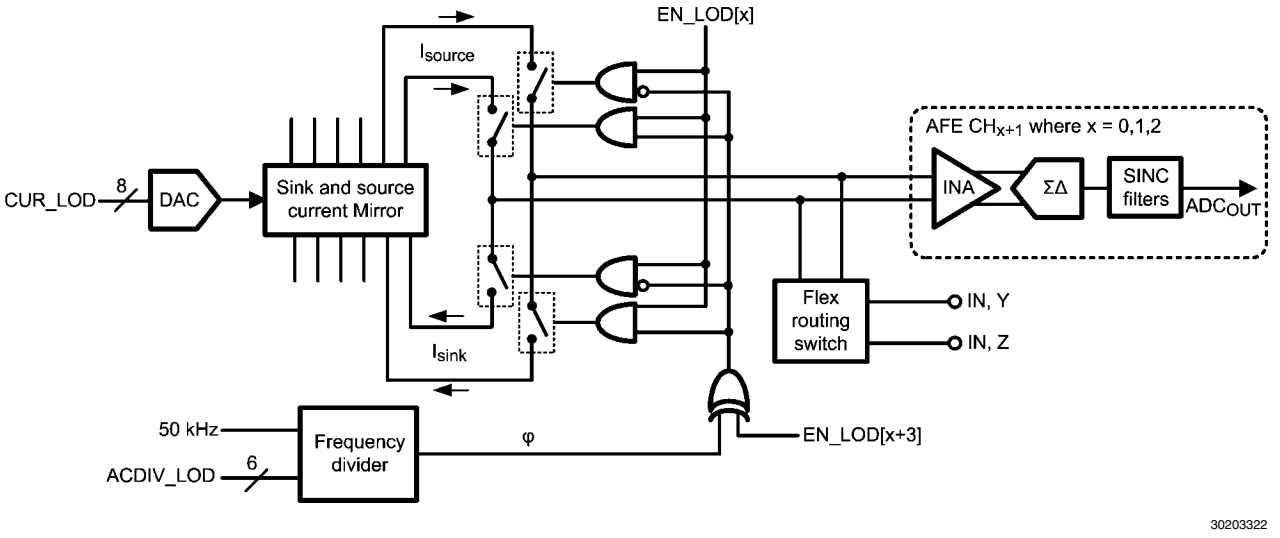


FIGURE 10. Simplified digital AC lead-off detect block diagram

14.8 CLOCK OSCILLATOR

The ADS1293 is designed to operate from a 409.6 kHz clock. This clock can either be provided externally on the bidirectional CLK pin or it can be generated internally by an on-chip crystal oscillator. The high-accuracy low-power on-chip crystal oscillator will work with an external 4.096 MHz crystal connected between the XTAL1 and XTAL2 pins, each of which must be loaded with a 20pF capacitor to get an accurate oscillation frequency. The output frequency of the on-chip crystal oscillator is divided by 10 to generate the required 409.6 kHz clock frequency as shown in *Figure 11*.

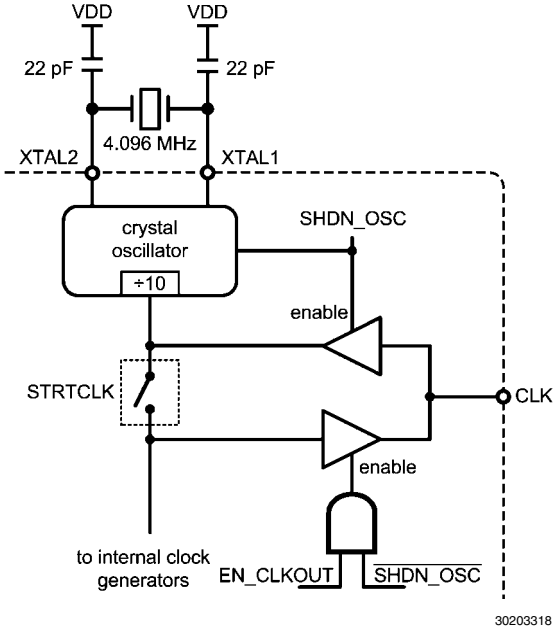


FIGURE 11. Block diagram of the CLOCK

Even though the required oscillation frequency of the external crystal is rated at 4.096 MHz, both the oscillator and the chip can tolerate a wider crystal oscillation frequency (3.3 MHz to 5.0 MHz). Note though that the output data rate and bandwidth of the SINC filters given in *Table 3* through *Table 6* will scale according to the crystal oscillation frequency.

When the internal clock is used, the generated clock can be brought out of the chip through the CLK pin. Its output driver is enabled by configuring bit EN_CLKOUT = 1 in the *OSC_CN: Clock Source and Output Clock Control* register, allowing a multi ADS1293 system to operate synchronously from a single crystal oscillator. Setting bit STRTCLK = 1 allows the internal 409.6 kHz clock to propagate to the digital circuitry and to the output driver of the CLK pin.

The internal crystal oscillator can be shut down to save power or when the clock of the device is to be provided externally. Configuring bit SHDN_OSC = 1 powers down the internal crystal oscillator and enables the input driver of the CLK pin. The external clock

should have a frequency of 409.6 kHz with a duty cycle from 30% to 70% to get the SINC filter bandwidth given in *Table 3* through *Table 6*. The chip can tolerate a wider frequency range (TBD to TBD) on this pin in exchange of scaling up or down the bandwidth of the SINC filters. Setting bit STRTCLK = 1 allows the external 409.6 kHz clock to propagate to the digital circuitry.

The STRTCLK bit is designed to ensure all critical blocks of the chip get a clean clock start. The clock source should first be configured and allowed to start up using the SHDN_OSC and EN_CLKOUT bits, and subsequently, the STRTCLK bit can be set high.

The oscillator control register bits are summarized in *Table 10*. In a multi ADS1293 system the CLK, pins of the master and slaves should be connected together, and the master should be configured to generate a clock on the CLK pin while the slaves should use the CLK pin as a clock input source.

TABLE 10. Clock oscillator configuration bits

STRTCLK	SHDN_OSC	EN_CLKOUT	Clock Propagation
0	X	X	No clock
1	0	0	Internal clock to digital circuitry
1	0	1	Internal clock to digital circuitry and CLK pin
1	1	X	External clock to digital circuitry

14.9 SERIAL DIGITAL INTERFACE

A serial peripheral interface (SPI) allows access to the control registers of the ADS1293. The serial interface is a generic 4-wire synchronous interface compatible with SPI type interfaces used on many microcontrollers and DSP controllers.

14.9.1 Digital Output Drive Strength

The strength of the transistors driving the serial digital output pin, SDO, can be programmed to four levels in the *DIGO_STRENGTH: Digital Output Drive Strength* register. The drive strength will affect the slope of the digital output signal edges, and the optimal drive strength will depend on the capacitive loading on the SDO pin, where larger capacitive loads require larger drive strength. The output drive strength configurability may help reduce interference from the SPI communication into the AFE signal path. In this sense, it is advised to use lower strengths for high VDDIO voltage levels and higher strengths for low VDDIO voltage levels.

14.9.2 SPI Protocol

A typical serial interface access cycle is exactly 16 bits long, which includes an 8-bit command field (R/WB + 7-bit address) to provide for a maximum of 128 direct access addresses, and an 8-bit data field. *Figure 12* shows the access protocol used by this interface. Extended access cycles are possible and they are described in *Section 14.9.4 Auto-incrementing Address* and *Section 14.9.5 Streaming*.

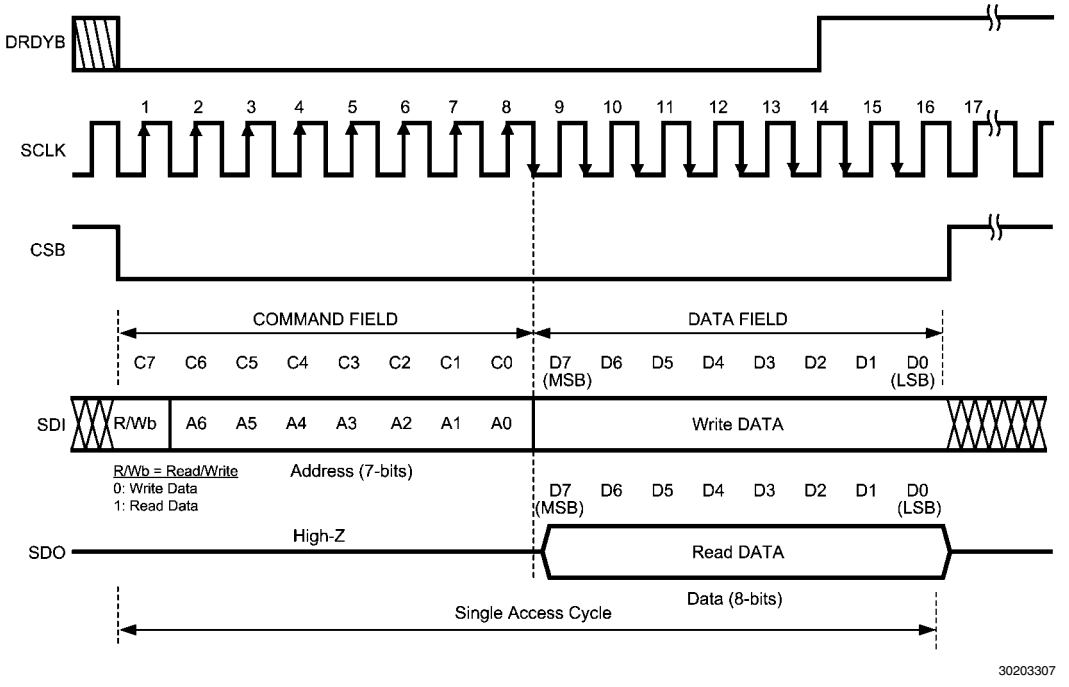


FIGURE 12. Serial Interface Protocol

Each assertion of CSB starts a new register access. The R/Wb bit in the command field configures the direction of the access operation; a value of 0 indicates a write operation and a value of 1 indicates a read operation. All output data is driven on the falling edge of SCLK, and for the 16-bit protocol, SDO read data is driven on the falling edge of clocks 8 through 15. All input data on SDI is sampled on the rising edge of SCLK and is written into the register on the rising edge of the 16th clock. The user is required to deassert CSB after the 16th clock; if CSB is deasserted before the 16th clock, no data write will occur.

14.9.3 Random Register Access Protocol

The 16-bit protocol is useful for random address access. CSB must be asserted during 16 clock cycles of SCLK.

14.9.4 Auto-incrementing Address

An access cycle may be extended to multiple registers by simply keeping the CSB asserted beyond the stated 16 clocks of the standard 16-bit protocol. In this mode, CSB must be asserted during 8*(1+N) clock cycles of SCLK, where N is the amount of bytes to write or read during the access cycle. The auto-incrementing address mode is useful to access a block of registers of incrementing addresses.

For example, to read the pace and ECG data registers located from address 0x30 to address 0x3F and worth 16 bytes of data, follow the next steps:

1. Execute a read command to address 0x30.
2. Extend the CSB assertion during 136 clock cycles.

During an auto-incrementing read access SDO outputs the register contents every 8 clock cycles after the initial 8 clocks of the command field. During an auto-incrementing write access the data is written to the registers every 8 clock cycles after the initial 8 clocks of the command field.

Automatic address increment stops at address 0x4F for both write and read operations.

