AFEx81H1 16-Bit and 14-Bit, Low-Power DACs With Internal HART® Modem, Voltage Reference, and Diagnostic ADC for 4mA to 20mA Loop-Powered Applications

1 Features

- Functional Safety-Capable
  - Documentation available to aid functional safety system design: AFE881H1, AFE781H1
- Low quiescent current: 180µA (typical)
- HART®-compliant physical layer modem
- 16-bit or 14-bit monotonic high-performance DAC
  - 1.8V supply: 0.15V to 1.25V, 0.2V to 1.0V
  - 5V supply: 0.3V to 2.5V, 0.4V to 2.0V
  - 4LSB INL at 16 bits
  - 0.07% FSR (max) TUE from –40°C to +125°C
- 12-bit 3.84-kSPS ADC for advanced diagnostics
- Integrated 1.25V reference at 10ppm/°C (max)
- Internal 1.2288MHz oscillator with clock output
- Digital interface
  - Serial peripheral interface (SPI): Shared bus for both DAC and HART
  - Universal asynchronous receiver-transmitter (UART): Shared bus for both DAC and HART
  - Both: SPI for DAC and UART for HART
- Fault detection: CRC bit error checking, windowed watchdog timer, diagnostic ADC
- Digital DAC slew-rate control
- Wide operating temperature: –55°C to +125°C

2 Applications

- 2-wire, 4mA to 20mA loop-powered transmitters
- Process control and industrial automation
- Smart transmitters

3 Description

The 16-bit AFE881H1 and 14-bit AFE781H1 (AFEx81H1) are highly-integrated, high-accuracy, extremely low-power digital-to-analog converters (DACs) with voltage outputs designed for HART-enabled sensor-transmitter applications.

The AFEx81H1 devices include most of the components required to design a 4-mA to 20-mA, 2-wire (loop-powered) sensor transmitter. In addition to the highly accurate DAC, these parts include a HART-certified FSK modem, 10-ppm/°C voltage reference, and diagnostic analog-to-digital converter (ADC). To accommodate intrinsic and functional safety concerns, external voltage-to-current conversion and power regulation are required.

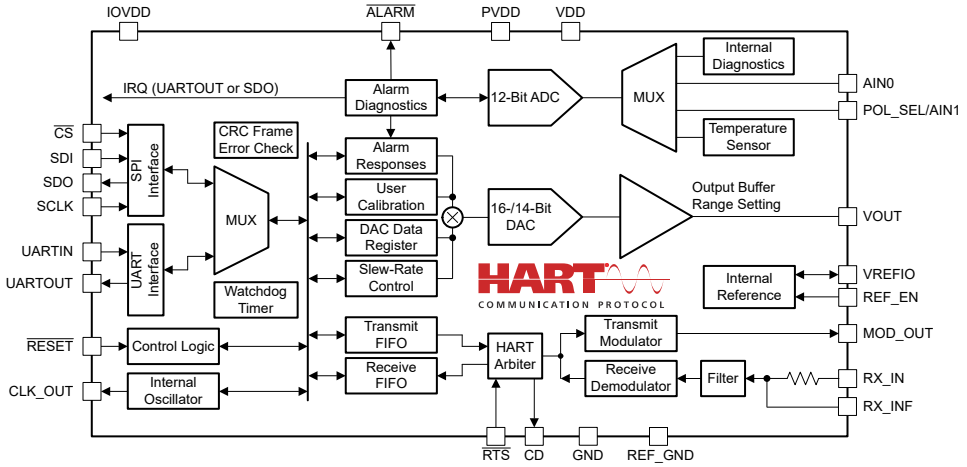
The internal diagnostic ADC is multiplexed to several internal nodes that enable an automatic self-health check. If any fault is detected from the diagnostic ADC, CRC frame-error checking, or windowed watchdog timer, the devices can optionally issue an interrupt, enter a fail-safe state corresponding to a standard NAMUR output value or user-specified custom value, or both.

These devices operate from supplies as low as 1.71 V with 220 µA maximum quiescent current. The devices are specified over the temperature range of –40°C to +125°C, but are functional from –55°C to +125°C.

Device Information

PART NUMBER	RESOLUTION	PACKAGE(1)
AFE781H1	14-bit	RRU (UQFN, 24) 4.00mm × 4.00mm
AFE881H1	16-bit	

(1) For all available packages, see the package option addendum at the end of the datasheet.



Functional Block Diagram

An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.

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4 Pin Configuration and Functions

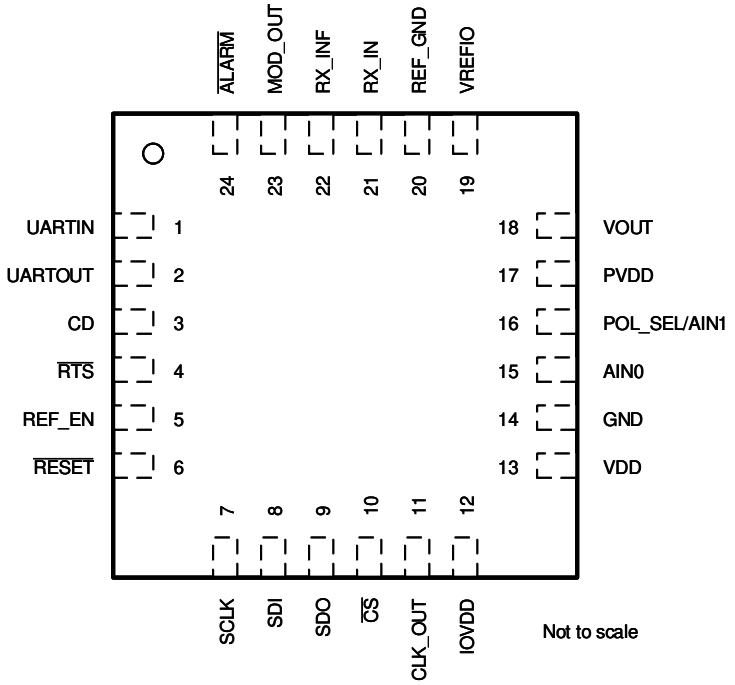


Figure 4-1. RRU (24-pin UQFN) Package, Top View

Table 4-1. Pin Functions

PIN		TYPE[1]	DESCRIPTION
NAME	NO.		
AIN0	15	AI	ADC input voltage. The input range is 0 V to VREF if PVDD = VDD, or 0 V to 2 × VREF if PVDD > 2.7 V.
$\overline{\text{ALARM}}$	24	DO	Alarm notification. Open drain. When alarm condition is asserted, this pin is held to logic low; otherwise, this pin is in a high-impedance state (Hi-Z).
CD	3	DO	Carrier detect. A logic high on this pin indicates a valid carrier is present.
CLK_OUT	11	DO	Clock output. This pin can be configured as a clock output for the 1.2288-MHz internal clock.
$\overline{\text{CS}}$	10	DI	SPI chip-select. Data bits are clocked into the serial shift register when $\overline{\text{CS}}$ is logic low. When $\overline{\text{CS}}$ is logic high, SDO is in a high-impedance state and data on SDI are ignored. Do not leave any digital input pins floating.
GND	14	P	Digital and analog ground. Ground reference point for all circuitry on the device.
IOVDD	12	P	Interface supply. Supply voltage for digital input and output circuitry. This voltage sets the logical thresholds for the digital interfaces.
MOD_OUT	23	AO	FSK output sinusoid. Maximum supported parallel load capacitance is 2 nF.
POL_SEL/AIN1	16	DI/AI	ADC input voltage if SPECIAL_CFG.AIN1_ENB bit is set to 1. The input range is 0 V to VREF if PVDD = VDD, or 0 V to 2 × VREF if PVDD > 2.7 V. Otherwise, this pin acts as ALMV_POL, which sets the polarity of the VOUT alarm voltage.
PVDD	17	P	Power supply for the internal low-dropout regulator (LDO), ADC input, and VOUT DAC output. When 2.7 V to 5.5 V is provided, the internal LDO turns on and drives VDD internally. When 1.71 V to 1.89 V is provided, the internal LDO is disabled.
REF_EN	5	DI	Internal VREF enable input. A logic high on this pin enables the internal VREF and the VREFIO pin outputs 1.25 V. A logic low on this pin disables the internal VREF and the external 1.25V reference is required at the VREFIO pin.
REF_GND	20	P	GND reference for VREFIO pin.
$\overline{\text{RESET}}$	6	DI	Reset. Logic low on this pin turns off the internal oscillator and resets the device. Logic high returns the device to normal operation. Do not leave any digital input pins floating.

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Table 4-1. Pin Functions (continued)

PIN		TYPE[1]	DESCRIPTION
NAME	NO.		
$\overline{RTS}$	4	DI	Request to send. A logic high on this pin enables the demodulator and disables the modulator. A logic low on this pin enables the modulator and disables the demodulator. Do not leave any digital input pins floating.
RX_IN	21	AI	HART FSK input if no external filter is used; otherwise, do not connect any signal to this pin.
RX_INF	22	AI	HART FSK input if using the external band-pass filter. If using the internal band-pass filter by connecting the HART FSK to RX_IN, then connect a 680pF capacitor to this pin.
SCLK	7	DI	SPI serial clock. Data can be transferred at rates up to 12.5 MHz. SCLK is a Schmitt-trigger logic input. Connect to GND or logic low if not used. Do not leave any digital input pins floating.
SDI	8	DI	SPI data input. Data are clocked into the 24-bit input shift register on the falling edge of the serial clock input. SDI is a Schmitt-Trigger logic input. Do not leave any digital input pins floating.
SDO	9	DO	SPI data output. Data are output on the rising edge of SCLK when $\overline{CS}$ is logic low. Interrupt request (IRQ) pin in the UART break mode (UBM). The output is in a Hi-Z state at power up and must be enabled in the CONFIG register.
UARTIN	1	DI	UART data input. Connect to IOVDD or logic high if not used. Do not leave any digital input pins floating.
UARTOUT	2	DO	UART data output. This pin can be configured to function as the IRQ pin in SPI only mode.
VDD	13	P/AO	Power supply. When 2.7 V to 5.5 V is provided on PVDD pin, the internal LDO drives VDD internally. Connect a 1-µF to 10-µF capacitor to this pin. When 1.71 V to 1.89 V is provided on the PVDD pin, an external power supply must be provided on this pin.
VOUT	18	AO	DAC output voltage.
VREFIO	19	AI/AO	When the internal VREF is enabled by REF_EN pin, this pin outputs the internal VREF voltage. In this case, a load capacitance of 70nF to 130nF is required for stability. When disabled, this pin is the external 1.25-V reference input.

(1) AI = analog input, AO = analog output, DI = digital input, DO = digital output, P = power.

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5 Specifications

5.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

			MIN	MAX	UNIT
	Voltage	PVDD, IOVDD to GND	–0.3	5.5	V
		VDD to GND	–0.3	1.98	V
		AIN0, POL_SEL/AIN1, VOUT to GND	–0.3	PVDD + 0.3	V
		Digital Input/Output to GND	–0.3	IOVDD + 0.3	V
		VREFIO to GND	–0.3	VDD + 0.3	V
		REF_GND to GND	–0.3	0.3	V
	HART voltage	RX_IN, RX_INF, MOD_OUT to GND	–0.3	VDD + 0.3	V
	Input current	Current into any pin	–10	10	mA
T_J	Junction temperature		–55	150	°C
T_{stg}	Storage temperature		–65	150	

(1) Operation outside the *Absolute Maximum Ratings* may cause permanent device damage. *Absolute Maximum Ratings* do not imply functional operation of the device at these or any other conditions beyond those listed under *Recommended Operating Conditions*. If used outside the *Recommended Operating Conditions* but within the *Absolute Maximum Ratings*, the device may not be fully functional, and this may affect device reliability, functionality, performance, and shorten the device lifetime.

5.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human body model (HBM), per ANSI/ESDA/JEDEC JS-001, all pins(1)	±2000	V
		Charged device model (CDM), per ANSI/ESDA/JEDEC JS-002, all pins(2)	±500	

(1) JEDEC document JEP155 states that 500V HBM allows safe manufacturing with a standard ESD control process.
(2) JEDEC document JEP157 states that 250V CDM allows safe manufacturing with a standard ESD control process.

5.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

			MIN	NOM	MAX	UNIT
	PVDD to GND	PVDD > 2.7V, VDD internally generated	2.7		5.5	V
		PVDD = VDD	1.71		1.89	V
	VDD to GND		1.71		1.89	V
	IOVDD to GND		1.71		5.5	V
	VREFIO to GND	External VREF	1.2	1.25	1.3	V
T_A	Ambient temperature	Specified	–40		125	°C
		Operating	–55		125	

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5.4 Thermal Information

THERMAL METRIC[1]		AFEx81H1 RRU (UQFN) 24 PINS	UNIT
$R_{\theta JA}$	Junction-to-ambient thermal resistance	103.1	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	84.4	°C/W
$R_{\theta JC(bottom)}$	Junction-to-case (bottom) thermal resistance	N/A	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	69.5	°C/W
Ψ_{JT}	Junction-to-top characterization parameter	0.4	°C/W
Ψ_{JB}	Junction-to-board characterization parameter	68.4	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application note.

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5.5 Electrical Characteristics

all minimum and maximum values at T_A = –40°C to +125°C and all typical values at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
VOUT DAC STATIC PERFORMANCE						
	Resolution	AFE881H1	16			Bits
		AFE781H1	14			
INL	Integral nonlinearity(1)	AFE881H1	–4		4	LSB
		AFE781H1	–2		2	
DNL	Differential nonlinearity(1)		–1		1	LSB
TUE	Total unadjusted error(1)	T_A = –40°C to +125°C	–0.07		0.07	%FSR
		T_A = –40°C to +85°C	–0.05		0.05	
		T_A = 25°C	–0.04		0.04	
ZCE	Zero code error	T_A = –40°C to +125°C	–0.07		0.07	%FSR
		T_A = –40°C to +85°C	–0.05		0.05	
		T_A = 25°C	–0.03		0.03	
ZCE-TC	Zero code error temperature coefficient			±3		ppm/°C
OE	Offset error(1)	T_A = –40°C to +125°C	–0.07		0.07	%FSR
		T_A = –40°C to +85°C	–0.05		0.05	
		T_A = 25°C	–0.03		0.03	
OE-TC	Offset error temperature coefficient (1)			±3		ppm/°C
GE	Gain error(1)	T_A = –40°C to +125°C	–0.04		0.04	%FSR
		T_A = –40°C to +85°C	–0.04		0.04	
		T_A = 25°C	–0.03		0.03	
GE-TC	Gain error temperature coefficient(1)			±3		ppm FSR/°C
FSE	Full-scale error	T_A = –40°C to +125°C	–0.07		0.07	%FSR
		T_A = –40°C to +85°C	–0.06		0.06	
		T_A = 25°C	–0.04		0.04	
FSE-TC	Full-scale error temperature coefficient			±3		ppm FSR/°C
VOUT DAC DYNAMIC PERFORMANCE						
t_s	Output voltage settling time(4)	¼ to ¾ scale and ¾ to ¼ scale settling to ±2LSB, PVDD = VDD = 1.8V, VREFIO = 1.25V		65		µs
		10mV step settling to ±2LSB, PVDD = VDD = 1.8V, VREFIO = 1.25V		30		
SR	Slew rate(4)	Fullscale transition measured from 10% to 90%		30		mV/µs
V_n	Output noise(4)	0.1Hz to 10Hz, DAC at midscale, PVDD = VDD = 1.8V, VREFIO = 1.25V		0.25		LSB_{PP}
		100kHz bandwidth, DAC at midscale, PVDD = VDD = 1.8V, VREFIO = 1.25V		32		µVrms
V_n	Output noise density	Measured at 1kHz, DAC at midscale, PVDD = VDD = 1.8V, VREFIO = 1.25V		180		nV/√Hz
		Measured at 1kHz, DAC at midscale, PVDD = 5V, VREFIO = 1.25V		260		
	Power supply rejection ratio (AC)	200mV 50Hz to 60Hz sine wave superimposed on power supply voltage, DAC at midscale.		85		dB
	Code change glitch impulse	Midcode ±1LSB (including feedthrough) PVDD = VDD = 1.8V, VREFIO = 1.25V		4.5		nV-s
	Code change glitch magnitude	Midcode ±1LSB (including feedthrough) PVDD = 5V, VREFIO = 1.25V		1.5		mV
	Digital feedthrough	At SCLK = 1MHz, DAC output at midscale		1		nV-s

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5.5 Electrical Characteristics (continued)

all minimum and maximum values at T_A = –40°C to +125°C and all typical values at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
VOUT DAC OUTPUT CHARACTERISTICS						
	Output voltage range	RANGE = 0, PVDD = VDD	0.15		1.25	V
		RANGE = 1, PVDD = VDD	0.2		1.0	
		RANGE = 0, PVDD > 2.7V, VDD generated	0.3		2.5	
		RANGE = 1, PVDD > 2.7V, VDD generated	0.4		2.0	
	VOUT alarm output high	PVDD > 2.7V, VDD internally generated	–6%	2.5	+6%	V
		PVDD = VDD	–6%	1.25	+6%	
	VOUT alarm output low	PVDD > 2.7V, VDD internally generated	–5%	0.3	+5%	V
		PVDD = VDD	–5%	0.15	+5%	
R_{LOAD}	Resistive load[2]		10			kΩ
C_{LOAD}	Capacitive load[2]				100	pF
	Load regulation	DAC at midscale, –1mA ≤ I_{OUT} ≤ +1mA		10		µV/mA
	Short-circuit current	Full scale output shorted to GND		5		mA
		Zero output shorted to VDD		5		
	Output voltage headroom to PVDD	DAC at full code, I_{OUT} = 1mA (sourcing)	200			mV
	Output voltage footroom to GND	DAC at zero code, I_{OUT} = 1mA (sinking)	200			mV
Z_O	DC small signal output impedance	DAC at midscale		10		mΩ
		Output Hi-Z		500		kΩ
	Power supply rejection ratio (dc)	DAC at midscale; PVDD = 1.8V ± 10%		0.1		mV/V
	Output voltage drift vs time, 1000 hours	T_A = 35°C, VOUT = midscale, ideal VREF		±5		ppm FSR
DIAGNOSTIC ADC						
	Input voltage range	PVDD = VDD	0		1.25	V
		PVDD > 2.7V	0		2.5	
	Resolution			12		Bits
DNL	Differential nonlinearity	Specified 12-bit monotonic	–1	±0.2	1	LSB
INL	Integral nonlinearity		–4	±1	4	LSB
OE	Offset error	After calibration	–10	±1.6	10	LSB
GE	Gain error		–0.8	±0.13	0.8	%FSR
	Noise			±4		LSB
	Input capacitance			6		pF
	Input bias current	ADC not converting	–50		50	nA
	Acquisition time			52		µs
	Conversion time			210		µs
	Conversion rate				3.84	kSPS
	Temperature sensor accuracy			5		°C
INTERNAL OSCILLATOR						
	Frequency	T_A = –40°C to +125°C	1.2165	1.2288	1.2411	MHz

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5.5 Electrical Characteristics (continued)

all minimum and maximum values at T_A = –40°C to +125°C and all typical values at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
HART MODEM						
RX_IN INPUT (HART MODE)						
	Input voltage range	External or internal reference source, design architecture. Signal applied at the input to the dc blocking capacitor.	0		1.5	V_{PP}
	Receiver sensitivity	Threshold for successful carrier detection and demodulation, assuming ideal sinusoidal input FSK signals with valid preamble using internal filter.	80	100	120	mV_{PP}
	Carrier detect time	1200Hz of carrier frequency present at the input before CD asserted	3			baud
MOD_OUT OUTPUT (HART MODE)						
	Output voltage	Measured at MOD_OUT pin with 160Ω load, AC-coupled (2.2 µF)	400	500	800	mV_{PP}
	Mark frequency			1200		Hz
	Space frequency			2200		Hz
	Frequency error	T_A = –40°C to +125°C	–1		1	%
	Phase continuity error	Design architecture			0	Degrees
	Minimum resistive load	AC-coupled with 2.2 µF	160			Ω
	Transmit impedance	$\overline{RTS}$ low, measured at the MOD_OUT pin, 1mA measurement current		25		mΩ
	Transmit impedance	$\overline{RTS}$ high, measured at the MOD_OUT pin, ±200nA measurement current		50		kΩ