14.9.5 Streaming

A read access cycle can operate in streaming mode, also referred to as loop read back mode, by performing a read operation to the *DATA_LOOP: Loop Read Back Address* register and extending the CSB assertion beyond the standard 16 clocks. The streaming mode is supported for the *DATA_STATUS, DATA_CH1_PACE, DATA_CH2_PACE, DATA_CH3_PACE, DATA_CH1_ECG, DATA_CH2_ECG* and *DATA_CH3_ECG* registers described in *Section 16.12 Pace and ECG Data Read Back Registers*. The streaming mode is useful to access the block of pace and ECG data registers when not all data needs to be read. The channels to read in this mode are selected in the *CH_CNFG: Configure Channel for Loop Read Back Mode* register. In this mode, CSB must be asserted during 8*(1+N) clock cycles, where N is the number source bytes enabled in *CH_CNFG*. The source for pace data is 2 bytes long; the source for ECG data is 3 bytes long, and the source for data status is 1 byte long.

For example, to read the *DATA_STATUS, DATA_CH3_PACE* and *DATA_CH3_ECG* registers located at address 0x30, 0x35 and 0x3D and worth 6 bytes of data, follow the next steps:

1. Execute a write command to *CH_CNFG*, address 0x2F, with a write value of 0x49.
2. Execute a read command to *DATA_LOOP*, address 0x50.
3. Extend the CSB assertion for 56 clock cycles.

14.10 DRDYB - DATA READY BAR

DRDYB is an active low output signal and is asserted when new data is ready to be read. After DRDYB is asserted and an SPI read of ECG or PACE data occurs, DRDYB will be deasserted at the 14th rising edge of SCLK.

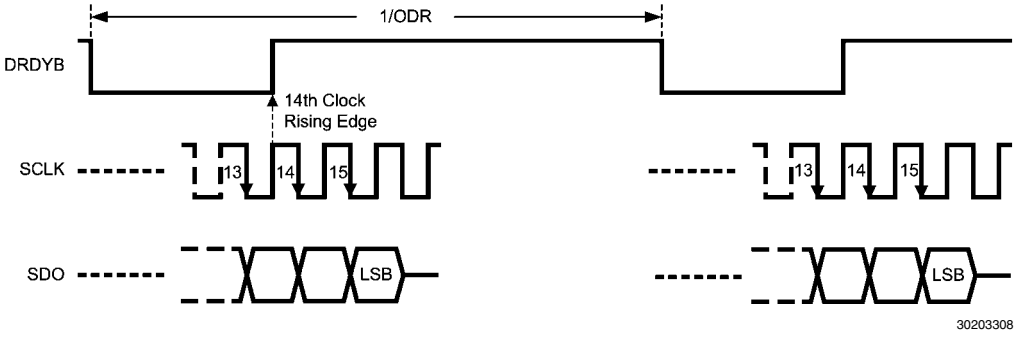


FIGURE 13. DRDYB behavior for a complete read operation

New data is available regardless of the serial interface being ready to read the data or not, and therefore, the data is lost if it is not read before the next DRDYB assertion. If DRDYB is asserted and the data is not read, DRDYB is automatically deasserted at least t_{DRDYB} seconds before the next DRDYB assertion. The value for t_{DRDYB} can be found in *Section 12.0 Timing Diagrams*.

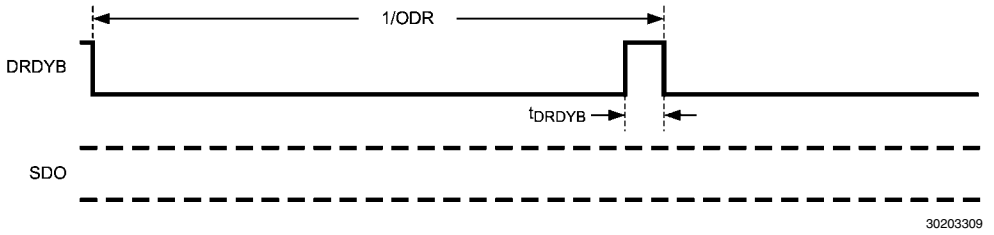


FIGURE 14. DRDYB behavior for an incomplete read operation

The source channel driving the assertion of the DRDYB signal can be configured in the *DRDYB_SRC: Data Ready Pin Source* register. In order to see the DRDYB output pin asserted, one bit of this register must be set to 1 to select the digital channel to drive it; multiple channels should not be selected to drive the DRDYB output pin, otherwise, it will result in unexpected behavior. The selected channel should not be shut down in the *AFE_SHDN_CN: Analog Front-End Shutdown Control* register, and if the source is an ECG channel, its filter should not be disabled in the *DIS_EFILTER: ECG Filter Disable* register. It is strongly recommended to select the channel with the fastest data rate as the source for the DRDYB signal to avoid loss of data.

By default, the DRDYB signal is masked during the first few data samples after the start of a conversion or when a synchronization error is detected. If any ECG channel is enabled, DRDYB is masked during the first six data samples of the slowest enabled ECG channel. If all ECG channels are disabled, DRDYB is masked for the first six data samples of the slowest enabled pace channel when the data rate is 1xODR, and for the first eleven data samples of the slowest enabled pace channel when the data rate is 2xODR. Masking can be disabled in the *MASK_DRDYB: Optional Mask Control for DRDYB Output* register.

14.11 SYNCHRONIZATION

There are three filter timing generators implemented to support independent filter settings. Under normal conditions, the filters always start synchronized when the START_CON bit in the *CONFIG: Main Configuration* register is set to 1, and will remain synchronized. Synchronization can also be continually enforced for the eventuality of a channel losing synchronization and it can be used in single-chip and multiple-chip systems.

14.11.1 Single-chip Channel Synchronization

The filter channels are synchronized when DRDYB assertion is at a fixed frequency and new data from each source is available at some integer multiple of DRDYB. This synchronization mode requires that the fastest output data source is selected to drive DRDYB in the *DRDYB_SRC: Data Ready Pin Source* register.

The filter channels will start synchronized if the output data rates in all channels are the same or integer multiples of each other. Synchronization between channels will be continuously enforced as long as the slowest output source is selected as the synchronization source in the *SYNCB_CN: SYNCB In/Out Pin Control* register. The SYNCB pin output driver can be disabled in a single device system, regardless of the synchronization source selected, and synchronization will continue to be enforced. The SYNCB output driver is disabled programming bit DIS_SYNCBOUT=1.

14.11.2 Multi-chip Synchronization

Synchronization in a multiple ADS1293 system is achieved when all the devices share a common clock and synchronization source. The common clock source, f_{OSC}, can be driven from the CLK pin of an ADS1293 when its CLK pin output driver is enabled in the *OSC_CN: Clock Source and Output Clock Control* register. The common synchronization source can be driven from the SYNCB pin of the device with the slowest data rate in the system. An ADS1293 is configured as a synchronization source by enabling its SYNCB output driver and selecting the slowest data rate channel to drive the line in the *SYNCB_CN: SYNCB In/Out Pin Control* register. The *SYNCB_CN* register of the other devices should be programmed to 0x40 to configure their SYNCB pins as inputs. When configured as an output, SYNCB is driven on the falling edge of f_{OSC} and when configured as an input, SYNCB is sampled on the rising edge of f_{OSC}.

14.11.3 Synchronization Errors

Detected synchronization events are reported to the *ERROR_SYNC: Synchronization Error* register. A phase error is generated when the phase of divided clocks of the timing generator has been adjusted to comply with the SYNCB input signal. A timing error is generated when the timing of the indicated channel has been updated to comply with the timing of the synchronization source, internal or external. By default, a synchronization error will propagate to the ALARMB output pin. Reporting of a synchronization error can be disabled in the *MASK_ERR: Mask Error on ALARMB Pin* register.

14.12 ALARM FUNCTIONS

The ADS1293 has multiple warning flags to diagnose possible fault conditions in the ECG monitoring application. The warning flags can be read in the error status registers in *Section 16.10 Error Status Registers*. The system errors are filtered by the digital circuitry (see *Section 14.13 ERROR FILTERING*), and for this reason, the master clock must be active for the alarms to be reflected in the error registers.

1. **ERROR_LOD:** The *ERROR_LOD* register indicates which input has a lead-off error. The lead-off detection was described in section *Section 14.7 LEAD-OFF DETECTION (LOD)*.
2. **ERROR_STATUS:** The *ERROR_STATUS* register contains the following error flags:

- **SYNCEDGEERR:** This flag is raised when a synchronization error occurs, as described in .
- **CH3ERR:** This flag is raised when one of the 5 LSBs of the *ERROR_RANGE3* register is a logic 1. It indicates an out of range condition at the AFE in channel 3. These error conditions are described in and in .
- **CH2ERR:** See above, but for channel 2.
- **CH1ERR:** See above, but for channel 1.
- **LEADOFF:** This error flag is raised when one of the OUT_LOD bits in the *ERROR_LOD* register is a logic 1.
- **BATLOW:**This error flag is raised when the supply voltage of the ADS1293 drops below 2.5V. This can be used as a warning sign to the microcontroller that the state of charge of a supply battery is almost zero. The ADS1293 is designed to function to spec for supplies larger than 2.7V but communication the digital communication interface will work down to 2.4V so that this alarm condition can still be communicated to the microcontroller. A low battery error propagates to the ALARMB pin unless the MASK_BATLOW bit in the register is set to 1. System alarms are filtered by the digital circuitry (see), and for this reason, the master clock must be active in order to capture an alarm.There is also a battery voltage monitoring feature that can be used to monitor the state of charge of the battery during normal operation described in .
- **RLDRAIL:** This error flag goes is raised when the output voltage of the right leg drive amplifier is approaching the supply rails. The flag goes high when the output voltage of the common mode detector is 200mV away from either supply rail. This condition would occur if the common mode on the patient's body is far away from the target value and as a result the right leg drive amplifier needs to deliver a lot of charge to the patient's body to restore the common mode voltage. In this scenario, the common mode may still be inside the range of the instrumentation amplifier and the ECG signal may still be accurately acquired.
- **CMOR:** The CMOR error flag is raised when the output voltage of the common mode detector is 750mV away from either supply rail. In this case, the common mode voltage detected on the patient's body is outside of the input CMVR where the instrumentation amplifier can process the full differential input signal (see). When this flag is raised the ECG signal accuracy may be lost.

3. Extend the CSB assertion for 56 clock cycles.

ERROR_RANGE1, ERROR_RANGE2, ERROR_RANGE3: These registers contain the out of range error signals of the AFEs in the three channels. The flags in these registers are described in *Section 14.2.1.1 Instrumentation Amplifier Fault Detection* and in *Section 14.2.2.1 Sigma Delta Modulator Fault Detection*.

ERROR_SYNC: This register contains flags that indicate certain synchronization errors have been detected. These errors have been described in *Section 14.11.3 Synchronization Errors*.

ERROR_MISC: This register contains status flags for common-mode out of range, right leg drive near rail and low battery errors.

14.13 ERROR FILTERING

The alarms that are generated by the analog circuitry inside the ADS1293 are filtered by digital logic. Alarms will only be accepted if they are active for a number of consecutive digital clock cycles, which toggle on the falling edge of the 409.6 kHz oscillator clock. The number of digital clock cycles that an alarm will have to be active before it is accepted is programmable between 1 and 16 counts using the *ALARM_FILTER: Digital Filter for Analog Alarm Signals* register. This register contains two separate filter parameters. The 4 LSBs in this register program the filtering of the lead-off detect error bits. The 4 MSBs program the filtering of the instrumentation amplifier signal out of range errors and the CMOR, RLDRAIL and BATLOW errors.

14.14 ALARMB PIN AND ERROR MASKING

The ADS1293 has an ALARMB output pin. This open drain output will go low when a new alarm condition occurs in the *ERROR_STATUS: Other Error Status* register. The ALARMB pin can be used as an interrupt signal to a microcontroller to warn about error conditions that can potentially corrupt the data that is being collected so that the microcontroller can take appropriate preventive action. The functionality of the ALARMB pin is flexible and programmable using the *MASK_ERR: Mask Error on ALARMB Pin* register. This register allows masking some of the errors in the *ERROR_STATUS* register so that certain alarm events will not trigger a high to low transition on the ALARMB pin.

14.15 ERROR REGISTER AUTOMATIC CLEARING DESCRIPTION

All error bits in the registers 0x18 through 0x1E are latched in a high state when an error occurs and will only return to zero after being read. The error bits will remember an error until the user reads the error. The sign bits in the CH1ERR, CH2ERR and CHR3ERR registers are latched on low to high transition of the DIF_HIGH transitions in the corresponding registers. In this way, when the differential signal goes out of range, the sign of the signal can also be detected when the alarm register is read. Upon read, the error bits will be cleared. If the error condition has disappeared before the error is read, the error bits will remain low after being read. For all error registers, except *ERROR_STATUS*, the error bits will return to their high state within a few internal clock cycles if the error condition is still present after a register read. The bits in the *ERROR_STATUS: Other Error Status* register only respond to new errors. If an error persists after the *ERROR_STATUS* register is read, the error condition will not be reflected in the error status register and the ALARMB pin will not pulse low again.

14.16 ALARM PROPAGATION

Figure 15 shows how the alarms propagate through the digital circuitry inside the ADS1293. The errors propagate from left to right. Synchronization errors are not filtered because they are generated synchronously inside the digital circuitry, and if they occur, they are latched in the *ERROR_SYNC* register. Lead-off detect errors are filtered by a counter programmed in the 4 LSBs of the *ALARM_FILTER: Digital Filter for Analog Alarm Signals* register and are latched in the *ERROR_LOD* register. The instrumentation amplifier out of range, sigma-delta over range, right-leg drive amplifier out of range, common mode amplifier out of range and low battery signals are also filtered by a counter programmed in the MSBs of the *ALARM_FILTER* register. The out of range signals

for the 3 channels are latched in the *ERROR_RANGE1, ERROR_RANGE2* and *ERROR_RANGE3* registers. The first 6 registers on the right hand side of the circuit all latch errors if they occur until the error is being read. After being read, the error bit will be reset, but it will return to a logic 1 if the internal alarm condition persists. After being filtered the alarms are all routed to a digital logic block that detects whether a new alarm has occurred. If this happens, the appropriate bit in the *ERROR_STATUS* register will be set and the ALARMB pin will be pulled down. The bits in the *ERROR_STATUS* register will be reset and the ALARMB pin will released when the *ERROR_STATUS* register is read.

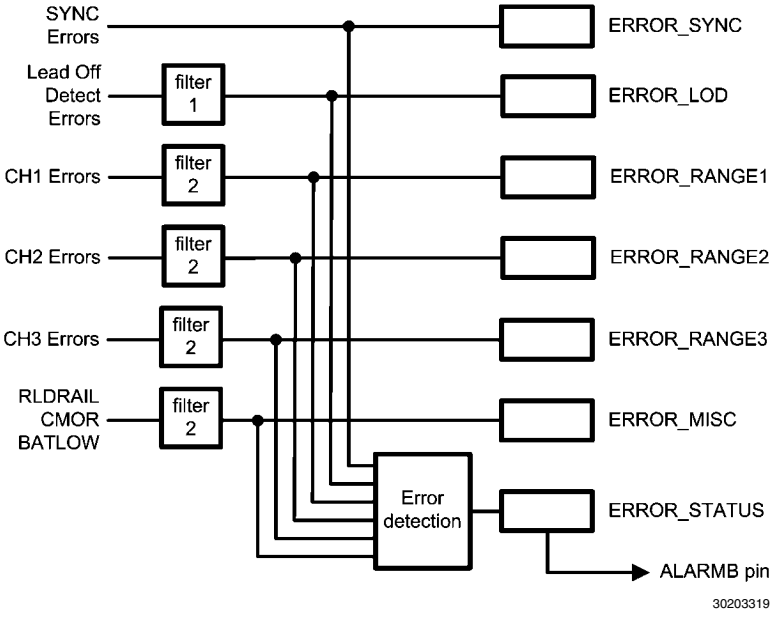


FIGURE 15. Graphical illustration of alarm propagation

14.17 REFERENCE VOLTAGE GENERATORS

There are three reference voltage generators Inside the ADS1293.

The timing LDO generates a 1.2V supply voltage for the clock generators in the sigma delta modulators. This reference voltage is powered on at all times when power is present at the VDD pin.

The common mode and right-leg drive reference generates VDD/2.2 volts, which are present on the RLDREF pin. This reference is used as an internal common-mode reference, as the reference for the analog pace channel, and should be powered on at all times when a sigma delta modulator is running. It can be powered down programming bit SHDN_CMREF=1 in the *REF_CN: Internal Reference Voltage Control* register. The RLDREF pin should have a 0.1µF bypass capacitor to ground.

The internal reference, V_{REF}, generates 2.4V, which are present on the CVREF pin. The CVREF pin should have a 1µF bypass capacitor to ground with low ESR and is not designed to be loaded with other circuitry. This reference should also be powered on at all times when a sigma delta modulator is running. It can be powered down programming bit SHDN_REF=1 in the *REF_CN* register. It is possible to provide the reference voltage externally on this pin when the internal reference generator is shut down.

All three voltage generators require a somewhat larger start up time compared to the other circuit blocks inside the ADS1293, which is why they are treated differently in the global power down or standby states, as will be described in the next section.

14.18 POWER MANAGEMENT

The ADS1293 has many features that allow the optimization of power consumption. The common mode detector and right leg drive amplifier can be configured to achieve the optimum AC performance to power consumption ratio in a given application environment. Almost all internal circuit blocks can be powered down to reduce power consumption. *Table 11* lists the power consumption budget for all of the circuit blocks that can be individually powered down.

There are two master control bits, PWR_DOWN and STANDBY, in addition to the power down control bits that are used to power down an individual circuit block, and they are located in the *CONFIG: Main Configuration* register. In the power down mode, all circuits that can be powered down are powered down, irrespective of the state of their individual shutdown bits. With the PWR_DOWN bit, the entire ADS1293 can be quickly placed in its minimal current consumption state without needing to do many individual configuration register writes. The STANDBY bit operates in a similar manner, but it does not affect the state of the three voltage generators and the crystal oscillator inside the ADS1293, which require a somewhat longer time to start up. When placing the ADS1293 in standby mode, the power consumption is somewhat higher than in the power down state but the ADS1293 can return to operation quicker. The difference between the current consumption in powerdown and in standby depends on the logic state of the shutdown bits of the three voltage generators as described in *Table 11*.

The table specifies the current consumption of the blocks that are always on in the first row. The second group in the table specifies the current consumption of the three voltage generators and the crystal oscillator that are powered down in powerdown mode but

that remain active during standby. The last group of circuit blocks in the table specifies the current consumption of the other circuit blocks. The ADS1293 will need about 100ms to return to operation after being powered down. The time to recover from standby is limited by the time latency of the programmable logic filters in the AFE channels, which is TBD sigma delta clock cycles.

TABLE 11. Typical Current Consumption per Block

Global Power Control	Block Name	Conditions / Notes	Current [µA]
Always on	Supporting circuitry		61
Off in power down	Reference voltage generator		17
	Sigma Delta voltage generator		15
	Right leg drive reference		9
	Crystal oscillator		10
Off in standby	Instrumentation amplifier	low power, per channel	35
		high resolution, per channel	130
	Sigma Delta modulator	102.4kHz, per channel	17
		204.8kHz, per channel	33
	Analog output channel		23
	Lead-off detect	Excluding excitation currents	10
	Wilson reference	low power, per channel	6
		high resolution, per channel	21
	Common mode detector	low speed, cap drive 1, 6 active leads	38
		high speed, cap drive 4, 6 active leads	88
	Right leg drive amplifier	low speed, cap drive 1	16
		high speed, cap drive 4	66