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5.5 Electrical Characteristics (continued)

all minimum and maximum values at T_A = –40°C to +125°C and all typical values at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
VOLTAGE REFERENCE INPUT						
Z_{VREFIO}	Reference input impedance (VREFIO)	RANGE = 0		125		kΩ
		RANGE = 1		180		
C_{VREFIO}	Reference input capacitance (VREFIO)			100		pF
VOLTAGE REFERENCE OUTPUT						
	Output (initial accuracy)(3)	T_A = 25°C	1.248	1.25	1.252	V
	Output drift(3)	T_A = –40°C to +125°C			10	ppm/°C
	Output impedance(3)			0.1		Ω
	Output noise(3)	0.1Hz to 10Hz		7.5		μV_{PP}
	Output noise density(3)	Measured at 10kHz, reference load = 100nF		200		nV/√Hz
	Load current(3)	Sourcing, 0.1% VREF change from nominal		2.5		mA
		Sinking, 0.1% VREF change from nominal			0.3	
	Load regulation(3)	Sourcing, 0mA to 2.5mA		4		µV/mA
C_{OUT}	Stable output capacitance	T_A = –40°C to +125°C, ESR from 10mΩ to 400mΩ	70	100	130	nF
	Line regulation(3)			80		µV/V
	Output voltage drift vs time(3)	T_A = 35°C, 1000 hours		±100		ppm
	Thermal hysteresis(3)	1st cycle		500		µV
		Additional cycles		25		µV
VDD VOLTAGE REGULATOR OUTPUT						
	Output voltage		1.71	1.8	1.89	V
	Output impedance(3)	PVDD = 3.3V, sourcing, 0.5mA to 2.5mA		3		Ω
	Load current(3)	PVDD = 3.3V, sourcing, 1% VDD change from nominal		4		mA
THERMAL ALARM						
	Alarm trip point			130		°C
	Warning trip point			85		°C
	Hysteresis			12		°C
	Trip point absolute accuracy			5		°C
	Trip point relative accuracy			2		°C
DIGITAL INPUT CHARACTERISTICS						
V_{IH}	High-level input voltage		0.7			V/IOVDD
V_{IL}	Low-level input voltage				0.3	V/IOVDD
	Hysteresis voltage		0.05			V/IOVDD
	Input current		–400		400	nA
	Pin capacitance	Per pin		10		pF
DIGITAL OUTPUT CHARACTERISTICS						
V_{OH}	High-level output voltage	I_{SOURCE} = 1mA	0.8			V/IOVDD
V_{OL}	Low-level output voltage	I_{SINK} = 1mA			0.2	V/IOVDD
V_{OL}	Open-drain low-level output voltage	I_{SINK} = 2mA			0.3	V
	Output pin capacitance			10		pF

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5.5 Electrical Characteristics (continued)

all minimum and maximum values at T_A = –40°C to +125°C and all typical values at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
POWER REQUIREMENTS						
I_{PVDD}	Current flowing into PVDD	PVDD only, VDD internally generated, DAC at zero-scale, ADC and SPI static		180	220	µA
		Shared PVDD and VDD connection, DAC at zero-scale, ADC and SPI static		32	45	
I_{LDO}	VDD LDO quiescent current	From PVDD		8		µA
I_{VDD}	Current flowing into VDD	Shared PVDD and VDD connection, DAC at zero-scale, ADC and SPI static, internal reference		140	170	µA
I_{REFIO}	Internal reference current consumption	From external or internally generated VDD		52	70	µA
I_{HART}	HART Tx modem current consumption	From external or internally generated VDD		10		µA
I_{ADC}	ADC current consumption	From PVDD, ADC converting at 3.84 kSPS		10		µA
C_{VDD}	Recommended VDD decoupling capacitance		1		10	µF
I_{IOVDD}	Current flowing into IOVDD	SPI static		5	20	µA
I_{VREFIO}	Current flowing into VREFIO	0.15V to 1.25V range, midscale code		10		µA

(1) End point fit between code 0 to code 65,535 for 16-bit, code 0 to code 16,383 for 14-bit, DAC output unloaded, performance under resistive and capacitive load conditions are specified by design and characterization.
(2) Not production tested.
(3) Derived from the characterization data.
(4) Output buffer gain (G) = 2, PVDD > 2.7V.

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5.6 Timing Requirements

all input signals are specified with $t_R = t_F$ = 1ns/V and timed from a voltage level of $(V_{IL} + V_{IH}) / 2$, 2.7V ≤ PVDD ≤ 5.5V, V_{IH} = 1.62V, V_{IL} = 0.15V, VREFIO = 1.25V, and T_A = –40°C to +125°C (unless otherwise noted)

PARAMETER		MIN	NOM	MAX	UNIT
SERIAL INTERFACE - WRITE AND READ OPERATION					
f_{SCLK}	Serial clock frequency			12.5	MHz
$t_{SCLKHIGH}$	SCLK high time	36			ns
$t_{SCLKLOW}$	SCLK low time	36			ns
t_{CSHIGH}	$\overline{CS}$ high time	80			ns
t_{CSS}	$\overline{CS}$ to SCLK falling edge setup time	30			ns
t_{CSH}	SCLK falling edge to $\overline{CS}$ rising edge	30			ns
t_{CSRI}	$\overline{CS}$ rising edge to SCLK falling edge ignore	30			ns
t_{CSFI}	SCLK falling edge ignore to $\overline{CS}$ falling edge	5			ns
t_{SDIS}	SDI setup time	5			ns
t_{SDIH}	SDI hold time	5			ns
t_{SDOZD}	$\overline{CS}$ falling edge to SDO tri-state condition to driven			40	ns
t_{SDODZ}	$\overline{CS}$ rising edge to SDO driven to tri-state condition			40	ns
t_{SDODLY}	SCLK to SDO output delay			40	ns
UART					
$t_{BAUDUART}$	Baud rate = 9600 ± 1%		104		µs
$t_{BAUDUART}$	Baud rate = 1200 ± 1%		833		µs
HART					
$t_{BAUDHART}$	Baud rate = 1200 ± 1%		833		µs
DIGITAL LOGIC					
$t_{DACWAIT}$	Sequential DAC update wait time	2.1			µs
t_{POR}	POR reset delay			100	µs
t_{RESET}	$\overline{RESET}$ pulse duration	100			ns
$t_{RESETWAIT}$	Wait time after $\overline{RESET}$ pulse	10			µs

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5.7 Timing Diagrams

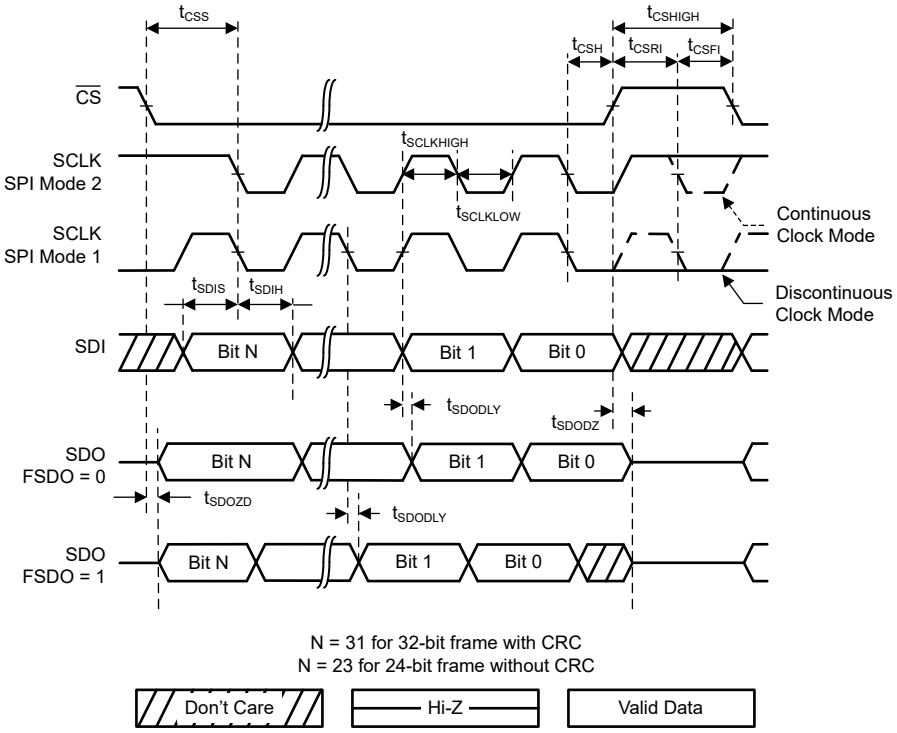


Figure 5-1. SPI Timing

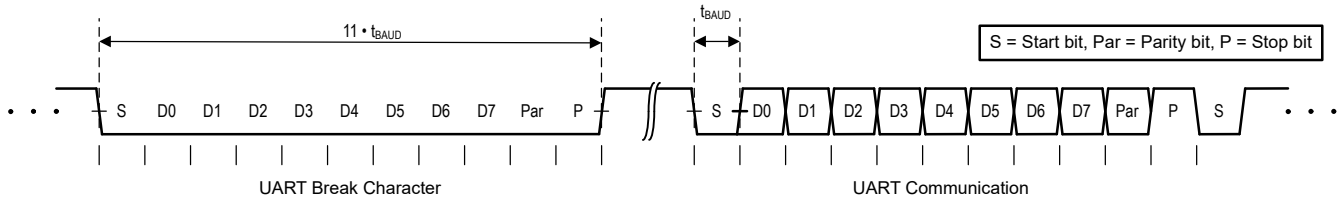


Figure 5-2. UBM Timing

5.8 Typical Characteristics: VOUT DAC

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

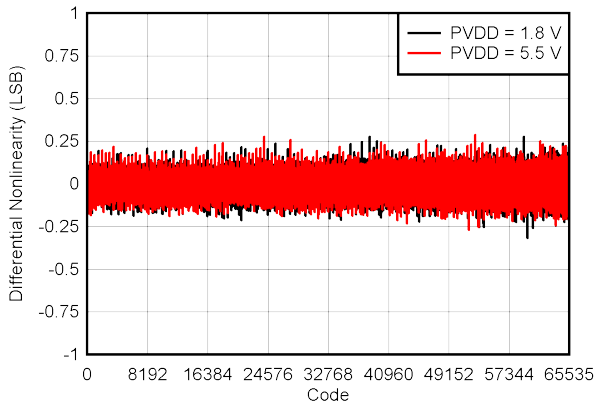


Figure 5-3. DAC DNL vs Digital Input Code

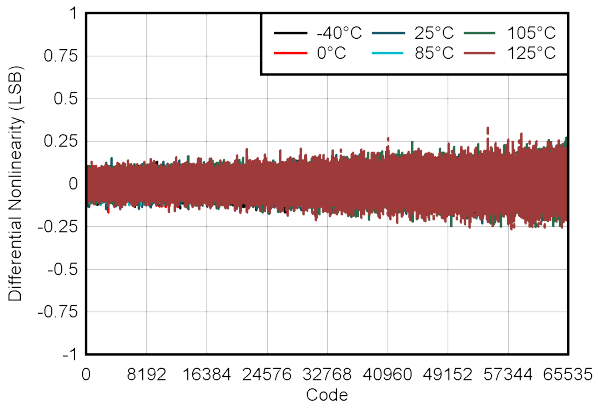


Figure 5-4. DAC DNL vs Digital Input Code

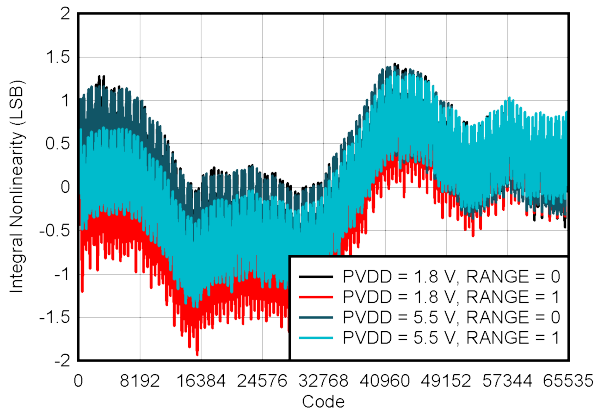


Figure 5-5. DAC INL vs Digital Input Code

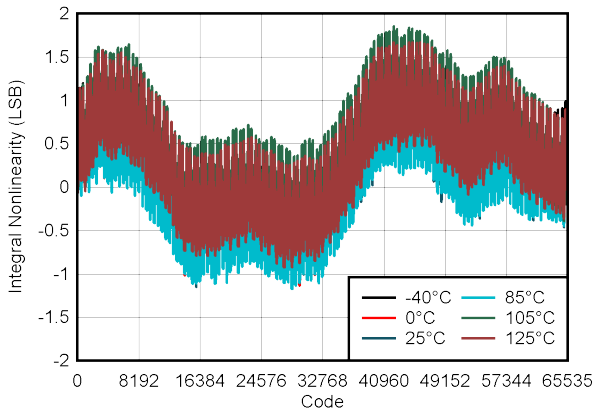


Figure 5-6. DAC INL vs Digital Input Code

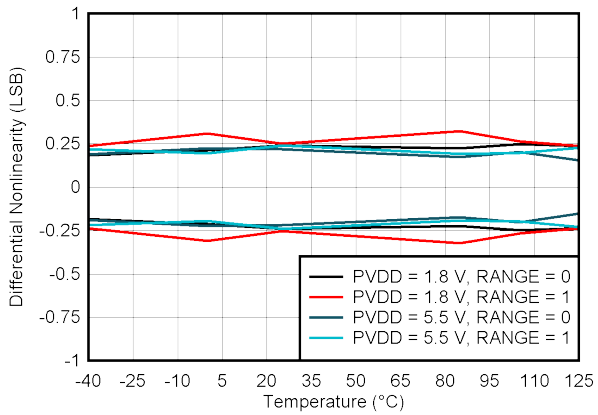


Figure 5-7. MIN and MAX DAC DNL Range vs Temperature

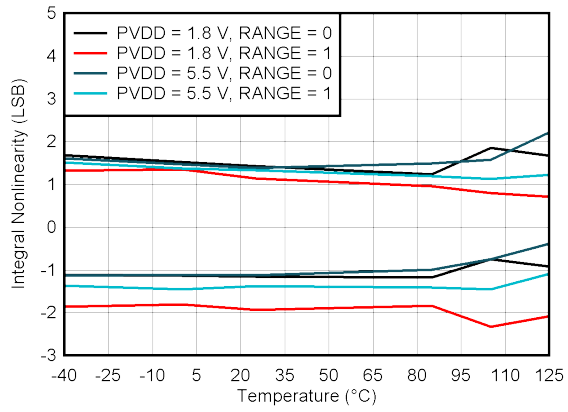


Figure 5-8. MIN and MAX DAC INL Range vs Temperature

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5.8 Typical Characteristics: VOUT DAC (continued)

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

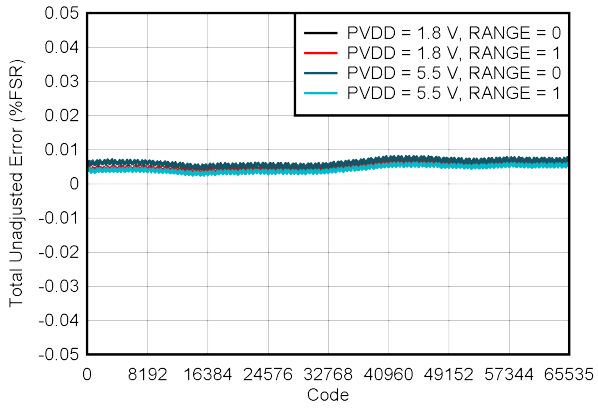


Figure 5-9. DAC TUE vs Digital Input Code

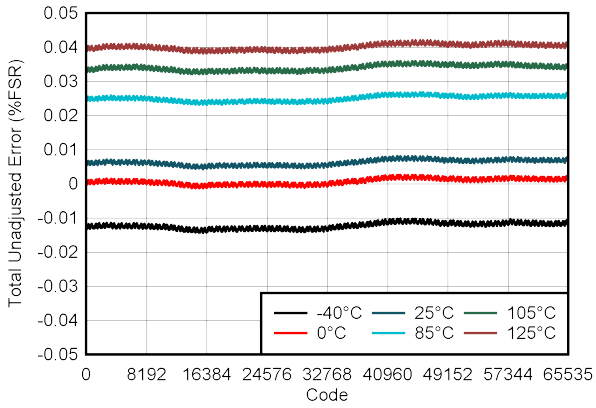


Figure 5-10. DAC TUE vs Digital Input Code

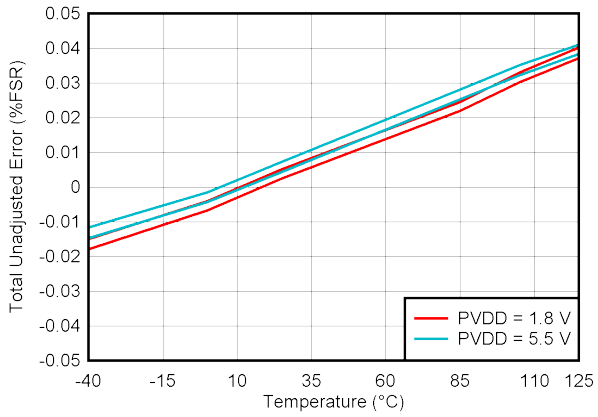


Figure 5-11. MIN and MAX DAC TUE vs Temperature

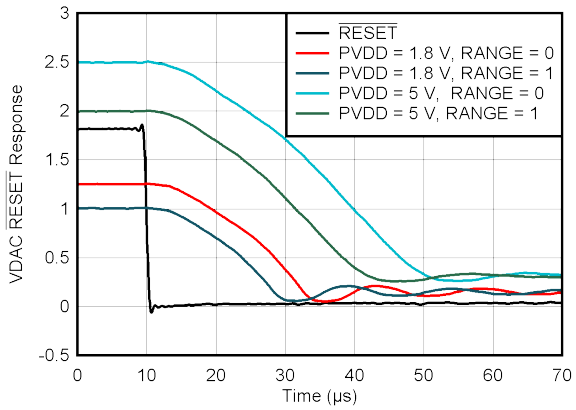
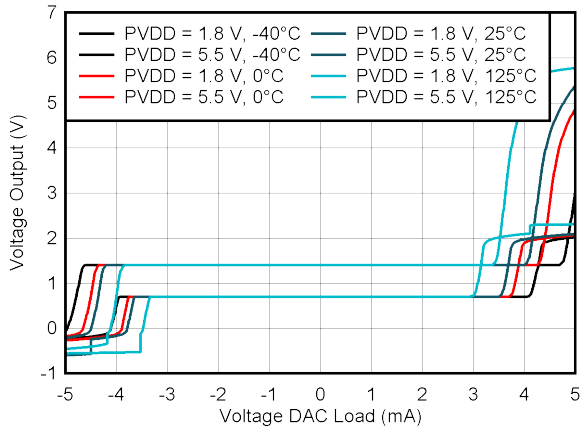
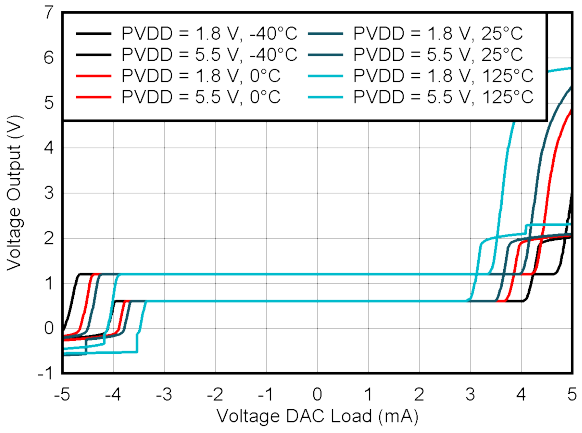