15.0 Application Information

15.1 GENERAL

15.2 EXAMPLE APPLICATIONS

15.2.1 3-Lead ECG Application

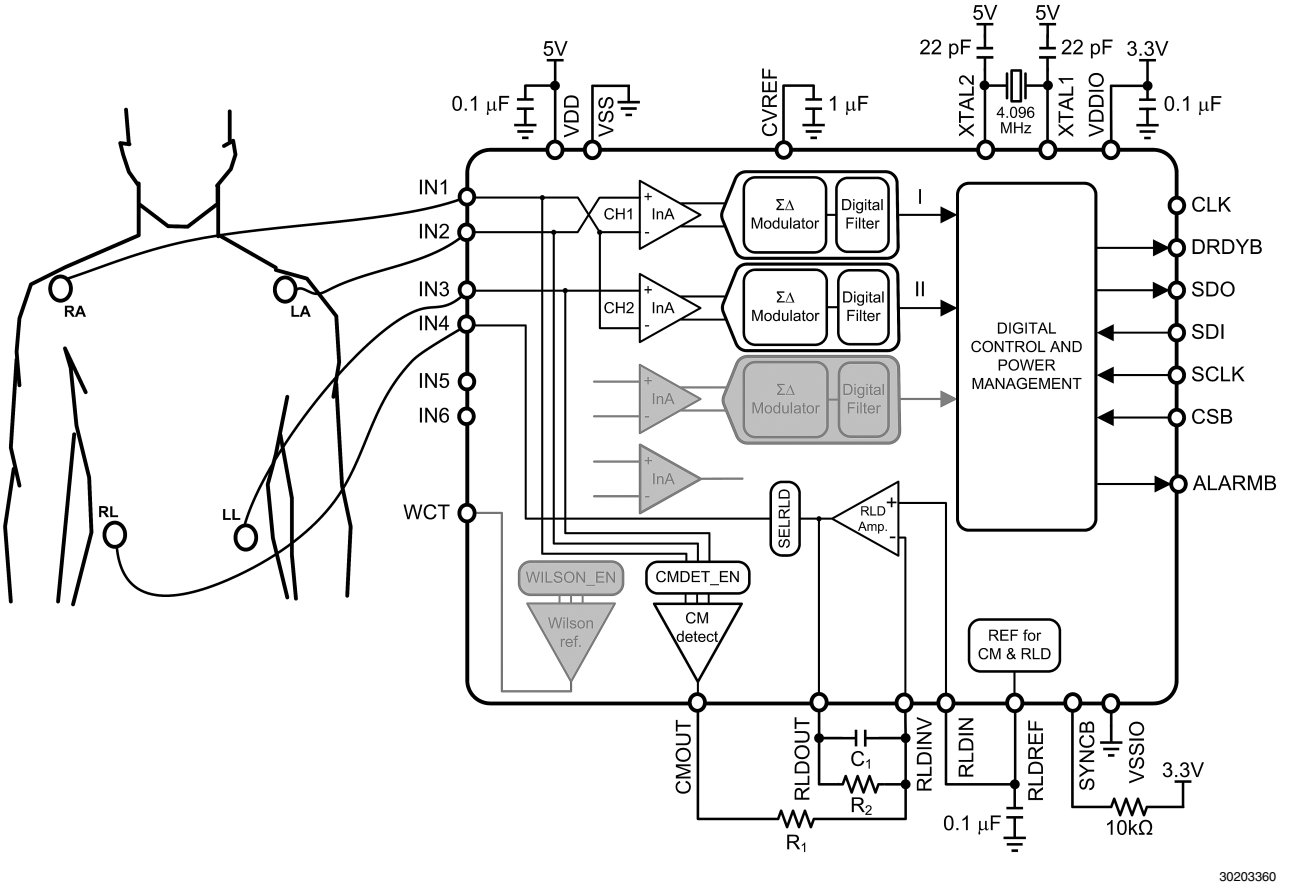


FIGURE 16. 3-Lead ECG Application

15.2.2 5-Lead ECG Application

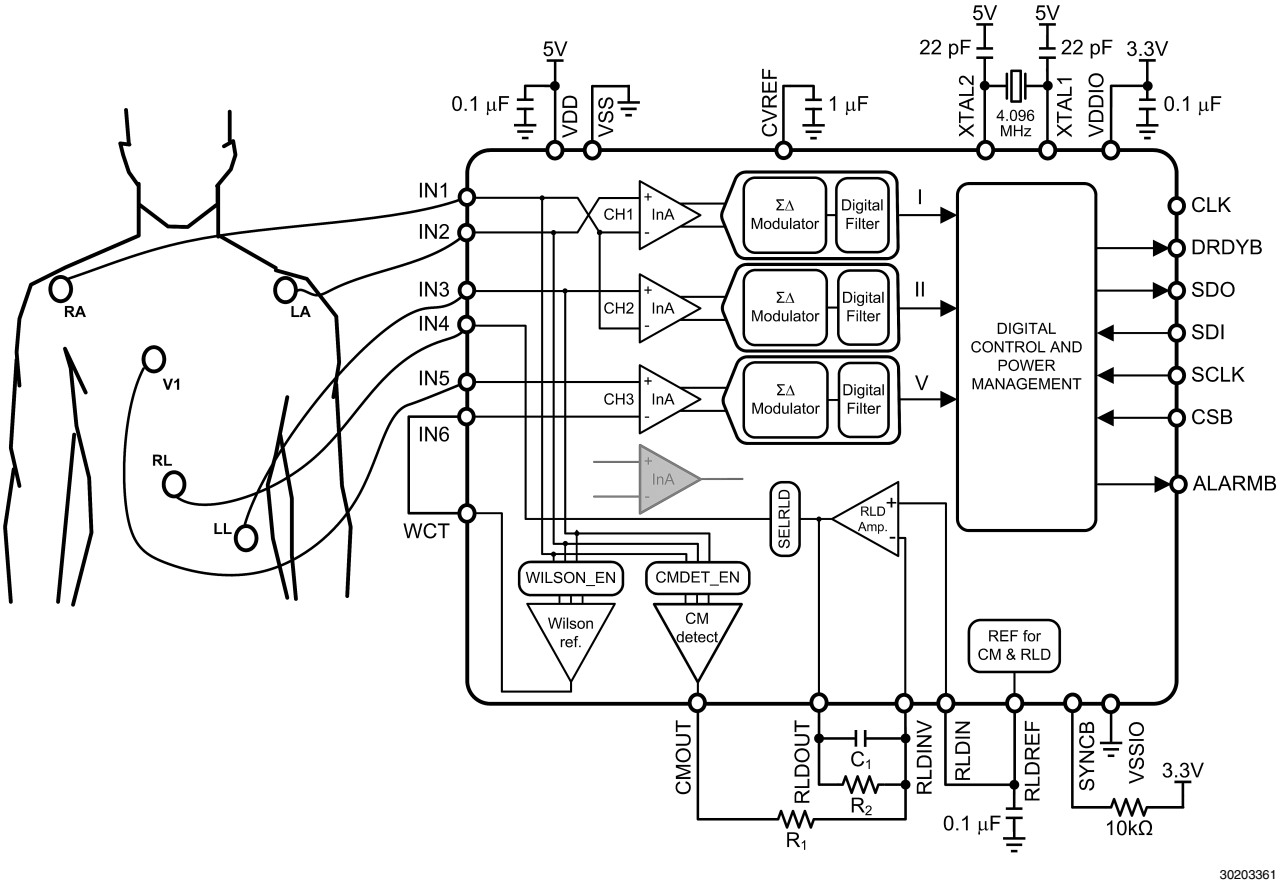


FIGURE 17. 5-Lead ECG Application

15.2.3 8-12-Lead ECG Application

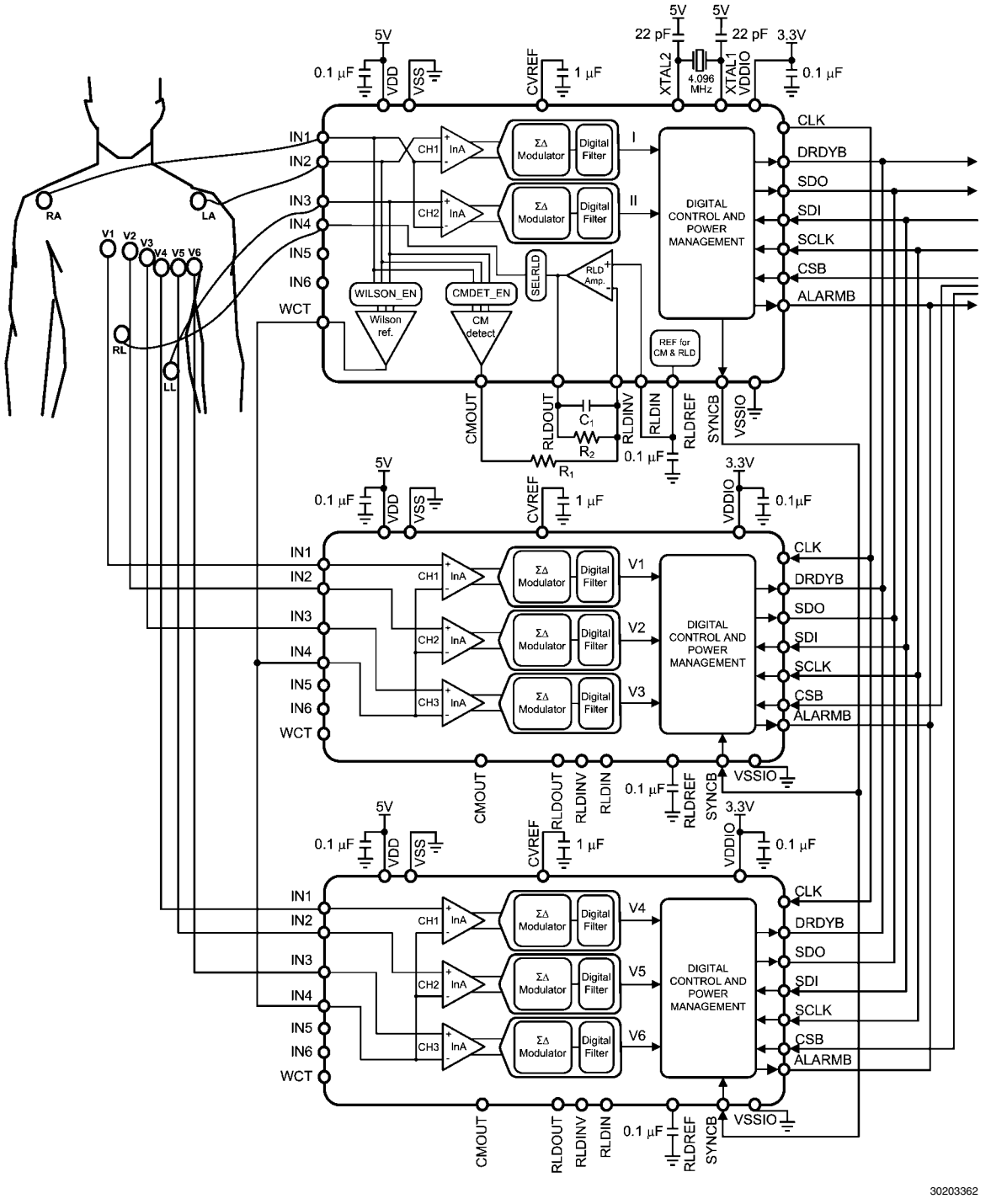


FIGURE 18. 8-12-Lead ECG Application

16.0 Registers

1. If written to, RESERVED bits must be written to 0 unless otherwise indicated.
2. Read back value of RESERVED bits and registers is unspecified and should be discarded.
3. Recommended values must be programmed and forbidden values must be not be programmed where they are indicated in order to avoid unexpected results.
4. If written to, registers indicated as Reserved must have the indicated default value as shown in the register map. Any other value can cause unexpected results.

16.1 Register Map

Register Name	Description	Address	Access	Default
Operation Mode Registers				
CONFIG	Main Configuration	0x00	R/W	0x02
Input Channel Selection Registers				
FLEX_CH1_CN	Flex Routing Switch Control for Channel 1	0x01	R/W	0x00
FLEX_CH2_CN	Flex Routing Switch Control for Channel 2	0x02	R/W	0x00
FLEX_CH3_CN	Flex Routing Switch Control for Channel 3	0x03	R/W	0x00
FLEX_PACE_CN	Flex Routing Switch Control for Pace Channel	0x04	R/W	0x00
FLEX_VBAT_CN	Flex Routing Switch for Battery Monitoring	0x05	R/W	0x00
Lead-off Detect Control Registers				
LOD_CN	Lead-Off Detect Control	0x06	R/W	0x08
LOD_EN	Lead-Off Detect Enable	0x07	R/W	0x00
LOD_CURRENT	Lead-Off Detect Current	0x08	R/W	0x00
LOD_AC_CN	AC Lead-Off Detect Control	0x09	R/W	0x00
Common Mode Detection and Right Leg Drive Feedback Control Registers				
CMDET_EN	Common Mode Detect Enable	0x0A	R/W	0x00
CMDET_CN	Common Mode Detect Control	0x0B	R/W	0x00
RLD_CN	Right Leg Drive Control	0x0C	R/W	0x00
Wilson Control Registers				
WILSON_EN1	Wilson Reference Input one Selection	0x0D	R/W	0x00
WILSON_EN2	Wilson Reference Input two Selection	0x0E	R/W	0x00
WILSON_EN3	Wilson Reference Input three Selection	0x0F	R/W	0x00
WILSON_CN	Wilson Reference Control	0x10	R/W	0x00
Reference Registers				
REF_CN	Internal Reference Voltage Control	0x11	R/W	0x00
OSC Control Registers				
OSC_CN	Clock Source and Output Clock Control	0x12	R/W	0x00
AFE Control Registers				
AFE_RES	Analog Front-End Frequency and Resolution	0x13	R/W	0x00
AFE_SHDN_CN	Analog Front-End Shutdown Control	0x14	R/W	0x00
AFE_FAULT_CN	Analog Front-End Fault Detection Control	0x15	R/W	0x00
RESERVED	-	0x16	R/W	0x00
AFE_PACE_CN	Analog Pace Channel Output Routing Control	0x17	R/W	0x01
Error Status Registers				
ERROR_LOD	Lead-Off Detect Error Status	0x18	RO	–
ERROR_STATUS	Other Error Status	0x19	RO	–
ERROR_RANGE1	Channel 1 AFE Out of Range Status	0x1A	RO	–
ERROR_RANGE2	Channel 2 AFE Out of Range Status	0x1B	RO	–
ERROR_RANGE3	Channel 3 AFE Out of Range Status	0x1C	RO	–
ERROR_SYNC	Synchronization Error	0x1D	RO	–
ERROR_MISC	Miscellaneous Errors	0x1E	RO	0x00
Digital Registers				