Figure 5-12. DAC $\overline{\text{RESET}}$ Response



RANGE = 0

Figure 5-13. DAC Source and Sink Current Capability



RANGE = 1

Figure 5-14. DAC Source and Sink Current Capability

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5.8 Typical Characteristics: VOUT DAC (continued)

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

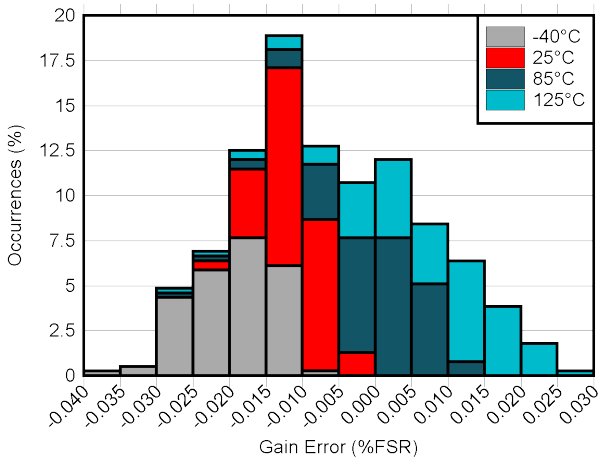


Figure 5-15. DAC Gain Error vs Temperature

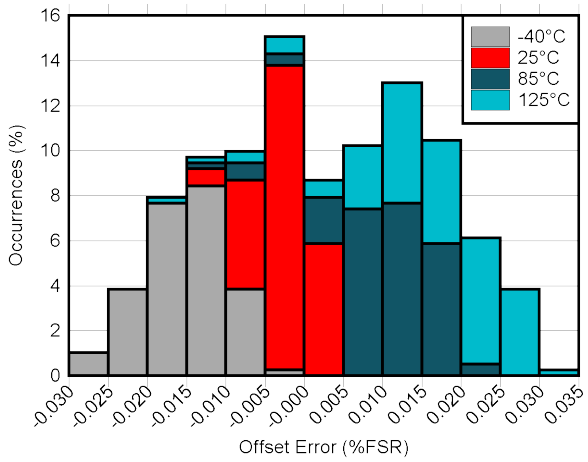


Figure 5-16. DAC Offset Error vs Temperature

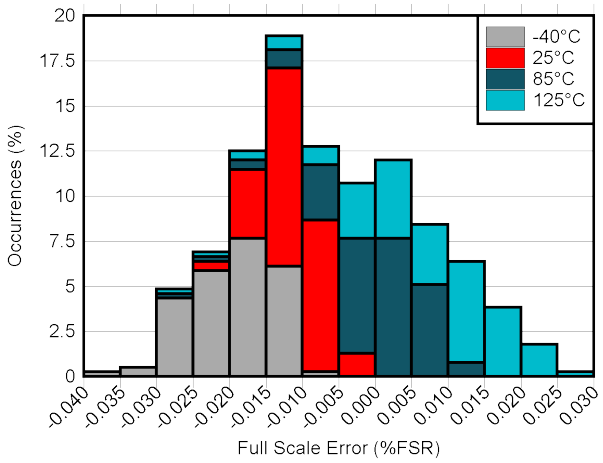


Figure 5-17. DAC Full Scale Error vs Temperature

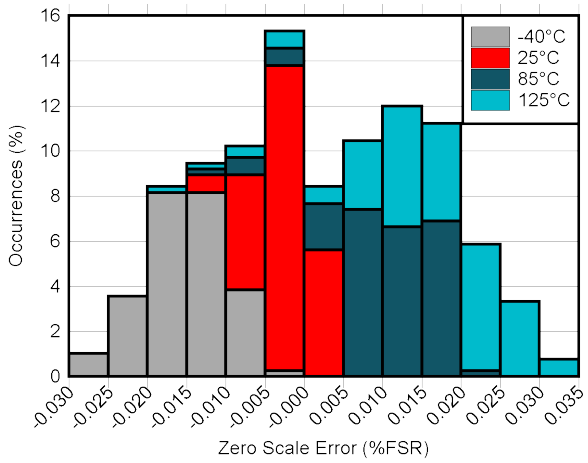
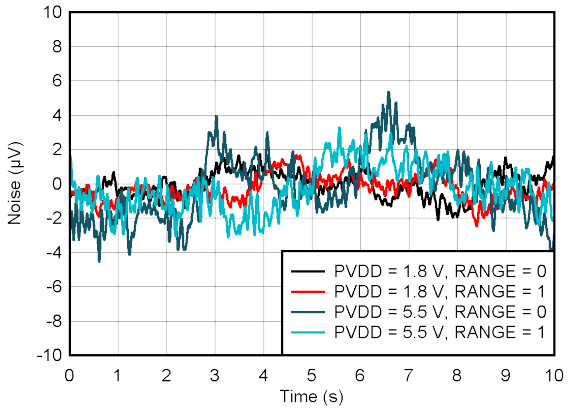
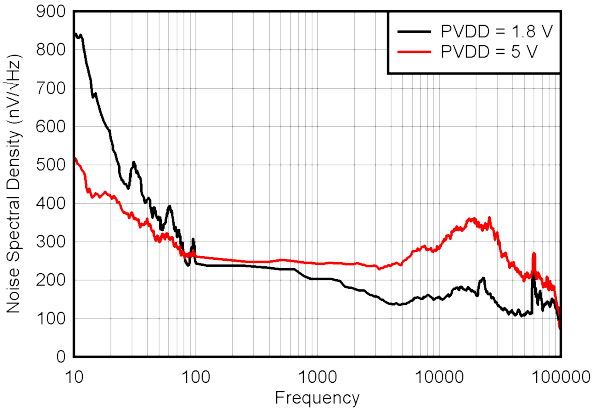


Figure 5-18. DAC Zero Scale Error vs Temperature



DAC at midcode

Figure 5-19. DAC Output Noise, 0.1Hz to 10Hz



DAC at midcode

Figure 5-20. DAC Output Noise Density vs Frequency

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5.8 Typical Characteristics: VOUT DAC (continued)

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

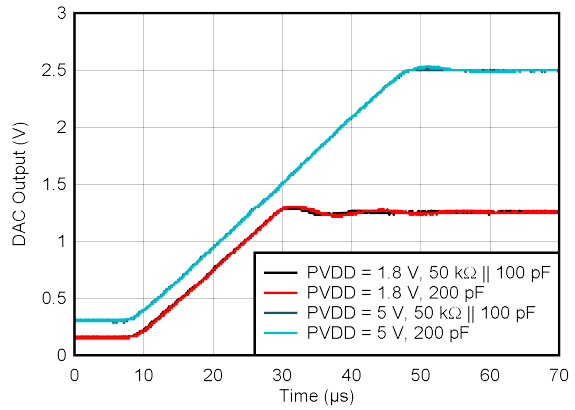


Figure 5-21. DAC Settling Time vs Load (Rising Voltage Step)

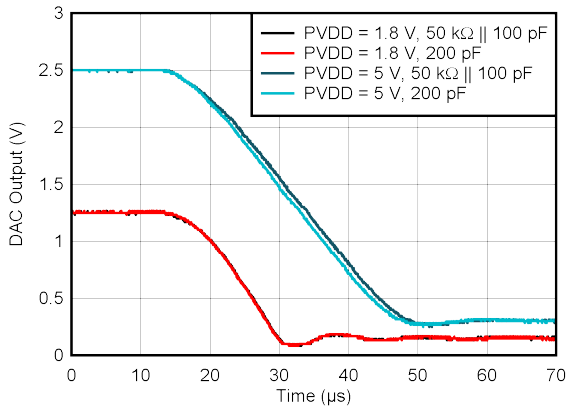


Figure 5-22. DAC Settling Time vs Load (Falling Voltage Step)

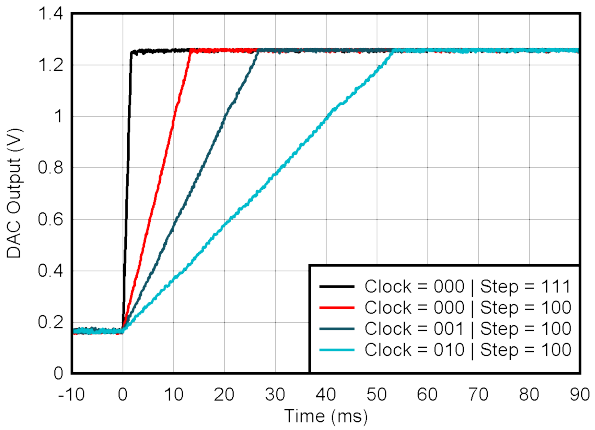


Figure 5-23. DAC Settling Time With Linear Slew Rate Control

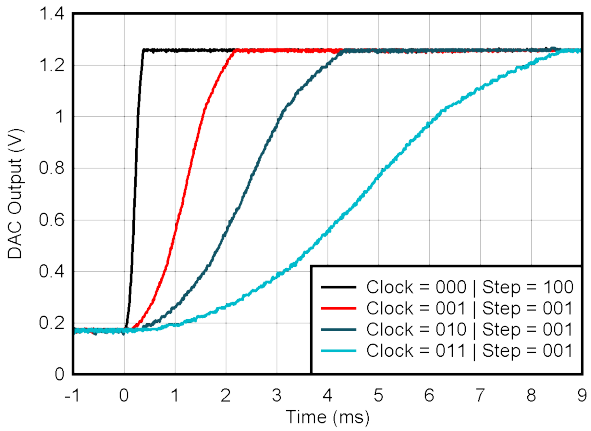


Figure 5-24. DAC Settling Time With Sinusoidal Slew Rate Control

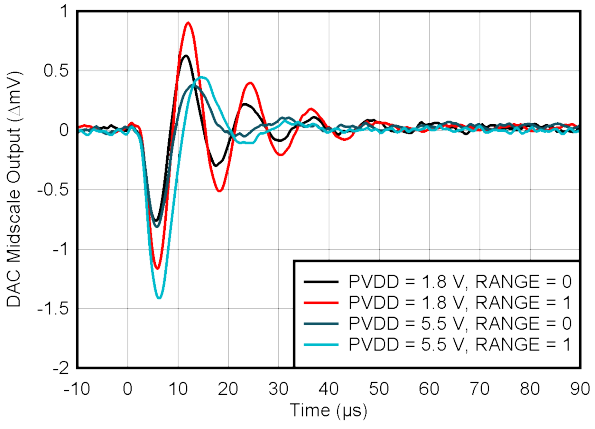


Figure 5-25. DAC Glitch Impulse Rising Edge

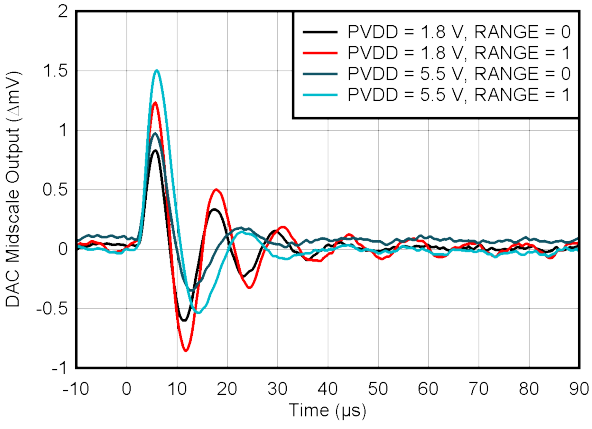


Figure 5-26. DAC Glitch Impulse Falling Edge

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5.8 Typical Characteristics: VOUT DAC (continued)

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

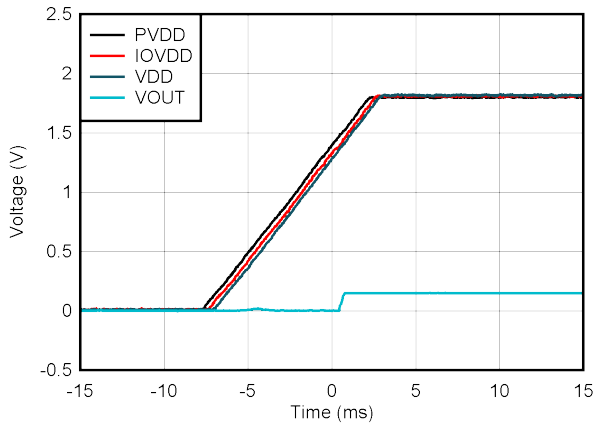


Figure 5-27. DAC Supply Power On, PVDD = 1.8V

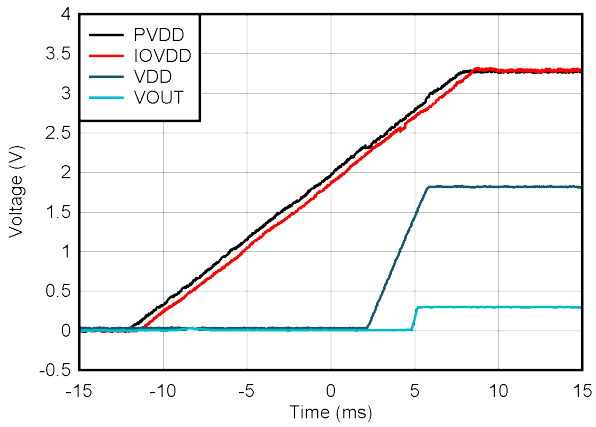
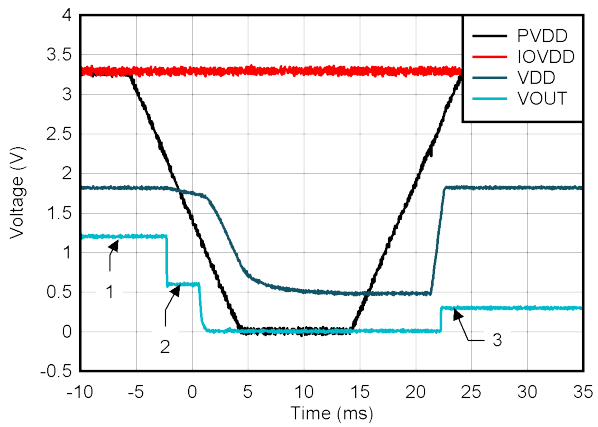
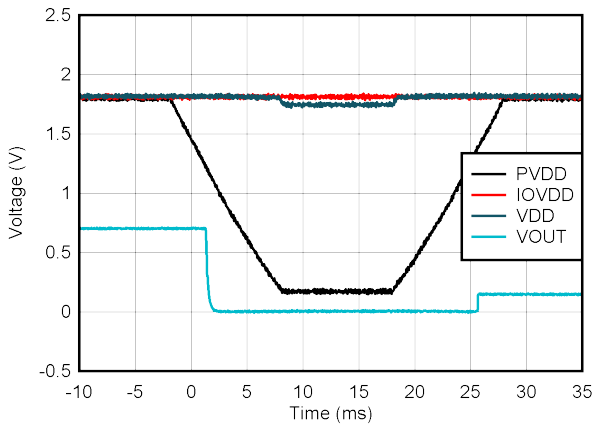


Figure 5-28. DAC Supply Power On, PVDD = 3.3V



1: 0.4V to 2V range, midcode
2: 0.2V to 1V range, midcode
3: 0.3V to 2.2V range, zero code

Figure 5-29. DAC PVDD Supply Collapse Response, RANGE = 1



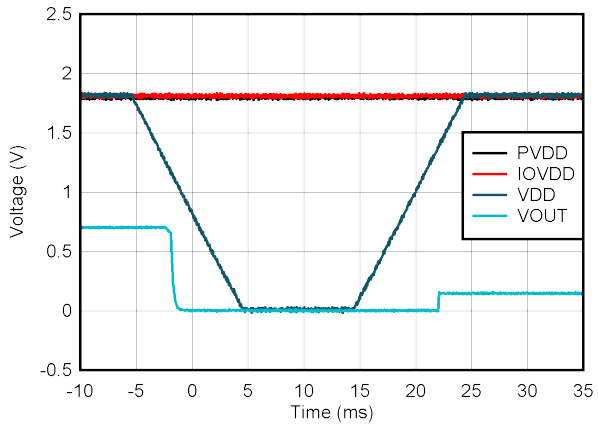
0.15V to 1.25V range, midcode

Figure 5-30. DAC PVDD Supply Collapse Response, RANGE = 0

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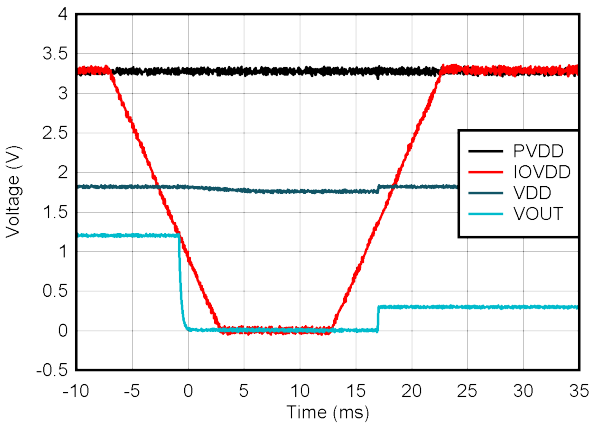
5.8 Typical Characteristics: VOUT DAC (continued)

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)



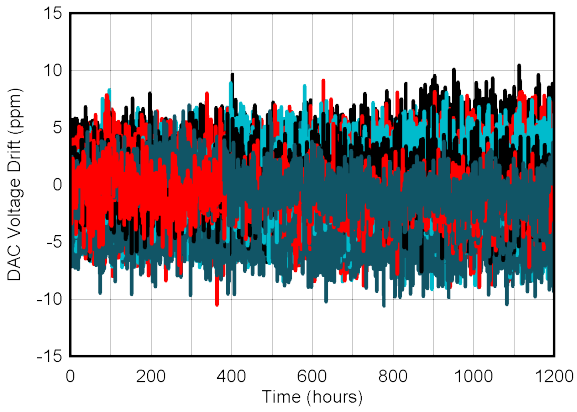
0.15V to 1.25V range, midcode

Figure 5-31. DAC VDD Supply Collapse Response, RANGE = 0



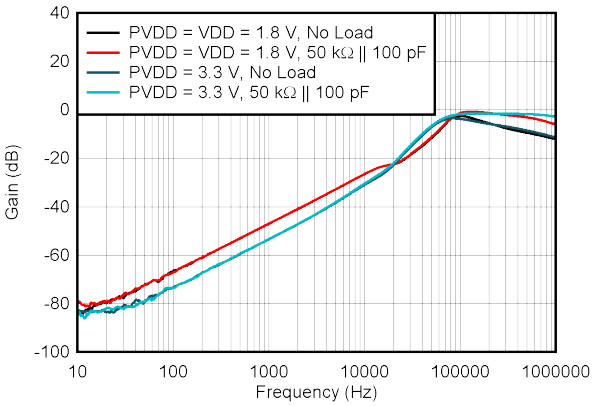
0.4V to 2V range, midcode

Figure 5-32. DAC IOVDD Supply Collapse Response, RANGE = 1



Ideal reference

Figure 5-33. DAC Output Voltage Long-Term Stability



Internal Reference

Figure 5-34. DAC AC PSRR vs Frequency

5.9 Typical Characteristics: ADC

at T_A = 25°C, PVDD = VDD = IOVDD = 1.8V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