Register Name	Description	Address	Access	Default
DIGO_STRENGTH	Digital Output Drive Strength	0x1F	R/W	0x03
R2_RATE	R2 Decimation Rate	0x21	R/W	0x08
R3_RATE_CH1	R3 Decimation Rate for Channel 1	0x22	R/W	0x80
R3_RATE_CH2	R3 Decimation Rate for Channel 2	0x23	R/W	0x80
R3_RATE_CH3	R3 Decimation Rate for Channel 3	0x24	R/W	0x80
R1_RATE	R1 Decimation Rate	0x25	R/W	0x00
DIS_EFILTER	ECG Filter Disable	0x26	R/W	0x00
DRDYB_SRC	Data Ready Pin Source	0x27	R/W	0x00
SYNCB_CN	SYNCB In/Out Pin Control	0x28	R/W	0x40
MASK_DRDYB	Optional Mask Control for DRDYB Output	0x29	R/W	0x00
MASK_ERR	Mask Error on ALARMB Pin	0x2A	R/W	0x00
Reserved	-	0x2B	-	0x00
Reserved	-	0x2C	-	0x00
Reserved	-	0x2D	R/W	0x09
ALARM_FILTER	Digital Filter for Analog Alarm Signals	0x2E	R/W	0x33
CH_CNFG	Configure Channel for Loop Read Back Mode	0x2F	R/W	0x00
Pace and ECG Data Read Back Registers				
DATA_STATUS	ECG and Pace Data Ready Status	0x30	RO	–
DATA_CH1_PACE	Channel 1 Pace Data	0x31 0x32	RO	–
DATA_CH2_PACE	Channel 2 Pace Data	0x33 0x34	RO	–
DATA_CH3_PACE	Channel 3 Pace Data	0x35 0x36	RO	–
DATA_CH1_ECG	Channel 1 ECG Data	0x37 0x38 0x39	RO	–
DATA_CH2_ECG	Channel 2 ECG Data	0x3A 0x3B 0x3C	RO	–
DATA_CH3_ECG	Channel 3 ECG Data	0x3D 0x3E 0x3F	RO	–
REVID	Revision ID	0x40	RO	0x01
DATA_LOOP	Loop Read Back Address	0x50	RO	

16.2 Operation Mode Registers

CONFIG: Main Configuration

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x00						PWR_DOWN	STANDBY	START_CON

[7:3] RESERVED -

[2] PWR_DOWN **Power-down mode**

0: Disabled (default)
1: Circuit powered down

[1] STANDBY **Stand-by mode**

0: Disabled
1: Most circuits powered down (default)

[0] START_CON **Start conversion**

0: Disabled (default)
1: Conversion active
Note: Programming START_CON = 1 locks write access to registers 0x11, 0x12, 0x13 and 0x21–0x29.

16.3 Input Channel Selection Registers

FLEX_CH1_CN: Flex Routing Switch Control for Channel 1

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x01	CAL1		POS1			NEG1		

[7:6] CAL1 **Test signal selector**

00: Test signal disconnected and CH1 inputs determined by POS1and NEG1(default)
01: Connect channel one to positive test signal
10: Connect channel one to negative test signal
11: Connect channel one to zero test signal

[5:3] POS1 **Positive terminal of channel 1**

000: Positive terminal is disconnected (default)
001: Positive terminal connected to input IN1
010: Positive terminal connected to input IN2
011: Positive terminal connected to input IN3
100: Positive terminal connected to input IN4
101: Positive terminal connected to input IN5
110: Positive terminal connected to input IN6

[2:0] NEG1 **Negative terminal of channel 1**

000: Negative terminal is disconnected (default)
001: Negative terminal connected to input IN1
010: Negative terminal connected to input IN2
011: Negative terminal connected to input IN3
100: Negative terminal connected to input IN4
101: Negative terminal connected to input IN5
110: Negative terminal connected to input IN6

FLEX_CH2_CN: Flex Routing Switch Control for Channel 2

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x02	CAL2		POS2			NEG2		

[7:6] CAL2 **Test signal selector**

00: Test signal disconnected and CH2 inputs determined by POS2 and NEG2 (default)
01: Connect channel two to positive test signal
10: Connect channel two to negative test signal
11: Connect channel two to zero test signal

[5:3] POS2 **Positive terminal of channel 2**

000: Positive terminal is disconnected (default)
001: Positive terminal connected to input IN1
010: Positive terminal connected to input IN2
011: Positive terminal connected to input IN3
100: Positive terminal connected to input IN4
101: Positive terminal connected to input IN5
110: Positive terminal connected to input IN6

[2:0] NEG2 **Negative terminal of channel 2**

000: Negative terminal is disconnected (default)
001: Negative terminal connected to input IN1
010: Negative terminal connected to input IN2
011: Negative terminal connected to input IN3
100: Negative terminal connected to input IN4
101: Negative terminal connected to input IN5
110: Negative terminal connected to input IN6

FLEX_CH3_CN: Flex Routing Switch Control for Channel 3

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x03	CAL3		POS3			NEG3		

[7:6] CAL3 **Test signal selector**

00: Test signal disconnected and CH3 inputs determined by POS3 and NEG3 (default)
01: Connect channel three to positive test signal
10: Connect channel three to negative test signal
11: Connect channel three to zero test signal

[5:3] POS3 **Positive terminal of channel 3**

000: Positive terminal is disconnected (default)
001: Positive terminal connected to input IN1
010: Positive terminal connected to input IN2
011: Positive terminal connected to input IN3
100: Positive terminal connected to input IN4
101: Positive terminal connected to input IN5
110: Positive terminal connected to input IN6

[2:0] NEG3 **Negative terminal of channel 3**

000: Negative terminal is disconnected (default)
001: Negative terminal connected to input IN1
010: Negative terminal connected to input IN2
011: Negative terminal connected to input IN3
100: Negative terminal connected to input IN4
101: Negative terminal connected to input IN5
110: Negative terminal connected to input IN6

FLEX_PACE_CN: Flex Routing Switch Control for Pace Channel

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x04	CAL4		POS4			NEG4		

[7:6] CAL4 **Test signal selector**

00: Test signal disconnected and PACE inputs determined by POS4 and NEG4 (default)
01: Connect pace channel to positive test signal
10: Connect pace channel to negative test signal
11: Connect pace channel to zero test signal

[5:3] POS4 **Positive terminal of pace channel**

000: Positive terminal is disconnected (default)
001: Positive terminal connected to input IN1
010: Positive terminal connected to input IN2
011: Positive terminal connected to input IN3
100: Positive terminal connected to input IN4
101: Positive terminal connected to input IN5
110: Positive terminal connected to input IN6

[2:0] NEG4 **Negative terminal of pace channel**

000: Negative terminal is disconnected (default)
001: Negative terminal connected to input IN1
010: Negative terminal connected to input IN2
011: Negative terminal connected to input IN3
100: Negative terminal connected to input IN4
101: Negative terminal connected to input IN5
110: Negative terminal connected to input IN6

FLEX_VBAT_CN: Flex Routing Switch for Battery Monitoring

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x05						VBAT_ MONI_CH3	VBAT_ MONI_CH2	VBAT_ MONI_CH1

[7:3] RESERVED **-**

[2] VBAT_MONI_CH3 **Battery monitor configuration for channel 3**

0: Battery voltage monitor disabled (default)
1: Battery voltage monitor enabled and overrides FLEX_CH3_CN register

[1] VBAT_MONI_CH2 **Battery monitor configuration for channel 2**

0: Battery voltage monitor disabled (default)
1: Battery voltage monitor enabled and overrides FLEX_CH2_CN register

[0] VBAT_MONI_CH1 **Battery monitor configuration for channel 1**

0: Battery voltage monitor disabled (default)
1: Battery voltage monitor enabled and overrides FLEX_CH1_CN register

Note: The INA of the corresponding monitoring channel must be shut down in 0x14.

16.4 Lead-Off Detect Control Registers

LOD_CN: Lead-Off Detect Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x06				ACAD_LOD	SHDN_LOD	SELAC_LOD	ACLVL_LOD	

[7:5] RESERVED **-**

[4] ACAD_LOD **AC analog/digital lead-off mode select**

0: Digital AC lead-off detect (default)
1: Analog AC lead-off detect

[3] SHDN_LOD **Shut down lead-off detection**

0: Lead-off detection circuitry is active
1: Lead-off detection circuitry is shut down (default)

[2] SELAC_LOD **Lead-off detect operation mode**

0: DC lead-off mode (default)
1: AC lead-off mode

[1:0] ACLVL_LOD **Programmable comparator trigger level for AC lead-off detection**

00: Level 1 (default)
01: Level 2
10: Level 3
11: Level 4

LOD_EN: Lead-Off Detect Enable

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x07			EN_LOD					

[7:6] RESERVED -

[5] EN_LOD_6

DC or Analog AC Lead-off-Detection:
These bits enable the lead-off-detection for input IN6.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

Digital AC Lead-off-Detection:
These bits configure the phase of the current injected into channel CH3.
0: In-phase (default)
1: Anti-phase

[4] EN_LOD_5

DC or Analog AC Lead-off-Detection:
These bits enable the lead-off-detection for input IN5.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

Digital AC Lead-off-Detection:
These bits configure the phase of the current injected into channel CH2.
0: In-phase (default)
1: Anti-phase

[3] EN_LOD_4

DC or Analog AC Lead-off-Detection:
These bits enable the lead-off-detection for input IN4.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

Digital AC Lead-off-Detection:
These bits configure the phase of the current injected into channel CH1.
0: In-phase (default)
1: Anti-phase

[2] EN_LOD_3

DC or Analog AC Lead-off-Detection:
These bits enable the lead-off-detection for input IN3.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

Digital AC Lead-off-Detection:
These bits enable the lead-off-detection for channel CH3.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

[1] EN_LOD_2

DC or Analog AC Lead-off-Detection:
These bits enable the lead-off-detection for input IN2.
0: Lead-off detection disabled (default)
1: Lead-off detection enable

Digital AC Lead-off-Detection:
These bits enable the lead-off-detection for channel CH2.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

[0] EN_LOD_1

DC or Analog AC Lead-off-Detection:
These bits enable the lead-off-detection for input IN1.
0: Lead-off detection disabled (default)
1: Lead-off detection enable

Digital AC Lead-off-Detection:
These bits enable the lead-off-detection for channel CH1.
0: Lead-off detection disabled (default)
1: Lead-off detection enabled

LOD_CURRENT: Lead-Off Detect Current

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x08	CUR_LOD							

[7:0] CUR_LOD **Lead-off detect current select**

The lead-off detect current is programmable in a range of 2.04µA with steps of 8nA
00000000: 0.000 µA (default)
00000001: 0.008 µA
. .
. .
11111110: 2.032 µA
11111111: 2.040 µA

LOD_AC_CN: AC Lead-Off Detect Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x09	ACDIV_ FACTOR	ACDIV_LOD						

[7] ACDIV_FACTOR **AC lead off test frequency division factor**

0: Clock divider factor K = 1 (default)
1: Clock divider factor K = 16

[6:0] ACDIV_LOD **Clock divider ratio for AC lead off**

There are 7 bits available to program the clock divider that generates the AC lead off test frequency.

16.5 Common Mode Detection and Right Leg Drive Common Mode Feedback Control Registers

CMDET_EN: Common Mode Detect Enable

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x0A			CMDET_ EN_IN6	CMDET_ EN_IN5	CMDET_ EN_IN4	CMDET_ EN_IN3	CMDET_ EN_IN2	CMDET_ EN_IN1

[7:6] RESERVED **-**

[5:0] CMDET_EN_INx **Common mode detect input enable**

There is one bit available per input pin, where the MSB corresponds to input pin IN6 and the LSB corresponds to input pin IN1.
0: Disable (default)
1: Enable the corresponding pin's voltage to contribute to the average voltage of the common mode detect block.

CMDET_CN: Common Mode Detect Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x0B						CMDET_BW	CMDET_CAPDRIVE	

[7:3] RESERVED **-**

[2] CMDET_BW **Common mode detect bandwidth mode**

0: Low bandwidth mode (default)
1: High bandwidth mode

[1:0] CMDET_CAPDRIVE **Common mode detect capacitive load drive capability**

00: Low cap-drive mode (default)
01: Medium low cap-drive mode
10: Medium high cap-drive mode
11: High cap-drive mode

RLD_CN: Right Leg Drive Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x0C		RLD_BW	RLD_CAPDRIVE		SHDN_RLD	SELRLD		

[7] RESERVED -

[6] RLD_BW **Right leg drive bandwidth mode**

0: Low bandwidth mode (default)
1: High bandwidth mode

[5:4] RLD_CAPDRIVE **Right leg drive capacitive load drive capability**

00: Low cap-drive mode (default)
01: Medium low cap-drive mode
10: Medium high cap-drive mode
11: High cap-drive mode

[3] SHDN_RLD **Shut down right leg drive amplifier**

0: RLD amplifier powered up (default)
1: RLD amplifier powered down

[2:0] SELRLD **Right leg drive multiplexer**

000: Right leg drive output disconnected (default)
001: Right leg drive output connected to IN1
010: Right leg drive output connected to IN2
011: Right leg drive output connected to IN3
100: Right leg drive output connected to IN4
101: Right leg drive output connected to IN5
110: Right leg drive output connected to IN6

16.6 Wilson Control Registers

WILSON_EN1: Wilson Reference Input one Selection

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x0D						SELWILSON1		

[7:3] RESERVED -

[2:0] SELWILSON1 **Wilson reference routing for the first buffer amplifier**

000: No connection to the first buffer amplifier (default)
001: First buffer amplifier connected to input IN1
010: First buffer amplifier connected to input IN2
011: First buffer amplifier connected to input IN3
100: First buffer amplifier connected to input IN4
101: First buffer amplifier connected to input IN5
110: First buffer amplifier connected to input IN6

WILSON_EN2: Wilson Reference Input two Selection

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x0E						SELWILSON2		

[7:3] RESERVED -

[2:0] SELWILSON2 **Wilson reference routing for the second buffer amplifier**

000: No connection to the second buffer amplifier (default)
001: Second buffer amplifier connected to input IN1
010: Second buffer amplifier connected to input IN2
011: Second buffer amplifier connected to input IN3
100: Second buffer amplifier connected to input IN4
101: Second buffer amplifier connected to input IN5
110: Second buffer amplifier connected to input IN6

WILSON_EN3: Wilson Reference Input three Selection

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x0F						SELWILSON3		

[7:3] RESERVED -

[2:0] SELWILSON3 **Wilson reference routing for the third buffer amplifier**

000: No connection to the third buffer amplifier (default)
001: Third buffer amplifier connected to input IN1
010: Third buffer amplifier connected to input IN2
011: Third buffer amplifier connected to input IN3
100: Third buffer amplifier connected to input IN4
101: Third buffer amplifier connected to input IN5
110: Third buffer amplifier connected to input IN6

WILSON_CN: Wilson Reference Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x10						WILSON_ MODE	GOLDINT	WILSONINT

[7:3] RESERVED -

[2] WILSON_MODE **Wilson reference amplifiers mode**

0: Low bandwidth mode (default)
1: High bandwidth mode

[1] GOLDINT **Goldberger reference routing**

0: Goldberger reference disabled (default)
1: Goldberger reference outputs internally connected to IN4, IN5 and IN6.
Note: GOLDINT bit can not be 1 when WILSONINT is 1.

[0] WILSONINT **Wilson reference routing**

0: Wilson reference output internally disconnected from IN6 (default)
1: Wilson reference output internally connected to IN6
Note: WILSONINT bit can not be 1 when GOLDINT is 1.

16.7 Reference Registers

REF_CN: Internal Reference Voltage Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x11							SHDN_ CMREF	SHDN_REF

[7:2] RESERVED -

[1] SHDN_CMREF **Shut down the common mode and right-leg drive reference voltage circuitry**

0: CM and RLD reference voltage is on (default)
1: Shut down CM and RLD reference voltage
Note: Enable this bit to save power when the analog block is shut down (SHDN_REF = 1). Power-down mode automatically shuts down the common mode and right-leg drive reference.

[0] SHDN_REF **Shut down internal 2.4V reference voltage**

0: Internal reference voltage is on (default)
1: Shut down internal reference voltage
Note: Enabling this bit allows driving the IC with an external reference voltage on the CVREF pin. Power-down mode automatically shuts down the internal 2.4V reference.

16.8 OSC Control Registers

OSC_CN: Clock Source and Output Clock Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x12						STRTCLK	SHDN_OSC	EN_CLKOUT

[7:3] RESERVED -

[2] STRTCLK **Start the clock**

0: Clock to digital disabled (default)
1: Enable clock to digital
Note: Set this bit high only after the oscillator has started up or after the oscillator has shut down and the external clock has started up.

[1] SHDN_OSC **Select clock source**

0: Use internal clock with external crystal on XTAL1 and XTAL2 pins (default)
1: Shut down internal oscillator and use external clock from CLK pin
Note: STRTCLK bit should be low at the time this bit is reconfigured.

[0] EN_CLKOUT **Enable CLK pin output driver**

0: Clock output driver disabled (default)
1: Clock output driver enabled

16.9 AFE Control Registers

AFE_RES: Analog Front-End Frequency and Resolution

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x13			FS_HIGH_CH3	FS_HIGH_CH2	FS_HIGH_CH1	EN_HIRES_CH3	EN_HIRES_CH2	EN_HIRES_CH1

[7:6] RESERVED

[5] FS_HIGH_CH3 **Clock frequency for channel 3**

0: 102400 Hz (default)
1: 204800 Hz

[4] FS_HIGH_CH2 **Clock frequency for channel 2**

0: 102400 Hz (default)
1: 204800 Hz

[3] FS_HIGH_CH1 **Clock frequency for channel 1**

0: 102400 Hz (default)
1: 204800 Hz

[2] EN_HIRES_CH3 **High resolution mode for channel 3 instrumentation amplifier**

0: Disabled (default)
1: Enabled

[1] EN_HIRES_CH2 **High resolution mode for channel 2 instrumentation amplifier**

0: Disabled (default)
1: Enabled

[0] EN_HIRES_CH1 **High resolution mode for channel 1 instrumentation amplifier**

0: Disabled (default)
1: Enabled

AFE_SHDN_CN: Analog Front-End Shutdown Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x14			SHDN_ SDM_CH3	SHDN_ SDM_CH2	SHDN_ SDM_CH1	SHDN_ INA_CH3	SHDN_ INA_CH2	SHDN_ INA_CH1

[7:6] RESERVED -

[5] SHDN_SDM_CH3 **Shut down the sigma-delta modulator for channel 3**

0: Active (default)
1: Shut down

[4] SHDN_SDM_CH2 **Shut down the sigma-delta modulator for channel 2**

0: Active (default)
1: Shut down

[3] SHDN_SDM_CH1 **Shut down the sigma delta modulator for channel 1**

0: Active (default)
1: Shut down

[2] SHDN_INA_CH3 **Shut down the instrumentation amplifier for channel 3**

0: Active (default)
1: Shut down

[1] SHDN_INA_CH2 **Shut down the instrumentation amplifier for channel 2**

0: Active (default)
1: Shut down

[0] SHDN_INA_CH1 **Shut down the instrumentation amplifier for channel 1**

0: Active (default)
1: Shut down

AFE_FAULT_CN: Analog Front-End Fault Detection Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x15						SHDN_ FAULTDET_ CH3	SHDN_ FAULTDET_ CH2	SHDN_ FAULTDET_ CH1

[7:3] RESERVED -

[2] SHDN_FAULTDET_CH3 **Disable the instrumentation amplifier fault detection for channel 3**

0: Fault detection active (default)
1: Disable the fault detection

[1] SHDN_FAULTDET_CH2 **Disable the instrumentation amplifier fault detection for channel 2**

0: Active (default)
1: Disable the fault detection

[0] SHDN_FAULTDET_CH1 **Disable the instrumentation amplifier fault detection for channel 1**

0: Active (default)
1: Disable the fault detection

AFE_PACE_CN: Analog Pace Channel Output Routing Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x17						PACE2RLDIN	PACE2WCT	SHDN_PACE

[7:3] RESERVED -

[2] PACE2RLDIN **Connect the analog pace channel output to RLDIN pin**

0: Analog pace channel output is disconnected from the RLDIN pin (default)
1: Connect the analog pace channel output to the RLDIN pin.
Note: The right leg drive amplifier is disconnected from the RLDIN pin and connected internally to the RLDREF pin when this bit is 1.

[1] PACE2WCT **Connect the analog pace channel output to WCT pin**

0: Analog pace channel output is disconnected from the WCT pin (default)
1: Connect the analog pace channel output to the WCT pin.
Note: The Wilson reference output is disconnected from the WCT pin when this bit is 1. The Wilson output can be connected internally to IN6 pin with the *WILSON_CN* register.

[0] SHDN_PACE **Shut down analog pace channel**

0: Analog pace channel is powered up
1: Analog pace channel is shut down (default)

16.10 Error Status Registers

ERROR_LOD: Lead Off Detect Error Status

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x18			OUT_LOD					

[7:6] RESERVED -

[5:0] OUT_LOD **Lead Off Detect Status**

There is one bit available per input pin, where the MSB corresponds to input pin IN6 and the LSB corresponds to input pin IN1.
1: Indicates a lead off error detected on the corresponding input pin.

Note: The clock to digital (internal or external) must be enabled in 0x12[2] for this error register to update.

ERROR_STATUS: Other Error Status

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x19	SYNC EDGEERR	CH3ERR	CH2ERR	CH1ERR	LEADOFF	BATLOW	RLDRAIL	CMOR

[7] SYNCEDGEERR **Digital synchronization error**

1: Indicates a digital synchronization error occurred

[6] CH3ERR **Channel 3 out of range error**

1: Indicates an out of range error detected on channel 3

[5] CH2ERR **Channel 2 out of range error**

1: Indicates an out of range error detected on channel 2

[4] CH1ERR **Channel 1 out of range error**

1: Indicates an out of range error detected on channel 1

[3] LEADOFF **Lead off detected**

1: Indicates a lead off was detected on at least one input pin

[2] BATLOW **Low battery**

1: Indicates the battery voltage has dropped below 2.7 V

[1] RLDRAIL **Right leg drive near rail**

1: Indicates the right leg drive amplifier output is approaching the supply rails

[0] CMOR **Common mode level out of range**

1: Indicates the level detected by the common mode detect block is outside of the input common mode range of the amplifiers in the analog front-end.