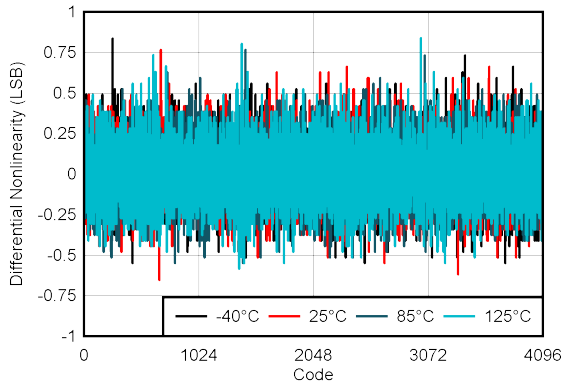


Figure 5-35. ADC DNL vs Digital Input Code

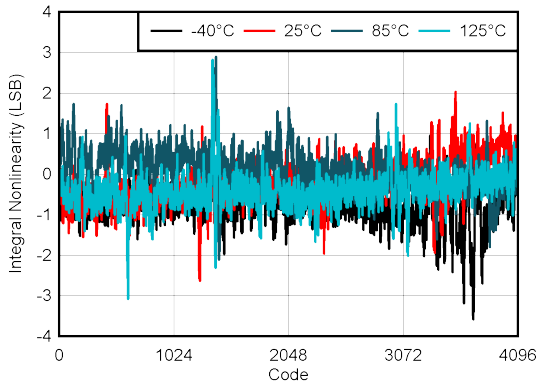


Figure 5-36. ADC INL vs Digital Input Code

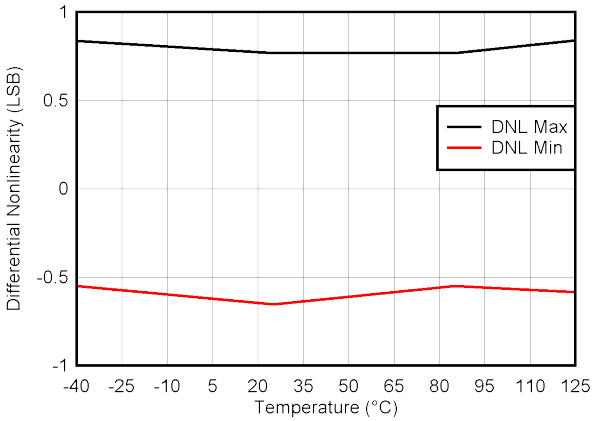


Figure 5-37. ADC DNL Range vs Temperature

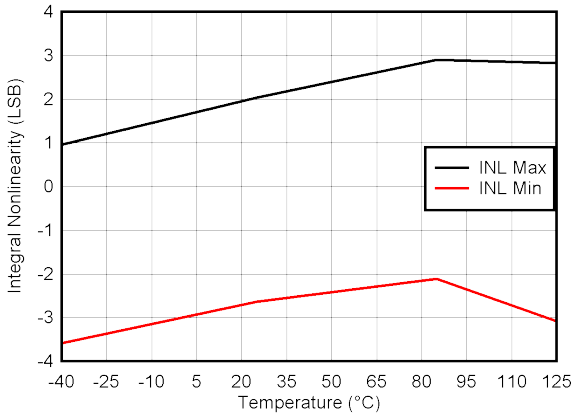


Figure 5-38. ADC INL Range vs Temperature

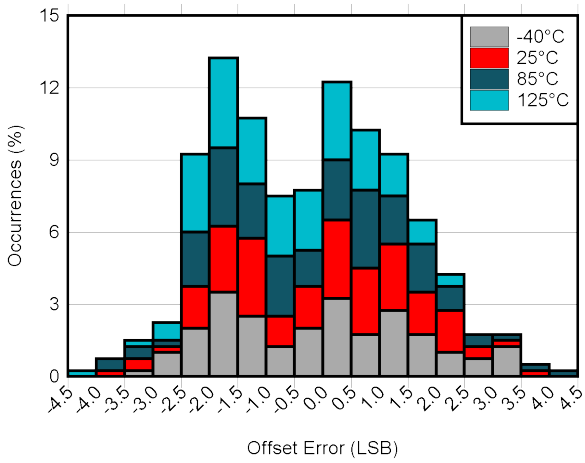


Figure 5-39. ADC Offset Error vs Temperature

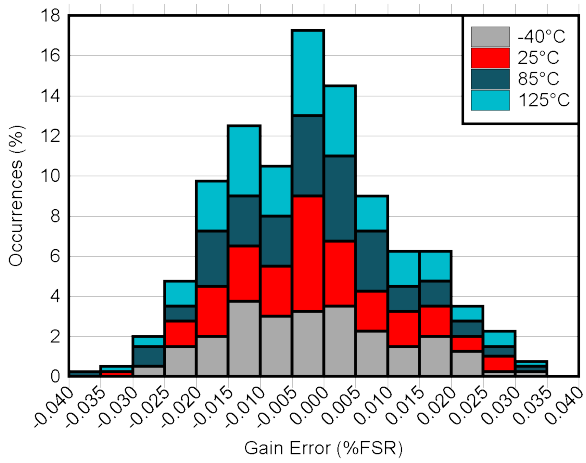
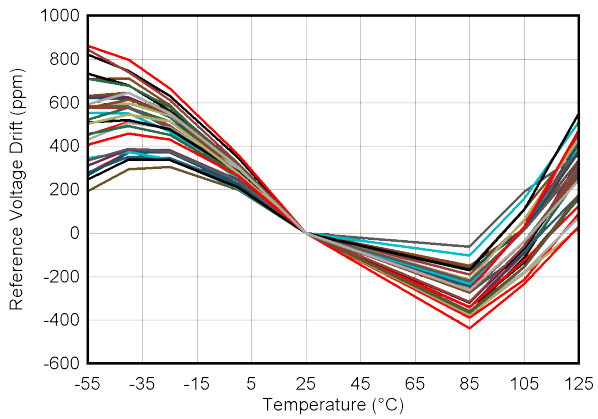


Figure 5-40. ADC Gain Error vs Temperature

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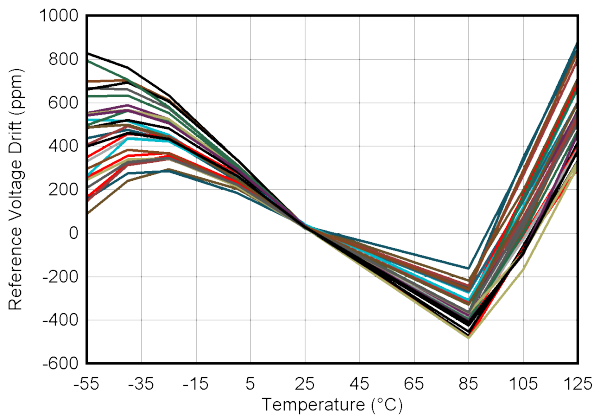
5.10 Typical Characteristics: Reference

at T_A = 25°C, PVDD = IOVDD = 3.3V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)



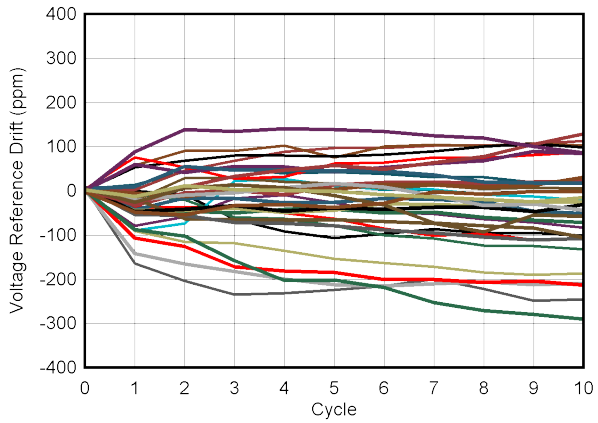
Pre-soldered

Figure 5-41. Reference Voltage Temperature Drift



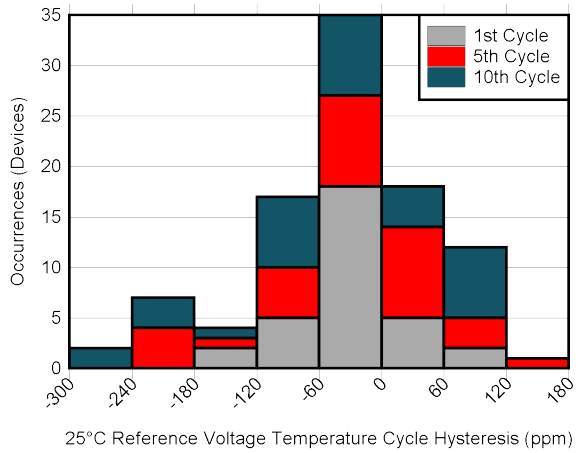
Post-soldered

Figure 5-42. Reference Voltage Temperature Drift



–40°C to +85°C cycles, 60 minutes per cycle

Figure 5-43. Multiple Temperature Cycle Hysteresis



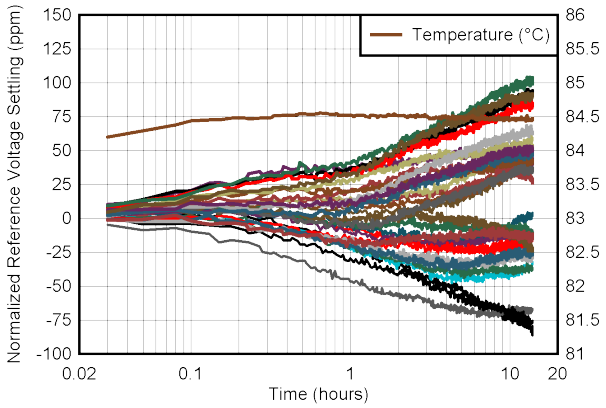
–40°C to +85°C cycles, 60 minutes per cycle

Figure 5-44. Multiple Temperature Cycle Hysteresis

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5.10 Typical Characteristics: Reference (continued)

at T_A = 25°C, PVDD = IOVDD = 3.3V, external or internal VREFIO = 1.25V, R_{LOAD} = 50kΩ to GND, C_{LOAD} = 100pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)



Two minutes after 25°C to 85°C temperature step

Figure 5-45. Ambient Temperature Change Settling

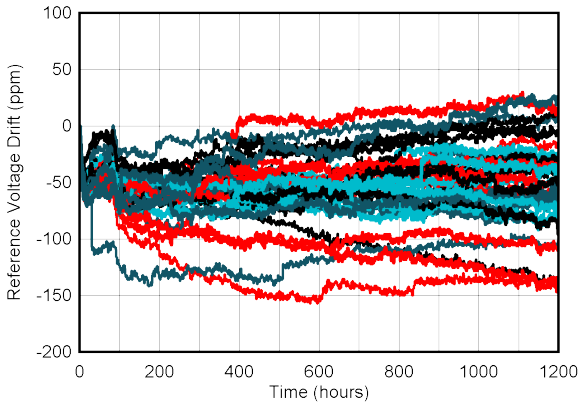


Figure 5-46. Reference Voltage Long-Term Stability

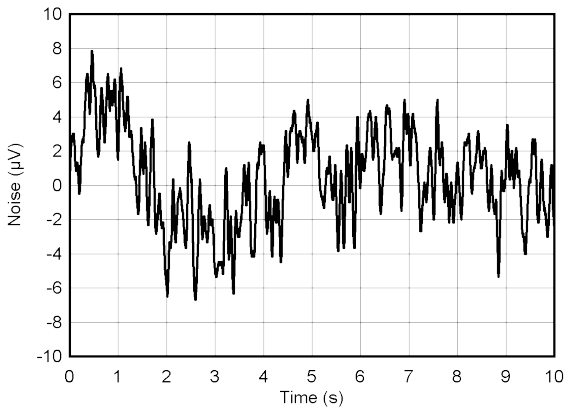


Figure 5-47. Reference Output Noise, 0.1Hz to 10Hz

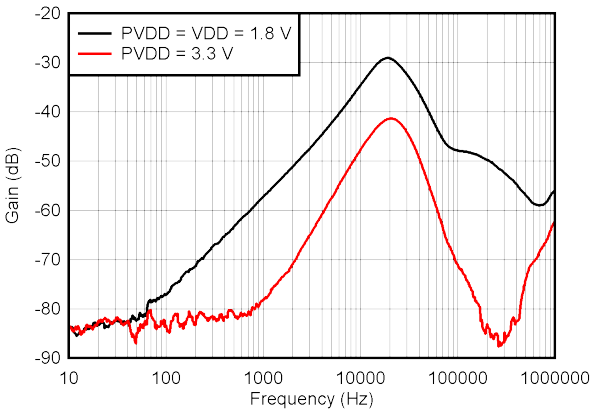


Figure 5-48. Reference AC PSRR vs Frequency

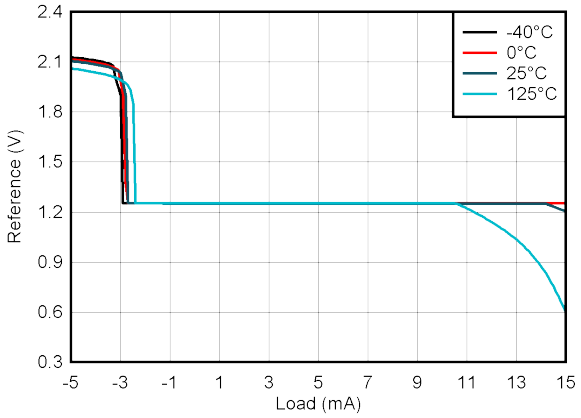


Figure 5-49. Reference Source and Sink Current Capability

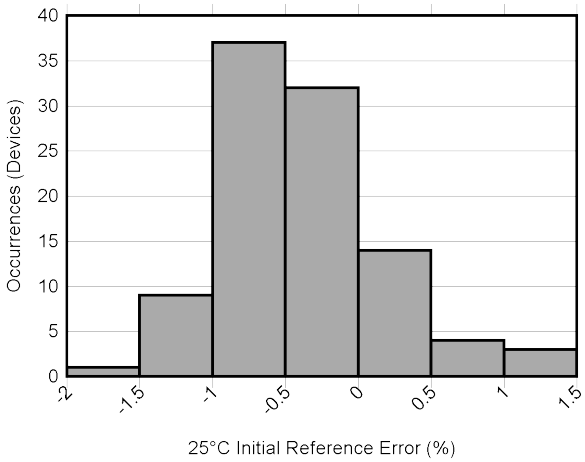
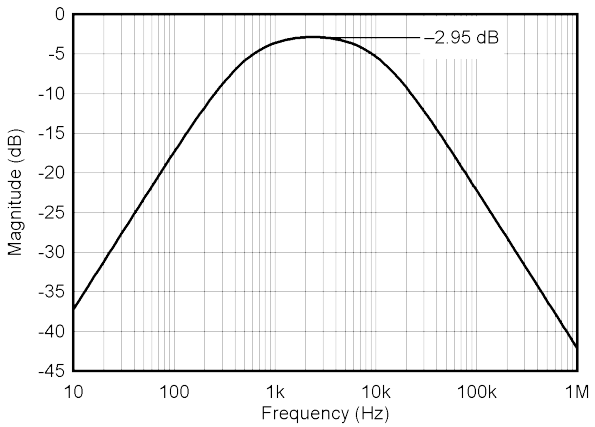


Figure 5-50. Initial Accuracy Distribution

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5.11 Typical Characteristics: HART Modem

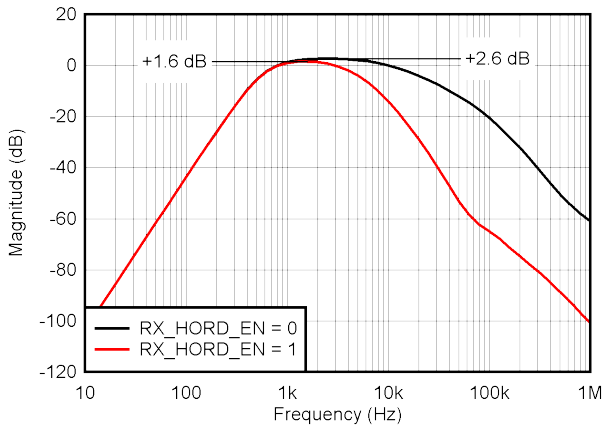
at T_A = 25°C, PVDD = IOVDD = 3.3 V, external or internal VREFIO = 1.25 V, R_{LOAD} = 50 kΩ to GND, C_{LOAD} = 100 pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)



2.2nF HART_RX Input Capacitor

680pF RX_INF Capacitor to Ground

Figure 5-51. HART Internal Mode First Stage Band-Pass Filter Response (From HART_RX Signal to RX_INF Pin)



2.2nF HART_RX Input Capacitor

680pF RX_INF Capacitor to Ground

Figure 5-52. HART Internal Mode Complete Band-Pass Filter Response (From HART_RX Signal to Internal Demodulator)

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5.12 Typical Characteristics: Power Supply

at T_A = 25°C, PVDD = IOVDD = 3.3 V, internal VREFIO, R_{LOAD} = 50 kΩ to GND, C_{LOAD} = 100 pF to GND, and digital inputs at IOVDD or GND (unless otherwise noted)

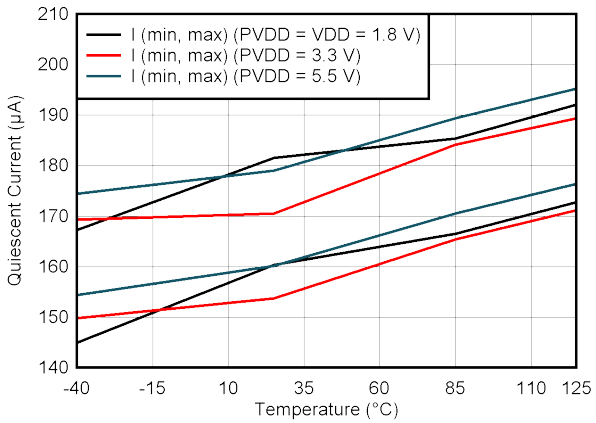


Figure 5-53. PVDD Supply Current vs Temperature

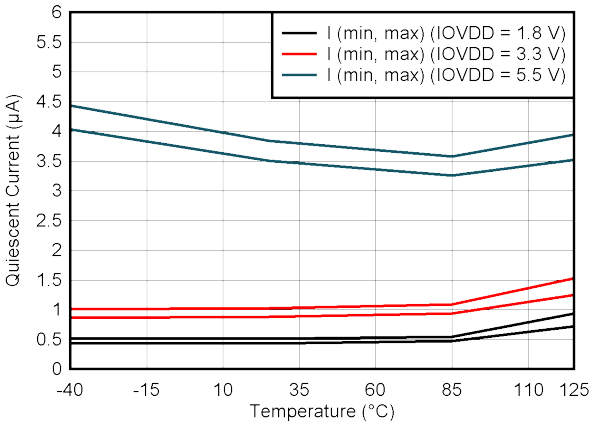


Figure 5-54. IOVDD Supply Current vs Temperature

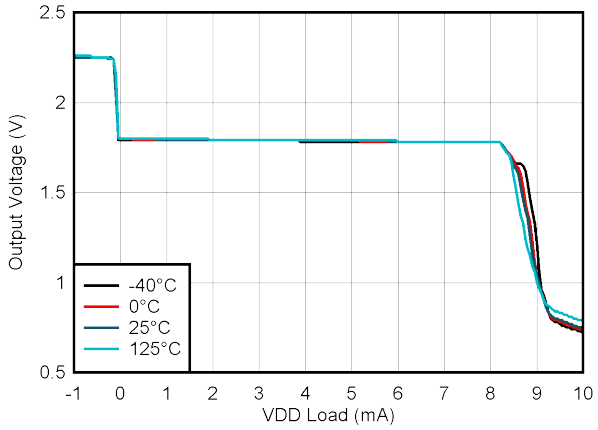


Figure 5-55. VDD Voltage vs Load Current

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6 Detailed Description

6.1 Overview

The AFEx81H1 feature a 16-bit (AFE881H1) or 14-bit (AFE781H1) string DAC with voltage output buffer. Both devices are capable of operating from supplies as low as 1.71 V at very low power, and are designed for 4mA to 20mA, loop-powered applications. The AFEx81H1 have two different DAC output voltage ranges depending on supply voltage, and two other ranges depending on configuration. The DAC has calibration registers for setting gain and offset values for adjusting the DAC outputs. The DAC also has different output slewing modes that allow for a programmable linear slew and a sinusoidal shaped output slew.