Note: The clock to digital (internal or external) must be enabled in 0x12[2] for this error register to update.

ERROR_RANGE1: Channel 1 AFE Out of Range Status

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x1A		SDM_ OR_CH1	SIGN_CH1	OUTN_ LOW_CH1	OUTN_ HIGH_CH1	OUTP_ LOW_CH1	OUTP_ HIGH_CH1	DIF_HIGH_ CH1

[7] RESERVED **-**

[6] SDM_OR_CH1 **Channel 1 sigma-delta modulator over range**

1: Indicates an over range detected for channel 1 SDM

[5] SIGN_CH1 **Channel 1 instrumentation amplifier output sign**

This bit specifies the sign of the output signal of the instrumentation amplifier for channel 1.
0: Positive output of INA larger than negative output
1: Positive output of INA smaller than negative output

[4] OUTN_LOW_CH1 **Channel 1 instrumentation amplifier negative output near negative rail**

1: Indicates the negative output of the instrumentation amplifier is close to the negative rail for channel 1.

[3] OUTN_HIGH_CH1 **Channel 1 instrumentation amplifier negative output near positive rail**

1: Indicates the negative output of the instrumentation amplifier is close to the positive rail for channel 1.

[2] OUTP_LOW_CH1 **Channel 1 instrumentation amplifier positive output near negative rail**

1: Indicates the positive output of the instrumentation amplifier is close to the negative rail for channel 1.

[1] OUTP_HIGH_CH1 **Channel 1 instrumentation amplifier positive output near positive rail**

1: Indicates the positive output of the instrumentation amplifier is close to the positive rail for channel 1.

[0] DIF_HIGH_CH1 **Channel 1 instrumentation amplifier output out of range**

1: Indicates the differential output voltage of the amplifier is out of range for channel 1.

Note: The clock to digital (internal or external) must be enabled in 0x12[2] for this error register to update.

ERROR_RANGE2: Channel 2 AFE Out of Range Status

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x1B		SDM_ OR_CH2	SIGN_CH2	OUTN_ LOW_CH2	OUTN_ HIGH_CH2	OUTP_ LOW_CH2	OUTP_ HIGH_CH2	DIF_HIGH_ CH2

[7] RESERVED **-**

[6] SDM_OR_CH2 **Channel 2 sigma-delta modulator over range**

1: Indicates an over range detected for channel 2 SDM

[5] SIGN_CH2 **Channel 2 instrumentation amplifier output sign**

This bit specifies the sign of the output signal of the instrumentation amplifier for channel 2.
0: Positive output of INA is greater than negative output
1: Negative output of INA is greater than positive output

[4] OUTN_LOW_CH2 **Channel 2 instrumentation amplifier negative output near negative rail**

1: Indicates the negative output of the instrumentation amplifier is close to the negative rail for channel 2.

[3] OUTN_HIGH_CH2 **Channel 2 instrumentation amplifier negative output near positive rail**

1: Indicates the negative output of the instrumentation amplifier is close to the positive rail for channel 2.

[2] OUTP_LOW_CH2 **Channel 2 instrumentation amplifier positive output near negative rail**

1: Indicates the positive output of the instrumentation amplifier is close to the negative rail for channel 2.

[1] OUTP_HIGH_CH2 **Channel 2 instrumentation amplifier positive output near positive rail**

1: Indicates the positive output of the instrumentation amplifier is close to the positive rail for channel 2.

[0] DIF_HIGH_CH2 **Channel 2 instrumentation amplifier output out of range**

1: Indicates the differential output voltage of the amplifier is out of range for channel 2.

Note: The clock to digital (internal or external) must be enabled in 0x12[2] for this error register to update.

ERROR_RANGE3: Channel 3 AFE Out of Range Status

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x1C		SDM_ OR_CH3	SIGN_CH3	OUTN_ LOW_CH3	OUTN_ HIGH_CH3	OUTP_ LOW_CH3	OUTP_ HIGH_CH3	DIF_HIGH_ CH3

[7] RESERVED **-**

[6] SDM_OR_CH3 **Channel 3 sigma-delta modulator over range**

1: Indicates an over range detected for channel 3 SDM

[5] SIGN_CH3 **Channel 3 instrumentation amplifier output sign**

This bit specifies the sign of the output signal of the instrumentation amplifier for channel 3.
0: Positive output of INA is greater than negative output.
1: Negative output of INA is greater than positive output.

[4] OUTN_LOW_CH3 **Channel 3 instrumentation amplifier negative output near negative rail**

1: Indicates the negative output of the instrumentation amplifier is close to the negative rail for channel 3.

[3] OUTN_HIGH_CH3 **Channel 3 instrumentation amplifier negative output near positive rail**

1: Indicates the negative output of the instrumentation amplifier is close to the positive rail for channel 3.

[2] OUTP_LOW_CH3 **Channel 3 instrumentation amplifier positive output near negative rail**

1: Indicates the positive output of the instrumentation amplifier is close to the negative rail for channel 3.

[1] OUTP_HIGH_CH3 **Channel 3 instrumentation amplifier positive output near positive rail**

1: Indicates the positive output of the instrumentation amplifier is close to the positive rail for channel 3.

[0] DIF_HIGH_CH3 **Channel 3 instrumentation amplifier output out of range**

1: Indicates the differential output voltage of the amplifier is out of range for channel 3.

Note: The clock to digital (internal or external) must be enabled in 0x12[2] for this error register to update.

ERROR_SYNC: Synchronization Error

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x1D					SYNC_ PHASEERR	SYNC_ CH3ERR	SYNC_ CH2ERR	SYNC_ CH1ERR

[7:4] RESERVED **-**

[3] SYNC_PHASEERR **Clock timing generator phase error**

1: Timing generator phase adjusted to comply with SYNCB signal.

[2] SYNC_CH3ERR **Channel 3 synchronization error**

1: Channel's filter timing updated to comply with synchronization source.

[1] SYNC_CH2ERR **Channel 2 synchronization error**

1: Channel's filter timing updated to comply with synchronization source.

[0] SYNC_CH1ERR **Channel 1 synchronization error**

1: Channel's filter timing updated to comply with synchronization source.

ERROR_MISC: Miscellaneous Errors

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x1E						BATLOW_ STATUS	RLDRAIL_ STATUS	CMOR_ STATUS

[7:3] RESERVED **-**

[2] BATLOW_STATUS **Low battery error status**

1: Indicates the battery voltage has dropped below 2.7 V

[1] RLDRAIL_STATUS **Right leg drive near rail error status**

1: Indicates the right leg drive amplifier output is approaching the supply rails.

[0] CMOR_STATUS **Common mode level out of range error status**

1: Indicates the level detected by the common mode detect block is outside of the input common mode range of the amplifiers in the analog front-end

Note: The clock to digital (internal or external) must be enabled in 0x12[2] for this error register to update.

16.11 Digital Registers

DIGO_STRENGTH: Digital Output Drive Strength

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x1F							DIGO_STRENGTH	

[7:2] RESERVED **-**

[1:0] DIGO_STRENGTH **Digital Output Drive Strength**

00: Low drive mode
01: Mid-low drive mode
10: Mid-high drive mode
11: High drive mode (Default)

R2_RATE: R2 Decimation Rate

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x21					R2_RATE			

[7:4] RESERVED **-**

[3:0] R2_RATE **R2 decimation rate**

0001: 4
0010: 5
0100: 6
1000: 8 (default)
Note: The register sets to its default value if none or more than one bit are enabled.

R3_RATE_CH1: R3 Decimation Rate for Channel 1

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x22	R3_RATE1							

[7:0] R3_RATE_CH1 **R3 decimation rate for channel 1**

00000001: 4
00000010: 6
00000100: 8
00001000: 12
00010000: 16
00100000: 32
01000000: 64
10000000: 128 (default)
Note: The register sets to its default value if none or more than one bit are enabled.

R3_RATE_CH2: R3 Decimation Rate for Channel 2

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x23	R3_RATE2							

[7:0] R3_RATE_CH2 **R3 decimation rate for channel 2**

00000001: 4
00000010: 6
00000100: 8
00001000: 12
00010000: 16
00100000: 32
01000000: 64
10000000: 128 (default)
Note: The register sets to its default value if none or more than one bit are enabled.

R3_RATE_CH3: R3 Decimation Rate for Channel 3

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x24	R3_RATE3							

[7:0] R3_RATE_CH3 **R3 decimation rate for channel 3**

00000001: 4
00000010: 6
00000100: 8
00001000: 12
00010000: 16
00100000: 32
01000000: 64
10000000: 128 (default)
Note: The register sets to its default value if none or more than one bit are enabled.

R1_RATE: R1 Decimation Rate

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x25						R1_RATE_CH3	R1_RATE_CH2	R1_RATE_CH1

[7:3] RESERVED **-**

[2] R1_RATE_CH3 **Pace data rate for channel 3**

0: R1 = 4: Standard PACE Data Rate (default)
1: R1 = 2: Double PACE Data Rate

[1] R1_RATE_CH2 **Pace data rate for channel 2**

0: R1 = 4: Standard PACE Data Rate (default)
1: R1 = 2: Double PACE Data Rate

[0] R1_RATE_CH1 **Pace data rate for channel 1**

0: R1 = 4: Standard PACE Data Rate (default)
1: R1 = 2: Double PACE Data Rate

DIS_EFILTER: ECG Filter Disable

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x26						DIS_E3	DIS_E2	DIS_E1

[7:3] RESERVED -

[2] DIS_E3 **Disable the ECG filter for channel 3**

0: ECG filter enabled (default)
1: ECG filter disabled

[1] DIS_E2 **Disable the ECG filter for channel 2**

0: ECG filter enabled (default)
1: ECG filter disabled

[0] DIS_E1 **Disable the ECG filter for channel 1**

0: ECG filter enabled (default)
1: ECG filter disabled

DRDYB_SRC: Data Ready Pin Source

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x27			DRDYB_SRC					

[7:6] RESERVED -

[6:0] DRDYB_SRC **Select channel to drive the DRDYB pin**

000000: DRDYB pin not asserted (default)
000001: Driven by channel 1 pace
000010: Driven by channel 2 pace
000100: Driven by channel 3 pace
001000: Driven by channel 1 ECG
010000: Driven by channel 2 ECG
100000: Driven by channel 3 ECG

SYNCB_CN: SYNCB In/Out Pin Control

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x28		DIS_SYNCB OUT	SYNCB_SRC					

[7] RESERVED **-**

[6] DIS_SYNCBOUT **Disable the SYNCB pin output driver**

0: Driver enabled and pin configured as output
1: Driver disabled and pin configured as input (default)
Note: Bit should be set to 1 for slave devices.

[5:0] SYNCB_SRC **Select channel to drive the SYNCB pin**

000000: No source selected (default)
000001: Driven by channel 1 pace
000010: Driven by channel 2 pace
000100: Driven by channel 3 pace
001000: Driven by channel 1 ECG
010000: Driven by channel 2 ECG
100000: Driven by channel 3 ECG
Note: Choose the slowest pace or ECG channel as source. Bits[5:0] must be cleared to 0 for slave devices.

MASK_DRDYB: Optional Mask Control for DRDYB Output

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x29							DRDYB MASK_CTL1	DRDYB MASK_CT0

[7:2] RESERVED **-**

[1] DRDYBMASK_CTL1 **START_CON mask control for DRDYB output**

0: DRDYB signal is masked when START_CON is set. (default)
1: Disable initial DRDYB masking when START_CON is set.

[0] DRDYBMASK_CTL0 **Optional mask control for DRDYB output**

0: DRDYB signal is masked after out of sync is detected. (default)
1: Disable DRDYB masking after out of sync is detected.

Note: If an ECG channel is enabled, DRDYB is masked during 6 ECG output data periods.
If all ECG channels are disabled, DRDYB is masked during 6 or 11 pace output data periods, for 1x pace or 2x pace mode respectively.

MASK_ERR: Mask Error on ALARMB Pin

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x2A	MASK_SYNC EDGEERR	MASK_ CH3ERR	MASK_ CH2ERR	MASK_ CH1ERR	MASK_ OUTLOD	MASK_ BATLOW	MASK_ RLDRAIL	MASK_ CMOR

[7] MASK_SYNCEDGEERR **Mask alarm condition when SYNCEDGEERR=1**

0: Alarm condition is active (default)
1: Alarm condition is masked

[6] MASK_CH3ERR **Mask alarm condition for CH3ERR=1**

0: Alarm condition active (default)
1: Alarm condition is masked

[5] MASK_CH2ERR **Mask alarm condition for CH2ERR=1**

0: Alarm condition active (default)
1: Alarm condition is masked

[4] MASK_CH1ERR **Mask alarm condition for CH1ERR=1**

0: Alarm condition active (default)
1: Alarm condition is masked

[3] MASK_LEADOFF **Mask alarm condition for LEADOFF=1**

0: Alarm condition active (default)
1: Alarm condition is masked

[2] MASK_BATLOW **Mask alarm condition for BATLOW=1**

0: Alarm condition active (default)
1: Alarm condition is masked

[1] MASK_RLDRAIL **Mask alarm condition for RLDRAIL=1**

0: Alarm condition active (default)
1: Alarm condition is masked

[0] MASK_CMOR **Mask alarm condition for CMOR=1**

0: Alarm condition active (default)
1: Alarm condition is masked

ALARM_FILTER: Digital Filter for Analog Alarm Signals

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x2E	AFILTER_OTHER				AFILTER_LOD			

[7:4] AFILTER_OTHER **Filter for all other alarms count**

Number of consecutive analog alarm signal counts+1 before ALARMB is asserted.
0011: (default)

[3:0] AFILTER_LOD **Filter for OUT_LOD[5:0] alarm count**

Number of consecutive lead off alarm signal counts+1 before ALARMB is asserted.
0011: (default)

CH_CNFG: Configure Channel for Loop Read Back Mode

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x2F		E3_EN	E2_EN	E1_EN	P3_EN	P2_EN	P1_EN	STS_EN

[7] RESERVED **-**

[6] E3_EN **Enable DATA_CH3_ECG read back**

0: Disable data read back for this channel (default)
1: Enable data read back for this channel

[5] E2_EN **Enable DATA_CH2_ECG read back**

0: Disable data read back for this channel (default)
1: Enable data read back for this channel

[4] E1_EN **Enable DATA_CH1_ECG read back**

0: Disable data read back for this channel (default)
1: Enable data read back for this channel

[3] P3_EN **Enable DATA_CH3_PACE read back**

0: Disable data read back for this channel (default)
1: Enable data read back for this channel

[2] P2_EN **Enable DATA_CH2_PACE read back**

0: Disable data read back for this channel (default)
1: Enable data read back for this channel

[1] P1_EN **Enable DATA_CH1_PACE read back**

0: Disable data read back for this channel (default)
1: Enable data read back for this channel

[0] STS_EN **Enable DATA_STATUS read back**

0: Disable data status read back (default)
1: Enable data status read back

16.12 Pace and ECG Data Read Back Registers

DATA_STATUS: ECG and Pace Data Ready Status

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x30	E3_DRDY	E2_DRDY	E1_DRDY	P3_DRDY	P2_DRDY	P1_DRDY	ALARMB	0

[7] E3_DRDY — **Channel 3 ECG data ready**
1: Channel 3 ECG data ready

[6] E2_DRDY — **Channel 2 ECG data ready**
1: Channel 2 ECG data ready

[5] E1_DRDY — **Channel 1 ECG data ready**
1: Channel 1 ECG data ready

[4] P3_DRDY — **Channel 3 pace data ready**
1: Channel 3 pace data ready

[3] P2_DRDY — **Channel 2 pace data ready**
1: Channel 2 pace data ready

[2] P1_DRDY — **Channel 1 pace data ready**
1: Channel 1 pace data ready

[1] ALARMB — **ALARMB status**
1: Alarm active (ALARMB output pin driven low)

[0] Reserved — **-**
0

DATA_CH1_PACE: Channel 1 Pace Data

Addr	BIT15	BIT14	BIT13	BIT12	BIT11	BIT10	BIT9	BIT8
0x31	DATA_CH1_PACE							
	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x32	DATA_CH1_PACE							

[15:8] DATA_CH1_PACE — **Channel 1 pace data**
Address 0x31 contains the upper byte.

[7:0] DATA_CH1_PACE — **Channel 1 pace data**
Address 0x32 contains the lower byte.

DATA_CH2_PACE: Channel 2 Pace Data

Addr	BIT15	BIT14	BIT13	BIT12	BIT11	BIT10	BIT9	BIT8
0x33	DATA_CH2_PACE							
	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x34	DATA_CH2_PACE							

[15:8] DATA_CH2_PACE **Channel 2 pace data**

Address 0x33 contains the upper byte.

[7:0] DATA_CH2_PACE **Channel 2 pace data**

Address 0x34 contains the lower byte.

DATA_CH3_PACE: Channel 3 Pace Data

Addr	BIT15	BIT14	BIT13	BIT12	BIT11	BIT10	BIT9	BIT8
0x35	DATA_CH3_PACE							
	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x36	DATA_CH3_PACE							

[15:8] DATA_CH3_PACE **Channel 3 pace data**

Address 0x35 contains the upper byte.

[7:0] DATA_CH3_PACE **Channel 3 pace data**

Address 0x36 contains the lower byte.

DATA_CH1_ECG: Channel 1 ECG Data

Addr	BIT23	BIT22	BIT21	BIT20	BIT19	BIT18	BIT17	BIT16
0x37	DATA_CH1_ECG							
	BIT15	BIT14	BIT13	BIT12	BIT11	BIT10	BIT9	BIT8
0x38	DATA_CH1_ECG							
	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x39	DATA_CH1_ECG							

[23:16] DATA_CH1_ECG **Channel 1 ECG data**

Address 0x37 contains the upper byte.

[15:8] DATA_CH1_ECG **Channel 1 ECG data**

Address 0x38 contains the middle byte.

[7:0] DATA_CH1_ECG **Channel 1 ECG data**

Address 0x39 contains the lower byte.

DATA_CH2_ECG: Channel 2 ECG Data

Addr	BIT23	BIT22	BIT21	BIT20	BIT19	BIT18	BIT17	BIT16
0x3A	DATA_CH2_ECG							
	BIT15	BIT14	BIT13	BIT12	BIT11	BIT10	BIT9	BIT8
0x3B	DATA_CH2_ECG							
	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x3C	DATA_CH2_ECG							

[23:16] DATA_CH2_ECG **Channel 2 ECG data**

Address 0x3A contains the upper byte.

[15:8] DATA_CH2_ECG **Channel 2 ECG data**

Address 0x3B contains the middle byte.

[7:0] DATA_CH2_ECG **Channel 2 ECG data**

Address 0x3C contains the lower byte.

DATA_CH3_ECG: Channel 3 ECG Data

Addr	BIT23	BIT22	BIT21	BIT20	BIT19	BIT18	BIT17	BIT16
0x3D	DATA_CH3_ECG							
	BIT15	BIT14	BIT13	BIT12	BIT11	BIT10	BIT9	BIT8
0x3E	DATA_CH3_ECG							
	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x3F	DATA_CH3_ECG							

[23:16] DATA_CH3_ECG **Channel 3 ECG data**

Address 0x3D contains the upper byte.

[15:8] DATA_CH3_ECG **Channel 3 ECG data**

Address 0x3E contains the middle byte.

[7:0] DATA_CH3_ECG **Channel 3 ECG data**

Address 0x3F contains the lower byte.

REVID: Revision ID

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x40	REVID							

[7:0] REVID **Revision ID**

00000001 (Default)

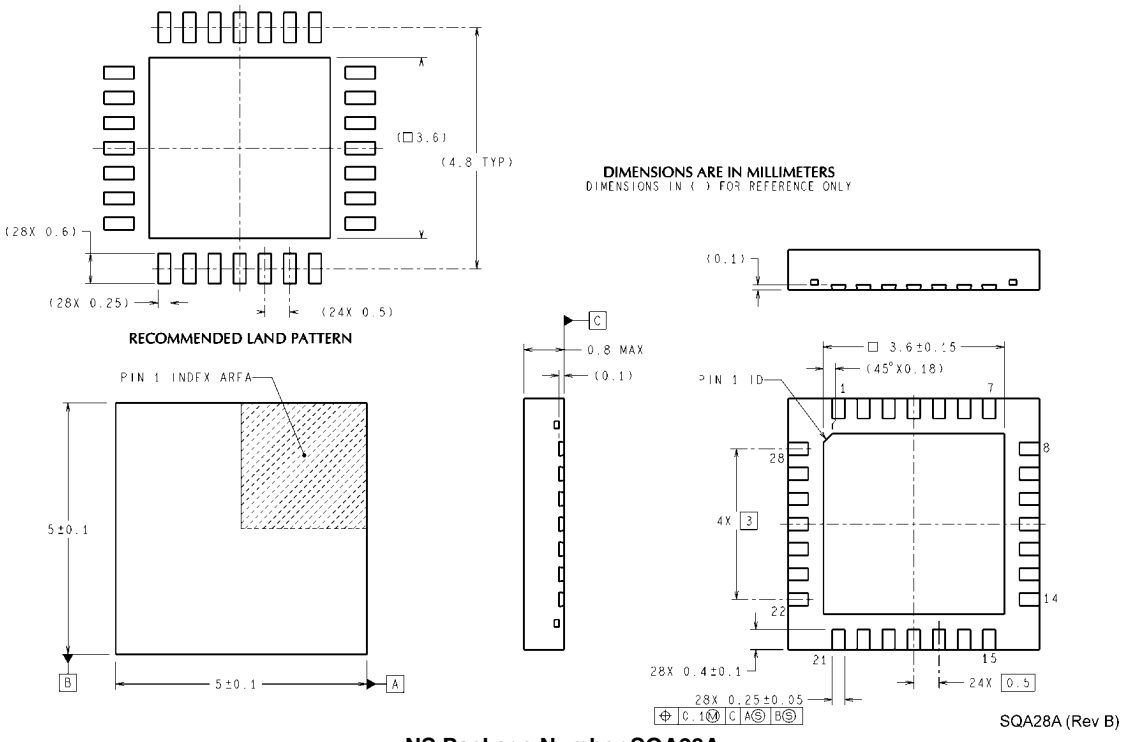
DATA_LOOP: Loop Read Back Address

Addr	BIT7	BIT6	BIT5	BIT4	BIT3	BIT2	BIT1	BIT0
0x50	PE_LPRD							

[7:0] PE_LPRD **Loop read back address**

Special address to enable loop read back 0x30 - 0x3F if enabled in CH_CNFG.

17.0 Physical Dimensions inches (millimeters) unless otherwise noted



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