The AFEx81H1 also feature a 12-bit SAR ADC that can be multiplexed to measure different inputs, including external nodes and internal nodes for diagnostic measurements on the device. The ADC is capable of making direct-mode measurements with on-demand conversions or auto-mode measurements through continuous conversions using a channel sequencer with a multiplexer. The devices have optional alarm configurations with fault detection and alarm actions.

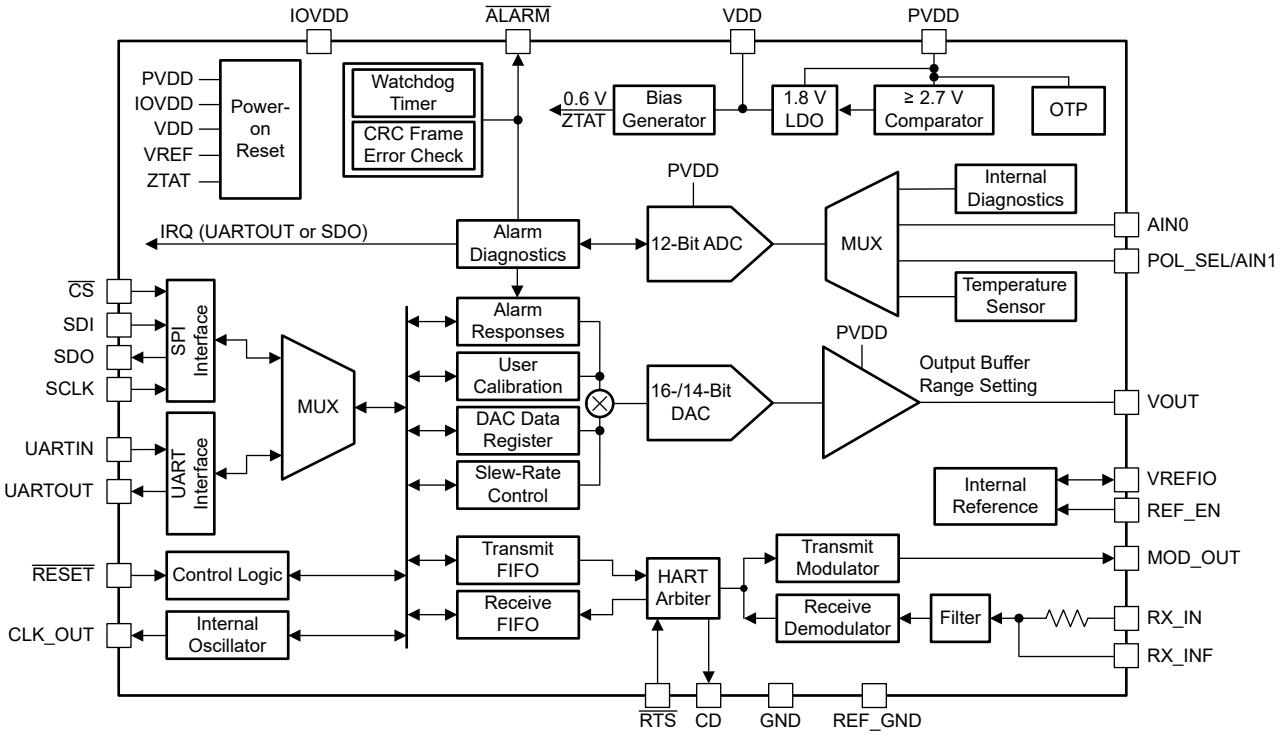
Device communication and programming are done through an SPI, SPI plus a UART interface, or through the UART break mode (UBM). With the SPI, a cyclic redundancy check (CRC) is implemented by default, which can be disabled. Additionally, communications can be monitored with a watchdog timer (WDT) that alerts the user if the device becomes unresponsive to periodic communication.

For the field transmitter, a HART interface is created through modulation and demodulation using the SPI or UART. The demodulation of the input signal is done using the combination of the external and internal band-pass filtering.

The AFEx81H1 feature a 1.25V, onboard precision voltage reference, and an integrated precision oscillator.

Throughout this datasheet, register and bit names are combined with a period to use the following format: <register_name>.<bit_name>. For example, the CLR bit in the DAC_CFG register is labeled DAC_CFG.CLR.

6.2 Functional Block Diagram



6.3 Feature Description

6.3.1 Digital-to-Analog Converter (DAC) Overview

The AFEx81H1 feature a 16-bit (AFE881H1) or 14-bit (AFE781H1) string DAC followed by an output voltage buffer. The DAC can be configured to support two low PVDD (0.15V to 1.25V and 0.2V to 1V), or high PVDD (0.3V to 2.5V and 0.4V to 2V) output ranges of operation depending on the PVDD supply voltage and the DAC_CFG.RANGE bit in the device configuration register. Using a voltage-to-current converter stage, these output voltages can be used to control a 4mA to 20mA loop. The narrow range corresponds to a 4mA to 20mA range. The full range allows for currents under and over the 4mA to 20mA range.

The devices continuously monitor the PVDD supply to provide proper operation based on the DAC range setting. Table 6-1 shows the valid supply ranges and corresponding VOUT DAC voltage ranges for the AFEx81H1.

Table 6-1. VOUT DAC Voltage Ranges

DAC CONFIGURATION	SUPPLY		DAC_CFG.RANGE	NAME	VOUT DAC VOLTAGE RANGE
	PVDD	VDD			
Invalid configuration	0V ≤ PVDD < 1.71V	0V ≤ VDD < 1.71V	NA	Alarm condition[1]	0.15V or 1.25V[2]
Low PVDD DAC range	1.71V ≤ PVDD ≤ 1.89V	1.71V ≤ VDD ≤ 1.89V	0	Full range	0.15V to 1.25V
			1	Narrow range	0.2V to 1V
Invalid configuration	1.89V < PVDD < 2.7V	VDD > 1.89V	NA	Alarm condition[1]	0.15V or 1.25V[2]
High PVDD DAC range	2.7V ≤ PVDD ≤ 5.5V	VDD is internally generated	0	Full range	0.3V to 2.5V
			1	Narrow range	0.4V to 2V
Invalid configuration	PVDD > 5.5V	VDD > 1.89V	NA	Alarm condition[1]	0.3V or 2.5V[2]

(1) See Table 6-7 for details.
(2) See Figure 6-12 for details.

If PVDD or VDD fall outside the specified threshold values associated with the supply configuration during operation, an alarm triggers and the DAC output sets according to the ALARM_ACT register settings.

6.3.1.1 DAC Resistor String

Figure 6-1 shows that the resistor string structure consists of a series of resistors, each of value R. The code loaded to the DAC determines the node on the string at which the voltage is tapped off to be fed into the output amplifier. The voltage is tapped off by closing one of the switches connecting the string to the amplifier. The resistor string architecture has inherent monotonicity, voltage output, and low glitch.

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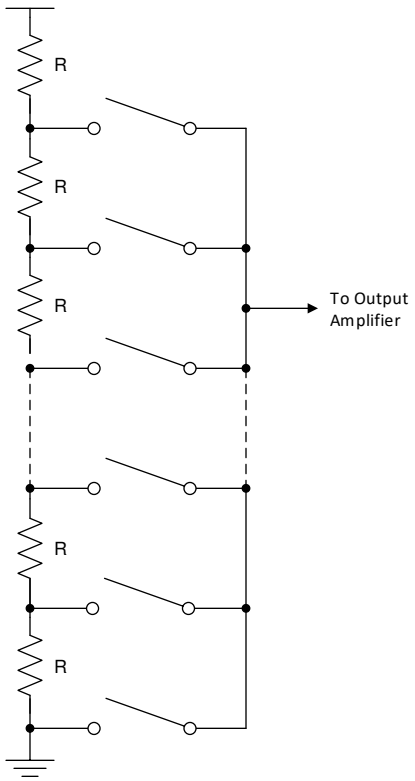


Figure 6-1. DAC Resistor String

6.3.1.2 DAC Buffer Amplifier

The VOUT output pin is driven by the DAC output buffer amplifier. The output amplifier default settings are designed to drive capacitive loads as high as 100pF without oscillation. The output buffer is able to source and sink 1mA. The device implements short-circuit protection for momentary output shorts to ground and VDD supply. The source and sink short-circuit current thresholds are set to 5mA.

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6.3.1.3 DAC Transfer Function

The following equation describes the DAC transfer function, which is the relationship between internal signal DAC_CODE and output voltage VOUT:

$$\text{VOUT} = \frac{\text{DAC_CODE}}{2^{\text{N}}} \times \text{FSR} + \text{V}_{\text{MIN}} \quad (1)$$

where

- DAC_CODE is an internal signal and the decimal equivalent of the gain and offset calibrated binary code loaded into the DAC_DATA register. DAC_CODE range = 0 to 2^N – 1.
- N = DAC_CODE resolution in bits (16 for the AFE881H1 and 14 for the AFE781H1).
- FSR = VOUT full-scale range for the selected output range in Table 6-2.
- V_{MIN} = the lowest voltage for the selected DAC output range.

Table 6-2. FSR and V_{MIN} for all VOUT Ranges

PVDD	DAC_CFG.RANGE	VOUT RANGE	FSR	V_{MIN}
1.8V	0	0.15V to 1.25V	1.1V	0.15V
1.8V	1	0.2V to 1.0V	0.8V	0.2V
≥ 2.7V	0	0.3V to 2.5V	2.2V	0.3V
≥ 2.7V	1	0.4V to 2.0V	1.6V	0.4V

The VOUT range for the DAC is determined by DAC_CFG.RANGE bit when not in the CLEAR state. In the CLEAR state, the range is determined by DAC_CFG.CLR_RANGE bit.

6.3.1.4 DAC Gain and Offset Calibration

The AFEx81H1 provide DAC gain and offset calibration capability to correct for end-point errors present in the system. Implement the gain and offset calibration using two registers, DAC_GAIN.GAIN and DAC_OFFSET.OFFSET. Update DAC_DATA register after gain or offset codes are changed for the new values to take effect. The DAC_GAIN can be programmed from 0.5 to 1.499985 using Equation 2.

$$\text{DAC_GAIN} = \frac{1}{2} + \frac{\text{GAIN}}{2^{\text{N}}} \quad (2)$$

where

- N = DAC_GAIN resolution in bits: 16 for the AFE881H1 and 14 for the AFE781H1.
- GAIN is the decimal value of the DAC_GAIN register setting.
- GAIN data are left justified; the last two LSBs in the DAC_GAIN register are ignored for the AFE781H1.

The example DAC_GAIN settings for the AFE881H1 are shown in Table 6-3.

Table 6-3. DAC_GAIN Setting vs GAIN Code

DAC_GAIN	GAIN (HEX)
0.5	0x0000
1.0	0x8000
1.499985	0xFFFF

The DAC_OFFSET is stored in the DAC_OFFSET register using 2's-complement encoding. The DAC_OFFSET value can be programmed from $–2^{(N–1)}$ to $2^{(N–1)} – 1$ using Equation 3.

$$\text{DAC_OFFSET} = -\text{OFFSET}_{\text{MSB}} \times 2^{(\text{N}-1)} + \sum_{\text{i}=0}^{(\text{N}-2)} \text{OFFSET}_{\text{i}} \times 2^{\text{i}} \quad (3)$$

where

- N = DAC_OFFSET resolution in bits: 16 for the AFE881H1 and 14 for the AFE781H1.

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- $OFFSET_{MSB}$ = MSB bit of the DAC_OFFSET register.
- $OFFSET_i$ = The rest of the bits of the DAC_OFFSET register.
- i = Position of the bit in the DAC_OFFSET register.
- OFFSET data are left justified; the last two LSBs in the DAC_OFFSET register are ignored for the device.

The most significant bit determines the sign of the number and is called the sign bit. The sign bit has the weight of $–2^{(N–1)}$ as shown in Equation 3.

The example DAC_OFFSET settings for the AFE881H1 are shown in Table 6-4.

Table 6-4. DAC_OFFSET Setting vs OFFSET Code

DAC_OFFSET	OFFSET (HEX)
32767	0x7FFF
1	0x0001
0	0x0000
–1	0xFFFF
–2	0xFFFE
–32768	0x8000

The following transfer function is applied to the DAC_DATA.DATA based on the DAC_GAIN and DAC_OFFSET values:

$$\mathrm{DAC_CODE} = (\mathrm{DATA} \times \mathrm{DAC_GAIN}) + \mathrm{DAC_OFFSET} \tag{4}$$

where

- DAC_CODE is the internal signal applied to the DAC.
- DATA is the decimal value of the DAC_DATA register.
- DAC_GAIN and DAC_OFFSET are the user calibration settings.
- DATA data are left justified; the last two LSBs in the DAC_DATA register are ignored for the AFE781H1.

Substituting DAC_GAIN and DAC_OFFSET in Equation 4 with Equation 2 and Equation 3 results in:

$$\mathrm{DAC_CODE} = \left(\mathrm{DATA} \times \left[\frac{1}{2} + \frac{\mathrm{GAIN}}{2^{\mathrm{N}}}\right]\right) - \mathrm{OFFSET_{MSB}} \times 2^{(\mathrm{N}-1)} + \sum_{\mathrm{i}=0}^{(\mathrm{N}-2)} \mathrm{OFFSET_i} \times 2^{\mathrm{i}} \tag{5}$$

The multiplier is implemented using truncation instead of rounding. This truncation can cause a difference of one LSB if rounding is expected. Figure 6-2 shows the DAC calibration path.

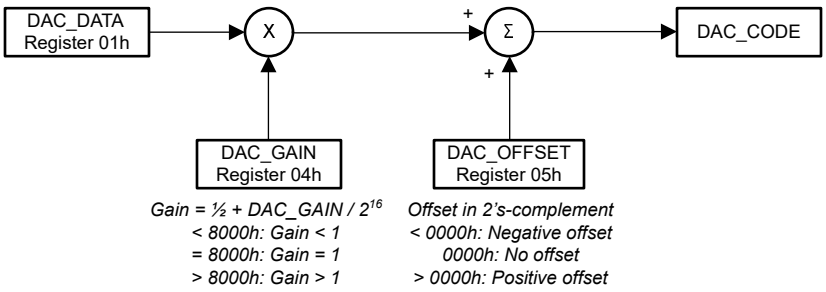


Figure 6-2. DAC Calibration Path

6.3.1.5 Programmable Slew Rate

The slew rate feature controls the rate at which the output voltage or current changes. This feature is disabled by default and is enabled by writing a logic 1 to the DAC_CFG.SR_EN bit. With the slew rate control feature disabled, the output changes smoothly at a rate limited by the output drive circuitry and the attached load.

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With this feature enabled, the output does not slew directly between the two values. Instead, the output steps digitally at a rate defined by DAC_CFG.SR_STEP[2:0] and DAC_CFG.SR_CLK[2:0]. SR_CLK defines the rate at which the digital slew updates. SR_STEP defines the amount by which the output value changes at each update. The register descriptions show different settings for SR_STEP and SR_CLK.

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The time required for the output to slew is expressed as Equation 6:

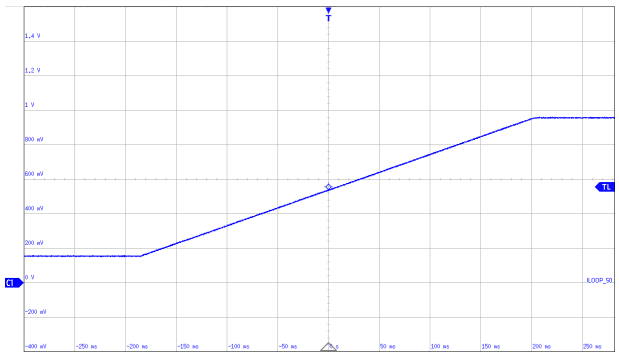
$$\text{Slew Time} = \frac{\text{Delta Code Change}}{\text{Slew Step} \times \text{Slew Clock Rate}} \quad (6)$$

where

- *Slew Time* is expressed in seconds
- *Slew Step* is controlled by DAC_CFG.SR_STEP
- *Slew Clock Rate* is controlled by DAC_CFG.SR_CLK

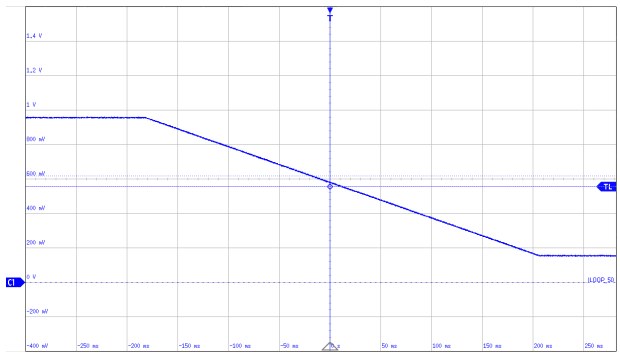
When the slew-rate control feature is enabled, the output changes at the programmed slew rate. This configuration results in a staircase formation at the output. If the clear code is asserted (see *DAC Register Structure and CLEAR State*), the output slews to the DAC_CLR_CODE value at the programmed slew rate. When new DAC data are written, the output starts slewing to the new value at the slew rate determined by the current DAC code and the new DAC data. The update clock frequency for any given value is the same for all output ranges. The step size, however, varies across output ranges for a given value of step size because the LSB size is different for each output range.

Two slew-rate control modes are available: linear (default) and sinusoidal. Figure 6-3 and Figure 6-4 show the typical rising and falling DAC output waveforms, respectively.



4mA (0x0BA3) to 24mA (0xF45D) measured on a 40Ω shunt

Figure 6-3. Linear Slew Rate: Rising

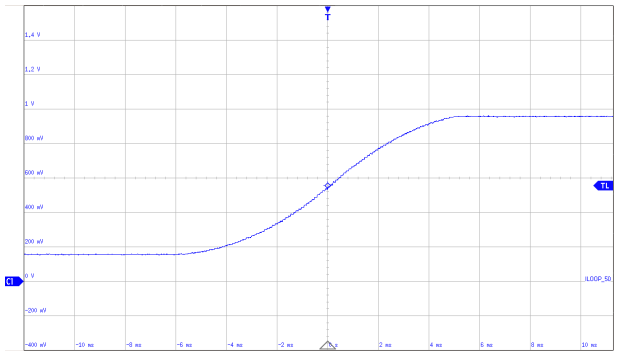


24mA (0xF45D) to 4mA (0x0BA3) measured on 40Ω shunt

Figure 6-4. Linear Slew Rate: Falling

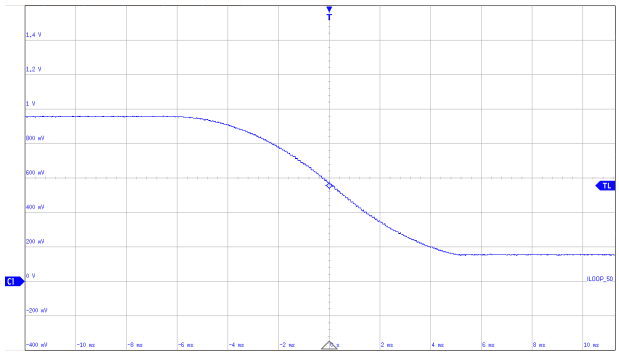
Sinusoidal mode enables fast DAC settling while improving analog rate of change characteristics. Sinusoidal mode is selected by the DAC_CFG.SR_MODE bit. Figure 6-5 and Figure 6-6 show the typical rising and falling DAC output waveforms with sinusoidal slew-rate control, respectively.

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4mA (0x0BA3) to 24mA (0xF45D) measured on a 40Ω shunt

Figure 6-5. Sinusoidal Slew Rate: Rising



24mA (0xF45D) to 4mA (0x0BA3) measured on a 40Ω shunt

Figure 6-6. Sinusoidal Slew Rate: Falling

If the slew-rate feature is disabled while the DAC is executing the slew-rate command, the slew-rate operation is aborted, and the DAC output goes to the target code.

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6.3.1.6 DAC Register Structure and CLEAR State

The AFE881H1 DAC has a 16-bit voltage output, and the AFE781H1 DAC has a 14-bit voltage output. Table 6-1 shows four possible VOUT DAC output ranges. With a voltage-to-current converter stage, the narrow range corresponds to a 4mA to 20mA range. The full range allows for undercurrents and overcurrents from 3mA to 25mA, and is controlled by DAC_CFG.RANGE.

The AFEx81H1 provide the option to quickly set the DAC output to the value set in the DAC_CLR_CODE register without writing to the DAC_DATA register, referred to as the CLEAR state. Setting the DAC to CLEAR state also sets the DAC output range according to DAC_CFG.CLR_RANGE. For register details, see Table 6-18.

Transitioning from the DAC_DATA to the DAC_CLR_CODE is synchronous to the clock. If slew mode is enabled, the output slews during the transition. Figure 6-7 shows the full AFEx81H1 DAC_DATA signal path. The devices synchronize the DAC_DATA code to the internal clock, causing up to 2.5 internal clock cycles of latency (2 µs) with respect to the rising edge of $\overline{CS}$ or the end of a UBM command. Update DAC_GAIN and DAC_OFFSET values when DAC_CFG.SR_EN = 0 to avoid an IRQ pulse generated by SR_BUSY.

Set the DAC to CLEAR state either by:

1. Setting DAC_CFG.CLR.
2. Configuring the DAC to transition to the CLEAR state in response to an alarm condition.
3. Using the SDI pin in UBM as the CLEAR state input pin.

Method 1 is a direct command to the AFEx81H1 to set the DAC to CLEAR state. Set the DAC_CFG.CLR bit to 1h to set the DAC to CLEAR state.

Method 2 is controlled by settings of ALARM_ACT register. For details of conditions and other masks required to use this method, see Table 6-29 and Section 6.3.3.2.

Method 3 supports setting the DAC to CLEAR state without writing to the AFEx81H1. This pin-based DAC CLEAR state function is available only in UBM on the SDI pin. For details of connection options based on communication modes and pins used in each mode, see Section 6.5.1. Set the appropriate pin high to drive the DAC to CLEAR state.

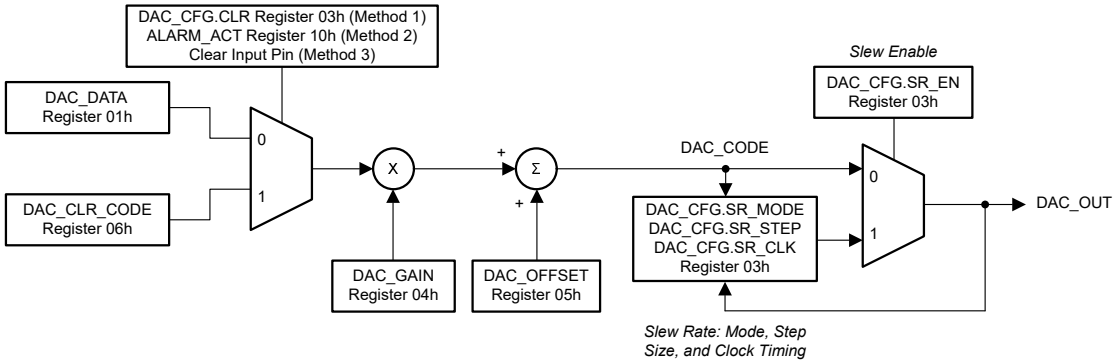


Figure 6-7. DAC Data Path

6.3.2 Analog-to-Digital Converter (ADC) Overview

The AFEx81H1 feature a monitoring system centered on a 12-bit successive approximation register (SAR) ADC and a highly flexible analog multiplexer. The monitoring system is capable of sensing up to two external inputs, as well as several internal device signals.

The ADC uses the VREFIO pin voltage as a reference. The ADC timing signals are derived from an on-chip oscillator. The conversion results are accessed through the device serial interface.

6.3.2.1 ADC Operation

The device ADC supports direct-mode and auto-mode conversions. Both conversion modes use a custom channel sequencer to determine which of the input channels are converted by the ADC. The sequence order is fixed. The user selects the start channel and stop channel of the conversion sequence. The conversion method and channel sequence are specified in the ADC Configuration registers. The default conversion method is auto-mode. Figure 6-8 shows the ADC conversion sequence.

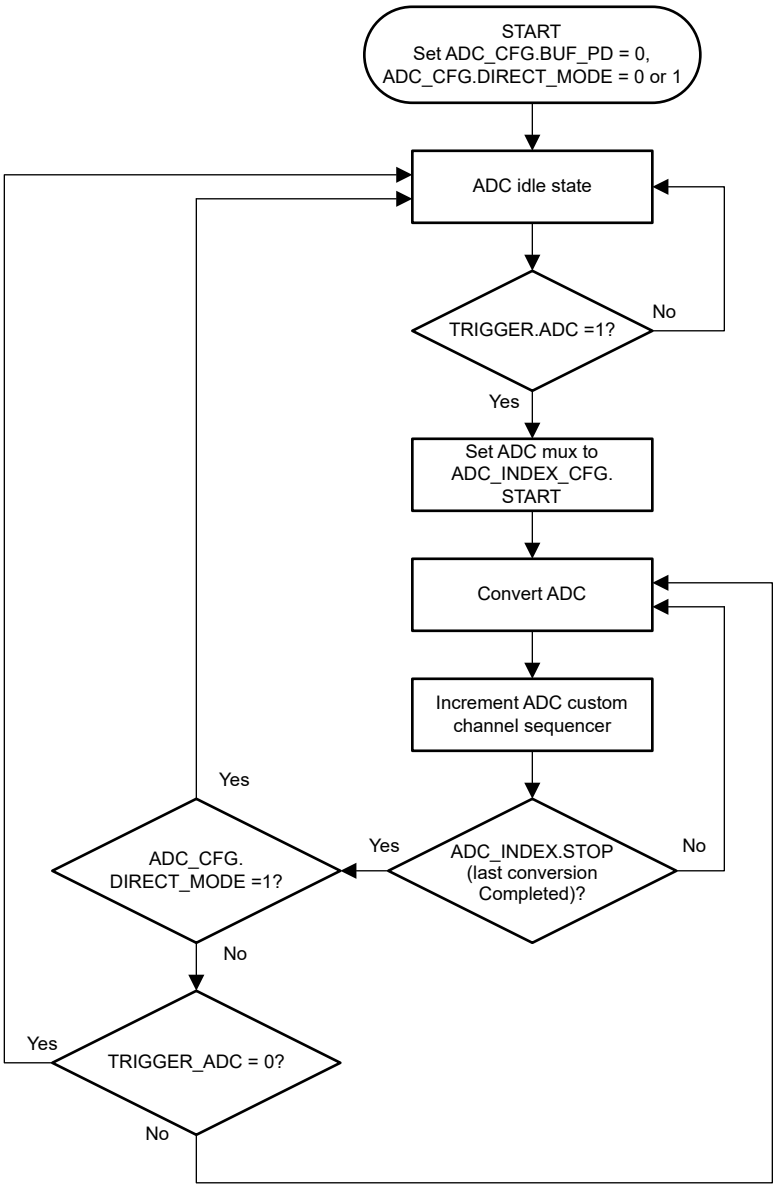


Figure 6-8. ADC Conversion Sequence

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To use the ADC, first enable the ADC buffer by setting ADC_CFG.BUF_PD = 0. Then wait at least 210 µs before setting the trigger using the TRIGGER.ADC bit. An internal delay is forced if the trigger signal is sent before the timer has expired. Make sure the ADC is not converting before setting the ADC_CFG.BUF_PD = 1. If ADC_CFG.BUF_PD is set to 1 while the ADC is still converting, the internal timer delays this command. When the timer expires, the enable signal for the ADC is cleared, and the current conversion finishes before powering down the ADC and the ADC Buffer.

A trigger signal must occur for the ADC to exit the idle state. The ADC trigger is generated through the TRIGGER.ADC bit. The ADC data registers have the latest available data. Accessing the data registers does not interfere with the conversion process, and thus provides continuous ADC operation.

In direct-mode conversion, the selected ADC input channels are converted on demand by issuing an ADC trigger signal. After the last enabled channel is converted, the ADC enters the idle state and waits for a new trigger. Read the results of the ADC conversion through the register map. Direct-mode conversion is typically used to gather the ADC data of any of the data channels. In direct-mode, use the ADC_BUSY bit to determine when a direct-mode conversion is complete and the ADC has returned to the idle state. Direct mode is set by writing ADC_CFG.DIRECT_MODE = 1.

In auto-mode conversion, the selected ADC input channels are converted continuously. The conversion cycle is initiated by issuing an ADC trigger. Upon completion of the first conversion sequence, another sequence is automatically started. Conversion of the selected channels occurs repeatedly until the auto-mode conversion is stopped by clearing the ADC trigger signal. Auto-mode conversion is not typically used to gather the ADC data. Instead, auto-mode conversions are used in combination with upper and lower ADC data thresholds to detect when the data has exceeded the programmable out-of-range alarm thresholds. Auto mode is set by writing ADC_CFG.DIRECT_MODE = 0.

Regardless of the selected conversion method, update the ADC configuration register only while the ADC is in the idle state. Do not change the ADC configuration bits while the ADC is converting channels. Before changing configuration bits, disable the ADC and verify that GEN_STATUS.ADC_BUSY = 0.

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6.3.2.2 ADC Custom Channel Sequencer

The device uses a custom channel sequencer to control the multiplexer of the ADC. The ADC sequencer allows the user to specify which channels are converted. The sequencer consists of 16 indexed slots with programmable start and stop index fields to configure the start and stop conversion points.

In direct-mode conversion, the ADC converts from the start index to the stop index once and then stops. In auto-mode conversion, the ADC converts from the start to stop index repeatedly until the ADC is stopped. Figure 6-9 shows the indexed custom channel sequence slots available in the device.

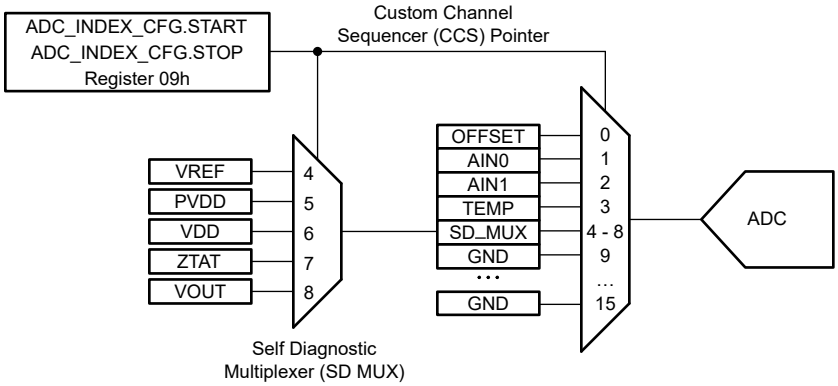


Figure 6-9. ADC MUX Control

Table 6-5 lists the ADC input channel assignments for the sequencer.

Table 6-5. Indexed Custom Channel Sequence

CCS POINTER	CHANNEL	CONV_RATE	RANGE
0	OFFSET	2560Hz	VREF
1	AIN0	Programmable	Programmable
2	AIN1	Programmable	Programmable
3	TEMP	2560Hz	VREF
4	SD0 (VREF)	2560Hz	VREF
5	SD1 (PVDD)	2560Hz	VREF
6	SD2 (VDD)	2560Hz	VREF
7	SD3 (ZTAT)	2560Hz	VREF
8	SD4 (VOUT)	2560Hz	VREF when PVDD = 1.8V 2 × VREF when PVDD ≥ 2.7V
9-15	GND	2560Hz	VREF

Use the ADC_INDEX_CFG register to select the channels. The order of the channels is fixed and shown in Table 6-5. Then, use ADC_INDEX_CFG.START and ADC_INDEX_CFG.STOP to select the range of indices to convert. If these two values are the same, then the ADC only converts a single channel. If the START and STOP values are different, then the ADC cycles through the corresponding indices. By default, all channels are configured to be converted; START = 0 and STOP = 8. If the AIN1 channel is not configured as an ADC input, then the result for this channel is 0x000. The minimum time for a conversion is still allotted to AIN1 if the channel is within the START and STOP range. If START is configured to be greater than STOP, then the device interprets the conversion sequence as if START = STOP.

In direct mode, each selected channel in the ADC_INDEX_CFG register is converted once per TRIGGER.ADC command. In auto mode, each channel selected in the ADC_INDEX_CFG register is converted once; after the last channel, the loop is repeated as long as the ADC is enabled. In auto mode, writing to TRIGGER.ADC = 1 starts the conversions. Writing TRIGGER.ADC = 0 disables the ADC after the current channel being converted

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finishes. In direct mode, writing TRIGGER.ADC = 1 starts the sequence. When the sequence ends, then TRIGGER.ADC is self-cleared.

A minimum of 20 clock cycles is required to perform one conversion. The ADC clock is derived from the internal oscillator and divided by 16, which gives an ADC clock frequency of 1.2288MHz / 16 = 76.8kHz, for a clock period = 13.02 µs.

Each of the internal nodes has a fixed conversion rate. Pins AIN0 and AIN1 have programmable conversion rates (see also the ADC_CFG register). Pins AIN0 and AIN1 also have a configurable range. If PVDD ≥ 2.7V, then the input range can be either 0 V to 1.25V or 0 V to 2.5V, depending on the ADC_CFG.AIN_RANGE bit. If PVDD = 1.8V, then only the 0 V to 1.25V range is allowed. In this case, the ADC_CFG.AIN_RANGE bit is prevented from being set.

If any ADC configuration bits are changed, the following sequence is recommended:

1. Disable the ADC
2. Wait for ADC_BUSY to go low
3. Change the configuration
4. Restart the conversions

ADC_BUSY can be monitored in the GEN_STATUS register.

If the ADC is configured for direct mode (ADC_CFG.DIRECT_MODE = 1), then after setting the desired channels to convert, write a 1 to TRIGGER.ADC. This bit is self-cleared when the sequence is finished converting. This command converts all the selected channels once. To initiate another conversion of the channels, send another TRIGGER.ADC command.

6.3.2.3 ADC Synchronization

The trigger signal must be generated for the ADC to exit the idle state and start conversions. The ADC trigger is generated through the TRIGGER.ADC bit. The ADC data registers have the latest available data. Accessing the data registers does not interfere with the conversion process, and thus provides continuous ADC operation.

In direct-mode, use the GEN_STATUS.ADC_BUSY bit to determine when a direct-mode conversion is complete, and the ADC has returned to the idle state. Similarly, monitor the TRIGGER.ADC bit to see if the ADC has returned to the idle state.

6.3.2.4 ADC Offset Calibration

Channel 0 of the CCS pointer is named OFFSET. The OFFSET channel is used to calibrate and improve the ADC offset performance. Convert the OFFSET channel, and use the result as a calibration for the ADC offset in subsequent measurements.

This ADC channel samples VREF / 2 and compares this result against 7FFh as a measure of the ADC offset. The data rate for the ADC measuring this channel is 2560Hz. The ADC conversion for the OFFSET channel is subtracted from 7FFh and the resulting value is stored in ADC_OFFSET (28h). The offset can be positive or negative; therefore, the value is stored in 2's complement notation.

With the subtraction from 7FFh, ADC_OFFSET is the negative of the offset. This value is subtracted from conversions of the ADC by default. For direct measurements of the ADC, set ADC_BYP.OFST_BYP_EN to 1 to enable the offset bypass; see Section 6.3.2.8.

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6.3.2.5 External Monitoring Inputs

The AFEx81H1 have two analog inputs for external voltage sensing. Channels 1 and 2 for the CCS pointer are for external monitoring inputs that can be measured by pins AIN0 and AIN1, respectively. The input range for the analog inputs is configurable to either 0 V to 1.25 V or 0 V to 2.5 V. The analog inputs conversion values are stored in straight binary format in the ADC registers. The ADC resolution can be computed by Equation 7:

$$1\ LSB = \frac{V_{RANGE}}{2^{12}} \tag{7}$$

where

- V_{RANGE} = 2.5 V for the 0-V to 2.5-V input range or 1.25 V for the 0-V to 1.25-V input range.

Figure 6-10 and Table 6-6 detail the transfer characteristics.

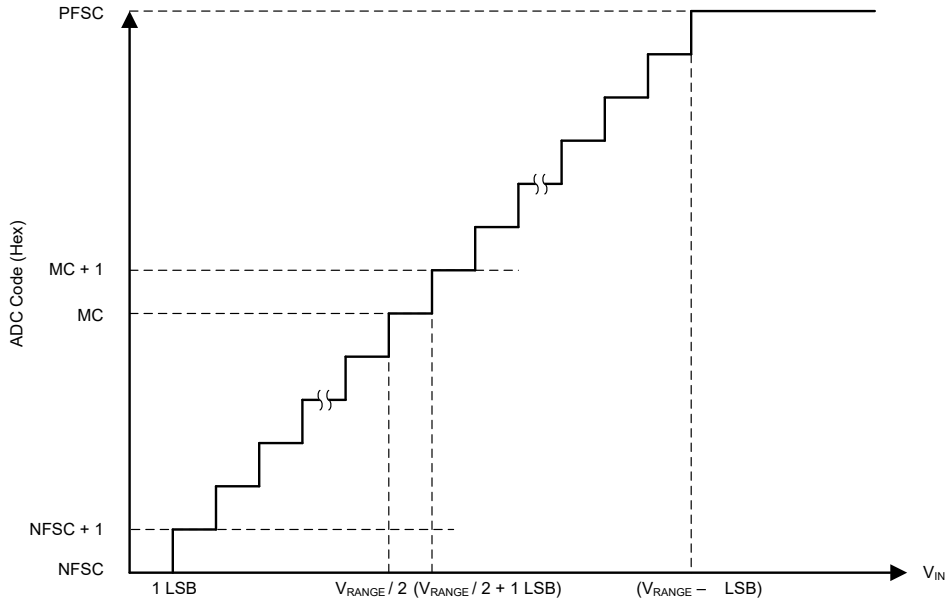


Figure 6-10. ADC Transfer Characteristics

Table 6-6. Transfer Characteristics

INPUT VOLTAGE	CODE	DESCRIPTION	IDEAL OUTPUT CODE
≤1LSB	NFSC	Negative full-scale code	000
1LSB to 2LSB	NFSC + 1	Negative full-scale code plus 1	001
(V_{RANGE} / 2) to (V_{RANGE} / 2) + 1LSB	MC	Midcode	800
(V_{RANGE} / 2) + 1LSB to (V_{RANGE} / 2) + 2 LSB	MC + 1	Midcode plus 1	801
≥ V_{RANGE} – 1LSB	PFSC	Positive full-scale code	FFF

For these external monitoring inputs, the ADC is configurable for both data rate and voltage range. The data rate is set to either 640 Hz, 1280 Hz, 2560 Hz, or 3840 Hz with the ADC_CFG.CONV_RATE bits. The range of the ADC measurement is set with the ADC_CFG.AIN_RANGE bit. The ADC range is 2 × VREF when the bit = 0; the ADC range is VREF when the bit = 1. ADC_CFG.AIN_RANGE only controls the range if PVDD > 2.7 V. When PVDD = 1.8 V, the range is VREF regardless of the setting.

When the ADC conversion is completed for AIN0 and AIN1, the resulting ADC data are stored in the ADC_AIN0.DATA and ADC_AIN1.DATA bits at 24h and 25h of the register map.

If the external monitoring inputs are not used, connect the AIN0 and AIN1 pins to GND through a 1kΩ resistor.

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6.3.2.6 Temperature Sensor

Channel 3 of the CCS is used to measure the die temperature of the device. The ADC measures an internal temperature sensor that measures a voltage complementary to the absolute temperature (CTAT). This CTAT voltage has a negative temperature coefficient. The ADC converts this voltage at a data rate of 2560Hz. When the ADC conversion is completed, the data are found in the ADC_TEMP.DATA bits (address 26h).

The relationship between the ambient temperature and the ADC code is shown in Equation 8:

$$\text{ADC Code} = 2681 - 11 \times T_A(°C) \quad (8)$$

6.3.2.7 Self-Diagnostic Multiplexer

In addition to the ADC offset, the two external monitoring inputs, and the temperature sensor, the ADC of the AFEx81H1 has five other internal inputs to monitor the reference voltage, the power supplies, a static voltage, and the DAC output. These five voltages measurements are part of the self-diagnostic multiplexer (SD0 to SD4) measurements of the ADC, and are reported in the ADC_SD_MUX register at 27h; see also Section 6.6.

Channel 4 (SD0) measures the reference voltage of the device. The ADC measures the reference voltage through a resistor divider (divide by two). Be aware that all ADC measurements are a function of the reference; using SD0 to measure the reference is not revealing as a diagnostic measurement. The data rate for this conversion is 2560Hz and the range of the ADC is set to VREF.

Channel 5 (SD1) measures the PVDD power supply of the device. The ADC measures the PVDD voltage through a resistor divider (divide by six). The data rate for this conversion is 2560Hz and the range of the ADC is set to VREF.

Channel 6 (SD2) measures the VDD power supply of the device. When channel 6 is selected, the ADC measures the VDD voltage through a resistor divider (divide by 2). The data rate for this conversion is 2560Hz and the range of the ADC is set to VREF.

Channel 7 (SD3) is a ZTAT (zero temperature coefficient) voltage. This internal voltage is nominally 0.6V with a low temperature drift and does not depend on the reference voltage. An ADC measurement of ZTAT voltage can be useful to determine the state of the reference voltage. The data rate for this conversion is 2560Hz and the range of the ADC is set to VREF.

Channel 8 (SD4) measures the VOUT of the DAC. The ADC measures the VOUT voltage through a resistor divider (divide by two). The data rate for this conversion is 2560Hz.

The input range for the DAC voltage monitoring input is scaled from either 0V to 2.5V or 0V to 1.25V, depending on PVDD voltage. As soon as the PVDD voltage exceeds 2.7V, the input range for the DAC voltage monitoring automatically switches to the 0V to 2.5V range. The DAC voltage conversion values are stored in straight-binary format in the ADC registers. The ADC resolution for these channels is computed by Equation 7.

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6.3.2.8 ADC Bypass

To test the offset, modify the ADC data path by programming the bypass data register, ADC_BYP.DATA (2Eh). This read/write register is used in two different ways.

First, by setting the ADC_BYP.OFST_BYP_EN to 1, this bypass data register is used as a substitute for the ADC_OFFSET. However, if the ADC_BYP.DATA data must be stored in the ADC_OFFSET register, use the second method.

Second, the ADC_BYP.DATA is used to set a known value into the ADC readback register of the channel being converted. Write the desired data into ADC_BYP.DATA, set the ADC_BYP.DATA_BYP_EN bit, and convert the selected channel. When ADC_BYP.DATA_BYP_EN bit is set to 1, the ADC conversion is bypassed, and the value of ADC_BYP.DATA is written into the selected ADC channel readback register. This setting is used to test the alarm settings of the ADC.

When the ADC bypass is unused, set the ADC_BYP.DATA to 000h.

Figure 6-11 shows the ADC bypass data flow.

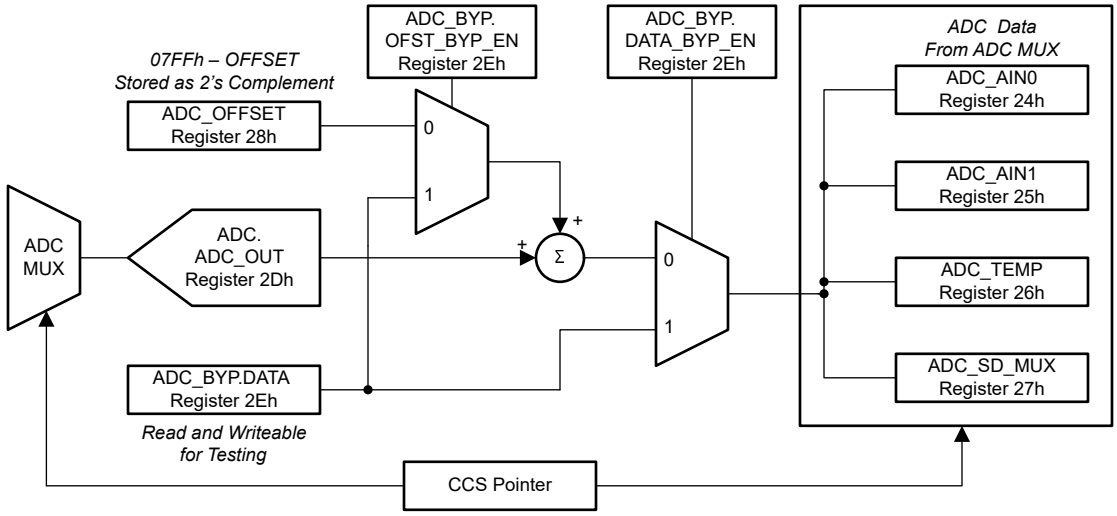


Figure 6-11. ADC Bypass Data Flow

6.3.3 Programmable Out-of-Range Alarms

The AFEx81H1 are capable of continuously analyzing the supplies, external ADC inputs, DAC output voltage, reference, internal temperature, and other internal signals for normal operation.

Normal operation for the conversion results is established through the lower- and upper-threshold registers. When any of the monitored inputs are out of the specified range, the corresponding alarm bit in the alarm status registers is set.

The alarm bits in the alarm status registers are latched. The alarm bits are referred to as being latched because the alarm bits remain set until read by software. This design does not miss out-of-limit events because the software is polling the device periodically. All bits are cleared when reading the alarm status registers, and all bits are reasserted if the out-of limit condition still exists on the next monitoring cycle. When the alarm event is cleared, the DAC is reloaded with the contents of the DAC active registers, which allows the DAC outputs to return to the previous operating point without any additional commands.

All alarms can be used to generate a hardware interrupt signal on the $\overline{\text{ALARM}}$ pin; see also Section 6.3.3.1. In addition, Section 6.3.3.2 describes how the alarm action is individually configured for each alarm.

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6.3.3.1 Alarm-Based Interrupts

One or more of the available alarms can be set to activate the $\overline{\text{ALARM}}$ pin. Connect the $\overline{\text{ALARM}}$ pin as an optional hardware interrupt to the host. The host can query the alarm status registers to determine the alarm source upon assertion of the interrupt. Any alarm event activates the pin, as long as the alarm is not masked in the ALARM_STATUS_MASK register. When an alarm event is masked, the occurrence of the event sets the corresponding status bit in the alarm status registers, but does not activate the $\overline{\text{ALARM}}$ pin.

Note

The $\overline{\text{ALARM}}$ pin output depends on ALARM_STATUS and ALARM_STATUS_MASK register settings, independent of ALARM_ACT register settings.

6.3.3.2 Alarm Action Configuration Register

The AFEx81H1 provides an alarm action configuration register: ALARM_ACT. Writing to this register selects the device action that automatically occurs for a specific alarm condition. The ALARM_ACT register determines how the main DAC responds to an alarm event from either an ADC conversion on the self-diagnostics channels (AIN0, AIN1, and TEMP), or from a CRC, WDT, VREF, TEMP_HI, or TEMP_LO fault. Only these faults cause a response by the DAC. Any other alarm status events trigger the $\overline{\text{ALARM}}$ pin. There are four options for alarm action. In case different settings are selected for different alarm conditions, the following low-to-high priority is considered when taking action:

- 0. → No action
- 1. → DAC CLEAR state
- 2. → VOUT alarm voltage
- 3. → VOUT Hi-Z

If option 1 is selected when the alarm event occurs, then the DAC is forced to the clear code and clear range. This operation is done by controlling the input code to the DAC and the range of the DAC.

If option 2 is selected when the alarm event occurs, then VOUT is forced to the alarm voltage. The alarm voltage is controlled by either pin or register bit. If SPECIAL_CFG.AIN1_ENB = 0, then the AIN1 pin controls alarm polarity. Also, register bit SPECIAL_CFG.ALMV_POL can be used. If either of these signals = 1, then the alarm voltage is high; otherwise, the alarm voltage is low. The SPECIAL_CFG register is only reset with POR, so the user setting remains intact through hardware or software resets.

If option 3 is selected when the alarm event occurs, then the VOUT buffer is put into Hi-Z. If multiple events occur, then the highest setting takes precedence. Option 3 has the highest priority.

To disable action response to an alarm, set the corresponding bits in ALARM_ACT to 0h. Alarm action response is cleared either when the triggered condition bit resets (behavior depends on whether the fault bit in ALARM_STATUS is sticky or not), or by changing the action configuration to 0h.

Note

An alarm action, as configured, executes when an alarm occurs depending on ALARM_STATUS and ALARM_ACT registers. Action response is independent of ALARM_STATUS_MASK settings.

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6.3.3.3 Alarm Voltage Generator

Figure 6-12 shows that the alarm voltage is generated independently from the DAC output voltage. The alarm polarity control logic selects the output level of the alarm voltage generator. The alarm action control logic selects between the DAC output and alarm voltage generator output voltages. The alarm action control logic also controls the output buffer Hi-Z switch.

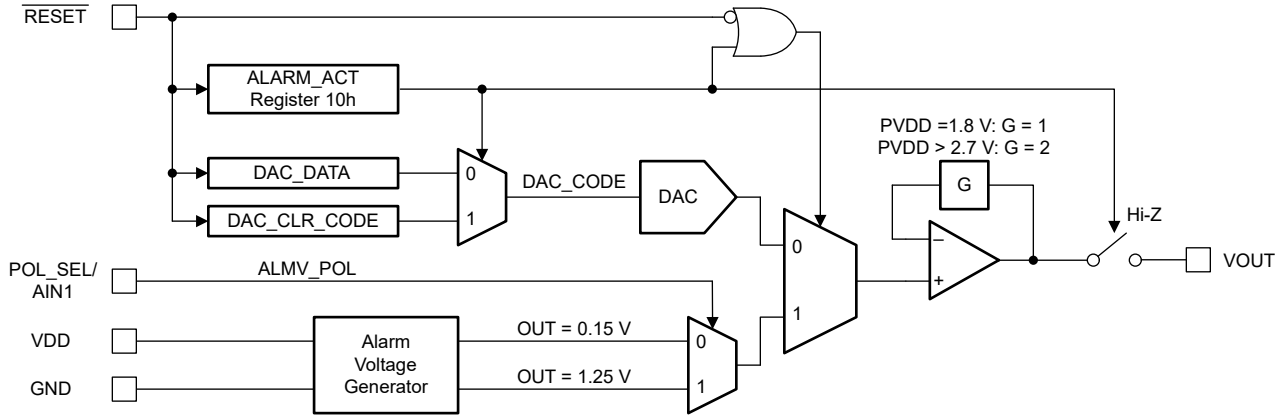


Figure 6-12. Alarm Voltage Generator Architecture

During normal operation, the expected VOUT voltage depends on the DAC_CODE. The ADC thresholds for the SD4 (VOUT) diagnostic channel are set around the programmed DAC_CODE. During the alarm condition, if the alarm action changes the VOUT voltage to the alarm voltage, or switches the VOUT buffer into Hi-Z mode, the VOUT voltage no longer depends on the DAC_CODE. In this case, the SD4 (VOUT) diagnostic channel also reports the alarm. To clear this alarm, as long as all other alarm conditions are cleared, set the alarm action to either no action or to the DAC clear code. Applying either alarm action sets the VOUT voltage within the expected ADC thresholds and clears the alarm after the next ADC measurement of the SD4 (VOUT) channel.

Give special consideration to the alarm logic during the transient events. When the new DAC_CODE goes beyond the SD4 (VOUT) alarm thresholds with the ADC monitoring the SD4 (VOUT) input in auto mode, the ADC conversion can occur while VOUT settles to a new value. This conversion can trigger a false alarm. There are two ways to prevent this false alarm:

1. Use direct mode and allow VOUT to settle before triggering the next ADC conversion.
2. Set ADC_CFG.FLT_CNT > 0. With this configuration, a single error in SD4 or any other measurement does not cause an alarm condition to be asserted.

6.3.3.4 Temperature Sensor Alarm Function

The AFEx81H1 continuously monitor the internal die temperature. In addition to the ADC measurement, the temperature sensor triggers a comparator to show a thermal warning and a thermal error. A thermal warning alarm is set when the temperature exceeds 85°C. Additionally, a thermal error alarm is set when the die temperature exceeds 130°C.

The thermal warning and thermal error alarms can be configured to set the $\overline{\text{ALARM}}$ pin and are indicated in the ALARM_STATUS register. These alarms can be masked with the ALARM_MASK register and also be configured to control the DAC output with the ALARM_ACT register.

6.3.3.5 Internal Reference Alarm Function

The devices provide out-of-range detection for the reference voltage. When the reference voltage exceeds ±5% of the nominal value, the reference alarm flag (VREF_FLT bit) is set. Make sure that a reference alarm condition has not been issued by the device before powering up the DAC output.

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6.3.3.6 ADC Alarm Function

The AFEx81H1 provide independent out-of-range detection for each of the ADC inputs. Figure 6-13 shows the out-of-range detection block. When the measurement is out of range, the corresponding alarm bit is set to flag the out-of-range condition.

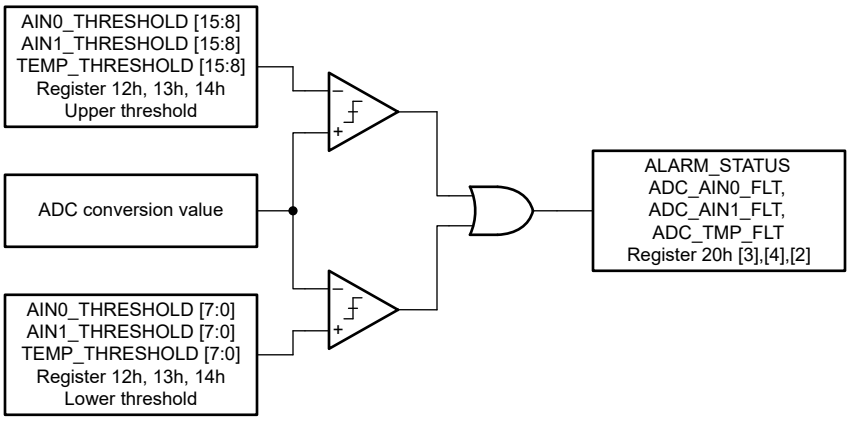


Figure 6-13. ADC Out-of-Range Alarm

An alarm event is only registered when the monitored signal is out of range for *N* number of consecutive conversions, where *N* is configured in the ADC_CFG.FLT_CNT false alarm register settings. If the monitored signal returns to the normal range before *N* consecutive conversions, an alarm event is not issued.

If an ADC input signal is out of range and the alarm is enabled, then the corresponding alarm bit is set to 1. However, the alarm condition is cleared only when the conversion result returns to a value less than the high-limit register setting and greater than the low-limit register setting by the number of codes specified by the hysteresis setting (see Figure 6-14). The hysteresis is a programmable value between 0LSB to 127LSB in the ADC_CFG.HYST register.

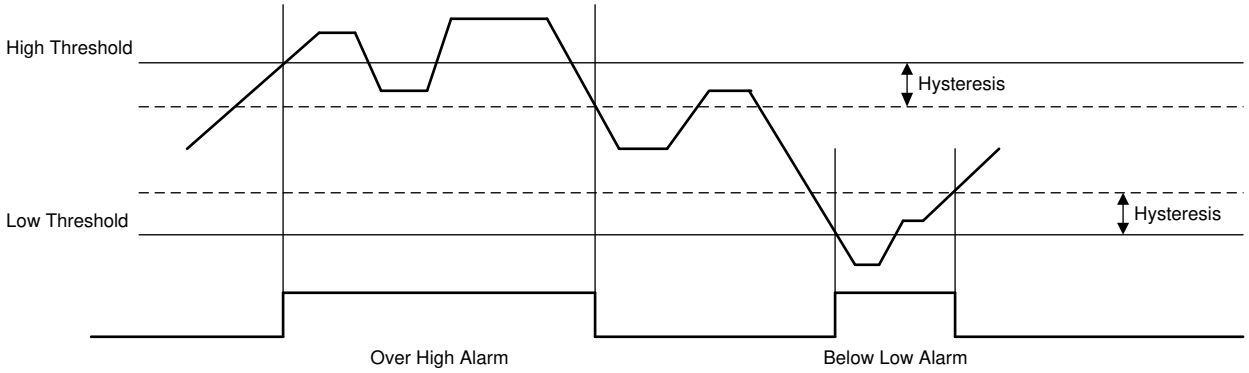


Figure 6-14. ADC Alarm Hysteresis

6.3.3.7 Fault Detection

There are two fields within the ADC_CFG register: FLT_CNT and HYST. These fields are applied to the assertion and deassertion of alarm conditions for all the ADC channels.

ADC_CFG.FLT_CNT determines the maximum number of accepted consecutive failures before an alarm condition is reported. For example, if ADC_CFG.FLT_CNT is set for two counts, then three consecutive conversions must be outside of the thresholds to trigger an alarm. Each failure counts towards the FLT_CNT limit even if the failures alternate between high threshold and low threshold.

ADC_CFG.HYST sets the hysteresis used by the alarm-detection circuit. After an alarm is triggered, the hysteresis is applied before the alarm condition is released. In the case of the high threshold, the hysteresis is subtracted from the threshold value. In the case of the low threshold limit, the hysteresis is added to the threshold value.

Channels AIN0, AIN1, and TEMP have high and low thresholds associated with them. If a conversion value falls outside of these limits (that is, if TEMP < low threshold or TEMP > high threshold), an alarm condition for that channel is set. The alarms are disabled by setting 0x000 for the low threshold and 0xFFF for the high threshold, respectively. These alarms are disabled by default. Because the configuration fields for the thresholds are only eight bits wide, the four LSBs are hardcoded for each threshold. The high thresholds four LSBs are hardcoded to 0xF, and the low thresholds four LSBs are hardcoded to 0x0.

All the self diagnostic (SD) channels have fixed thresholds, except SD4, which measures the VOUT of the main DAC. The threshold for SD4 tracks the VOUT with respect to the DAC code. Table 6-7 shows the calculations used to determine the high and low ADC thresholds for each SD channel. The limits in the two right-most columns are determined by the threshold columns to the left and given some margin. The four LSBs are assigned as described previously.

Table 6-7. Self Diagnostic (SD) Alarm ADC Thresholds

SD	ADC INPUT	ACCEPTED LOW VALUE	ACCEPTED HIGH VALUE	LOW THRESHOLD	HIGH THRESHOLD	ADC LOW (HEX)	ADC HIGH (HEX)
SD0	VREF/2	VREF/2 – 9% – 25mV	VREF/2 + 9% + 25mV	0.54375V	0.70625V	0x6D0	0x92F
SD1	PVDD/6	1.65/6 – 25mV	6/6 + 25mV	0.25V	1.025V	0x310	0xD3F
SD2	VDD/2	1.6/2 – 25mV	2/2 + 25mV	0.775V	1.025V	0x9C0	0xD3F
SD3	0.6V	0.6V – 9% – 25mV	0.6V + 9% + 25mV	0.521V	0.679V	0x690	0x8CF
SD4	VOUT/2	VOUT/2 – 6mV	VOUT/2 + 6mV	VOUT – 12mV	VOUT + 12mV	Expected – 0x040	Expected + 0x040

The alarm threshold for the SD4 input depends on the expected ADC measurement based on the DAC code. The threshold is different for each DAC range and is adjusted accordingly. Equation 9 shows the expected ADC code for RANGE = 0, and Equation 10 shows the expected ADC code for RANGE = 1.

$$\text{ADC Expected Code: RANGE } 0 = \frac{(\text{DAC_CODE}[\text{MSB}:\text{MSB} - 11] \times 113 \div 128) + 492}{2} \tag{9}$$

$$\text{ADC Expected Code: RANGE } 1 = \frac{(\text{DAC_CODE}[\text{MSB}:\text{MSB} - 11] \times 82 \div 128) + 655}{2} \tag{10}$$

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6.3.4 IRQ

The devices include an interrupt request (IRQ) to communicate the occurrence of a variety of events to the host controller. The IRQ block initiates interrupts that are reported internally in a status register, externally on the IRQ pin if the function is enabled, or on the $\overline{\text{ALARM}}$ pin if the condition is from the ALARM_STATUS register. Figure 6-15 shows the IRQ block diagram.

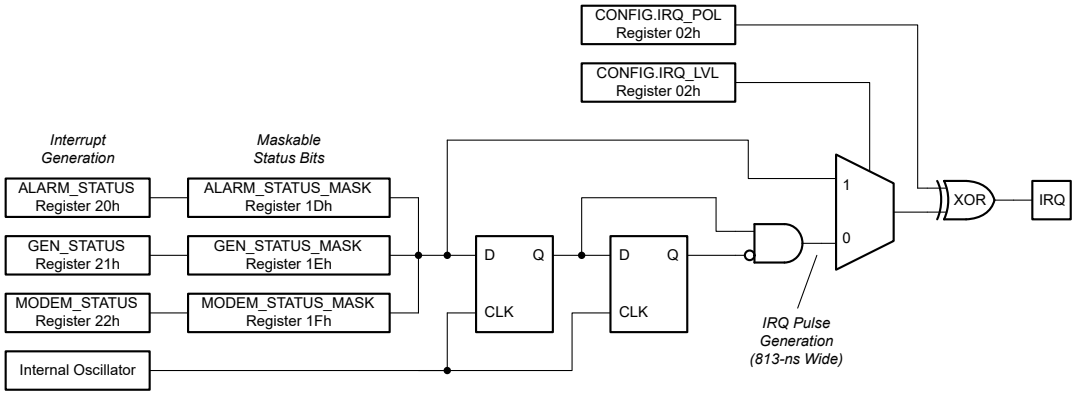


Figure 6-15. IRQ Block Diagram

There are three registers that can generate interrupts: GEN_STATUS, MODEM_STATUS, and ALARM_STATUS. Each of these registers has a corresponding STATUS_MASK register. The mask register controls which of the events trigger an interrupt. Writing a 1 in the mask register masks, or disables, the event from triggering an interrupt. Writing a 0 in the mask register allows the event to trigger an IRQ. All bits are masked by default. Some status bits are sticky. Reading the corresponding register clears a sticky bit, unless the condition still exists.

The IRQ is configured through CONFIG.IRQ_LVL to be edge- or level-sensitive. Set this bit to logic 1 to enable level-sensitive functionality (default). In edge-sensitive mode, the IRQ signal is a synchronous pulse, one internal clock period wide (813ns). In level-sensitive mode, the IRQ is set and remains set as long as the condition exists. After the IRQ condition is removed, the condition is cleared by reading the corresponding status register. Trying to clear the bit while the condition still exists does not allow the bit to be cleared if the bit is sticky.

CONFIG.IRQ_POL determines the active level of the IRQ. A logic 1 configures IRQ to be active high.

When using edge-sensitive IRQ signals, there is a clock cycle delay for synchronization and edge detection. With a 307.2kHz clock, this delay is up to 3.26µs. For level-sensitive mode, the delay is approximately 10ns to 20ns.

Most status bits have two versions within the design. The first version is an edge event that is created when the status is asserted. This signal is used to generate edge-sensitive IRQs. This edge detection prevents multiple status events from blocking one another. The second version is the sticky version of the status bit. This signal is set upon assertion of the status bit and cleared when the corresponding status register is read, as long as the status condition does not still persist. Signals GEN_IRQ, MODEM_IRQ, and ALARM_IRQ are driven by the logical OR of the of the status bits within the corresponding register.

If a status bit is unmasked and the sticky version of that bit has been asserted, and the IRQ is level-sensitive, then an interrupt is triggered as soon as the bit is unmasked. If the IRQ is edge-sensitive then a status event must occur after the bit has been unmasked to assert an interrupt.

FIFO flags are not sticky; therefore, an IRQ can be triggered, but the status flag can be deasserted by the time the status information is transmitted at the output. For example, If FIFO_U2H_LEVEL_FLAG is unmasked and the FIFO_U2H level drops below the set threshold, the IRQ triggers. If the device is configured to output UBM IRQ messages and a HART data byte is received on UARTIN after the IRQ, but before the UBM captures the IRQ status, then the IRQ status and data information reads back all zeros. If UBM IRQ mode is used, wait until the IRQ message is fully transmitted on UARTOUT before putting data on UARTIN.

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6.3.5 HART Interface

On the AFEx81H1, a HART frequency-shift keyed (FSK) signal can be modulated onto the MOD_OUT pin. Figure 6-16 illustrates the output current versus time operation for a typical HART interface.

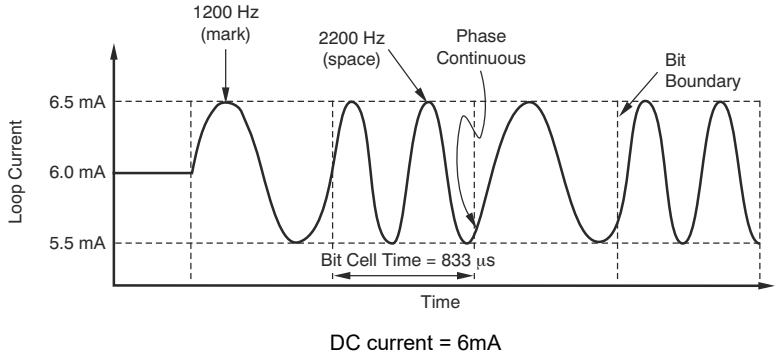


Figure 6-16. Output Current vs Time

To enable the HART interface, set the HART_EN bit in the MODEM_CFG register. An external capacitor, placed in series between the RX_IN pin and HART FSK source, is required to ac-couple the HART FSK signal to the RX_IN pin. The recommended capacitance for this external capacitor is 2.2nF.

If additional filtering is required, the AFEx81H1 also support an external band-pass filter. For this configuration, use the RX_INF pin instead of RX_IN pin.

6.3.5.1 FIFO Buffers

First-in, first-out (FIFO) buffers are used to transmit and receive HART data using both the SPI and UART. Both the transmit FIFO (FIFO_U2H) and receive FIFO (FIFO_H2U) buffers are 32 rows and 9-bits wide. The 9-bit width allows the storage of the parity bit with the data byte. Bit[8] is the parity bit as received by either the UART or HART demodulator, depending on the direction of the data flow. The device does not calculate the parity bit in this case, and transmits the data with the wrong parity bit if the wrong parity bit was received. Bits[7:0] are the data.

The AFEx81H1 HART implementation is shown in Figure 6-17.

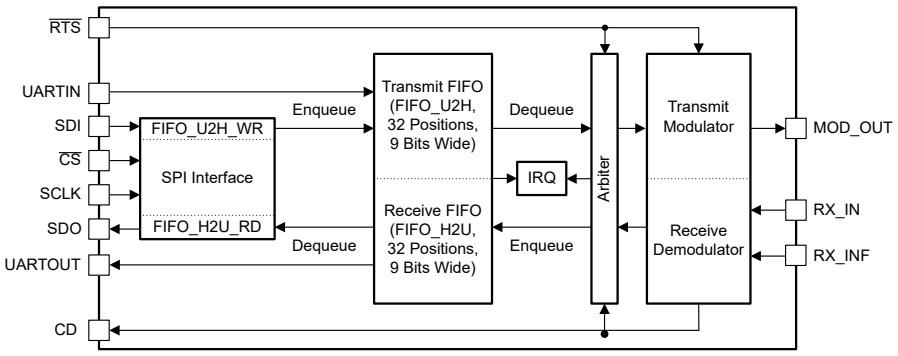


Figure 6-17. HART Architecture

HART data bytes are enqueued into a transmit FIFO_U2H buffer using the SPI or UART. The input data bits are translated into the *mark* (1200Hz) and *space* (2200Hz) FSK analog signals (see Figure 6-16) used in HART communication by the internal HART transmit modulator. The receive demodulator enqueues HART data into the receive FIFO_H2U buffer. An arbiter is implemented with signals to CD and from the $\overline{\text{RTS}}$ pins to manage the HART physical connections on MOD_OUT, and either the RX_IN or RX_INF pin. To enable efficient and

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error-free communication, the arbiter in conjunction with the two FIFO buffers can be used to produce an IRQ for the system controller.

An incorrect stop bit in the HART receive character causes a HART frame error. The device reports the frame error in the status register and discards the character. When the character is discarded, the HART data are not enqueued into FIFO_H2U. If the frame error check is not masked, an IRQ event is also triggered.

Similarly, an incorrect stop bit in the UARTIN character causes a UART frame error. The device reports the frame error in the status register and discards the character. When the character is discarded, the UART data are not enqueued into FIFO_U2H. If the frame error check is not masked, an IRQ event is also triggered.

6.3.5.1.1 FIFO Buffer Access

In SPI only mode, both FIFO buffers are accessed using register addresses. HART bus communication activity is reported to the host controller through the IRQ pin and MODEM_STATUS register. See Section 6.3.5.8 for recommended IRQ based communication techniques when using the AFEx81H1 to convert between the SPI and HART.

Write to the FIFO_U2H_WR register to enqueue the HART transmit data into FIFO_U2H. Calculate the correct parity bit and include the parity bit with the data. Do not attempt to read data from the FIFO_U2H because a read request from the FIFO_U2H_WR register is not supported. The read from the FIFO_U2H_WR register returns the data from the dequeue pointer location of FIFO_U2H, but does not dequeue the data.

Read the FIFO_H2U_RD register to dequeue the HART receive data from FIFO_H2U. If CRC is enabled and a CRC error occurs during a read request, no data are dequeued from the FIFO_H2U buffer, and the data in the readback frame are invalid. A write to the FIFO_H2U_RD register is ignored.

When communicating with the HART modem through the UART interface in SPI plus UART mode, any character received on the UARTIN pin is directly enqueued into FIFO_U2H. The character is then automatically dequeued from FIFO_U2H and transmitted on the MOD_OUT pin when the clear-to-send (CTS) response is asserted. Similarly, any character received on the RX_IN or RX_INF pin is directly enqueued into FIFO_H2U. The character is then automatically dequeued from FIFO_H2U and transmitted on UARTOUT as a normal UART character.

The FIFO buffers are accessed directly by the UART; therefore, do not use the FIFO_U2H_WR and FIFO_H2U_RD registers with the SPI. As a result of using FIFO_U2H in the data path, there is a latency from the UARTIN pin to the MOD_OUT pin; see also Section 6.3.5.6. Similarly, as a result of using FIFO_H2U, there is a latency from the RX_IN or RX_INF pin to the UARTOUT pin; see also Section 6.3.5.7.

HART bus communication activity is interfaced to the host controller through the CD and $\overline{\text{RTS}}$ pins. If the CD and $\overline{\text{RTS}}$ pins are not used, poll the MODEM_STATUS register regularly to monitor the status of the modem.

In UBM mode, any character received on the UARTIN pin that is not a part of a break command is directly enqueued into FIFO_U2H. The character is then automatically dequeued from FIFO_U2H and transmitted on the MOD_OUT pin when the CTS response is asserted. Although the UBM packets can access all registers, do not use the break command to write the HART transmit data into FIFO_U2H_WR register. Use the standard 8O1 UART character format to enqueue data into the FIFO_U2H buffer, and thus to the HART modulator.

Similarly, do not use the break command to read the HART receive data from the FIFO_H2U_RD register. HART receive data are automatically dequeued from FIFO_H2U and transmitted on UARTOUT as normal UART characters in UBM mode.

6.3.5.1.2 FIFO Buffer Flags

Status bits exist for both transmit and receive FIFO buffers in the MODEM_STATUS, FIFO_STATUS and FIFO_H2U_RD registers. These include full, empty, and level flags. Buffer level flags are used to trigger IRQs for HART communication; see also Section 6.3.5.8. The status fields in the FIFO_H2U_RD register represent the state of FIFO_H2U before the read is performed and the data byte is dequeued. This implementation means that if the EMPTY_ FLAG is set, the data byte received in that frame is invalid. Similarly, the LEVEL field represents the 4MSBs for the FIFO_H2U level before dequeuing. The LSB is not reported, and there are only five internal

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bits to represent 32 levels; therefore, the LEVEL = 0 is reported when the actual level is 0, 1, or 32. Use FULL_FLAG and EMPTY_FLAG when LEVEL = 0 to differentiate between these three cases.

The FIFO_H2U and FIFO_U2H buffers have 32 levels; however, the level setting for generating IRQ events only uses four bits. For the receive FIFO_H2U buffer, the LSB in the FIFO level threshold comparison is always 1 (FIFO_CFG.H2U_LEVEL_SET[3:0], 1). This configuration is designed to alert the user when FIFO_H2U is getting nearly full so as to enable a timely data dequeue, and prevent the loss of incoming HART data due to FIFO overload. For this reason, the FIFO_H2U_LEVEL_FLAG is also a greater-than (>) comparison to the FIFO_CFG.H2U_LEVEL_SET. For example, if FIFO_CFG.H2U_LEVEL_SET = 4'b1000, then when the level of the FIFO_H2U > 5'b10001, the FIFO_H2U_LEVEL_FLAG is set. Setting FIFO_CFG.H2U_LEVEL_SET = 4'b1111 (default) effectively disables this flag. Use FIFO_H2U_FULL_ FLAG to detect the FIFO_H2U full event. When the FIFO_H2U is full, the new incoming data are blocked from enqueuing into the FIFO and ignored to preserve the existing data.

Similarly, for the transmit FIFO_U2H buffer, the LSB in the FIFO level threshold comparison is always 0 (FIFO_CFG.U2H_LEVEL_SET[3:0], 0). This configuration is designed to alert the user when FIFO_U2H is getting nearly empty so as to enable a timely data enqueue, and prevent FIFO_U2H from becoming empty prematurely and causing a gap error on the HART bus. For this reason, the FIFO_U2H_LEVEL_FLAG is also a less-than (<) comparison with the FIFO_CFG.U2H_LEVEL_SET. For example, if FIFO_CFG.U2H_LEVEL_SET = 4'b1000, then when the level of the FIFO_U2H < 5'b10000, the FIFO_U2H_LEVEL_FLAG is set. Setting FIFO_CFG.U2H_LEVEL_SET = 4'b0000 (default) effectively disables this flag. Use FIFO_U2H_EMPTY_ FLAG to detect the FIFO_U2H empty event.

To avoid buffer overflow, monitor the level of FIFO_U2H by watching for a buffer-full or buffer-threshold event. If the FIFO_U2H_LEVEL_FLAG bit in the MODEM_STATUS_MASK register is set to 0, the IRQ pin toggles when the threshold is exceeded. Similarly, an alarm can be triggered based on the FIFO_U2H_FULL_FLAG bit in the MODEM_STATUS register. When the FIFO_U2H is full the new incoming data are blocked from enqueuing into the FIFO and ignored to preserve the existing data.

6.3.5.2 HART Modulator

The HART modulator implements a look-up table (LUT) containing 128, 8-bit, signed values that represent a single-phase, continuous sinusoidal cycle. A counter is implemented that incrementally loads the table values to a DAC at a clock frequency determined by the binary value of the input data. The DAC clock frequency is determined by the logical value of the data bit being transmitted. A logic 1 transmits at the internal clock frequency of 32 (default) steps times 1200Hz. A logic 0 transmits at the internal clock frequency of 32 (default) steps times 2200Hz. All frequencies are derived from 1.2288MHz. This process creates the *mark* and *space* analog output signals used to represent HART data. The default mode uses 32 sinusoidal codes per period from the LUT for power savings. To generate a 128-step-per-period sinusoidal signal set MODEM_CFG.TxRES = 1. Figure 6-18 shows the HART modulator architecture.

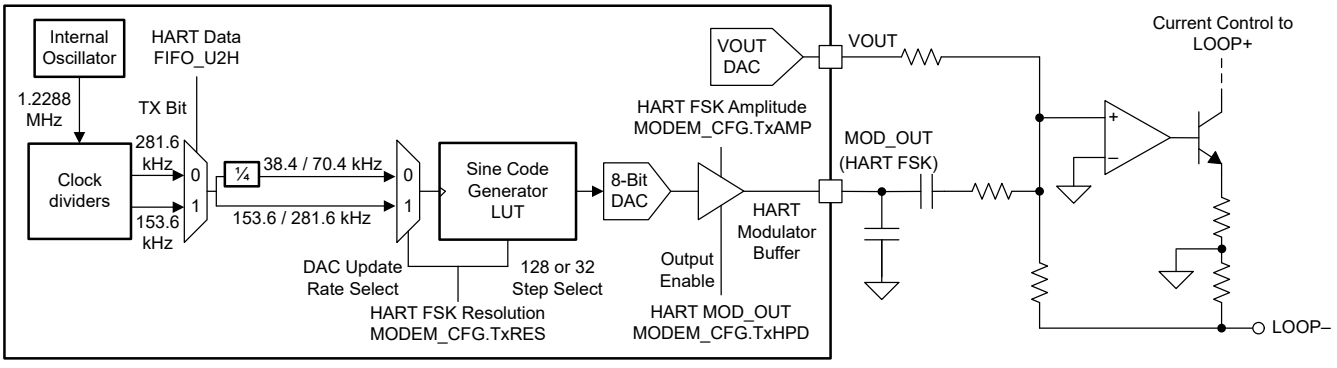


Figure 6-18. HART Modulator Architecture

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6.3.5.3 HART Demodulator

The HART demodulator converts the HART FSK input signals applied at the HART input pins (RX_IN and RX_INF) to binary data that are enqueued into the receive FIFO (FIFO_H2U). Data from the FIFO_H2U can then be dequeued by the host controller using the SPI or output on UARTOUT. Figure 6-19 shows the HART demodulator architecture. The AFEx81H1 supports two different input bandpass filter modes: internal and external.

In internal filter mode, the HART input signal is connected to the RX_IN pin through the high-pass filter capacitor. In this mode, the low-pass filter capacitor is connected to the RX_INF pin.

In external filter mode, the band-pass filter is implemented with external components for better flexibility, and the resulting band-pass-filtered signal is connected to the RX_INF pin. In this mode, float the RX_IN pin.

Use the MODEM_CFG.RX_EXFILT_EN bit to select between these two modes, depending on the external band-pass filter implementation and HART input signal connection.

The input band-pass filter (either fully external or partially internal with external capacitors and internal resistors) is followed by the internal second-order high-pass filter and the internal second-order low-pass filter. To enable the second-order low-pass filter, use the MODEM_CFG.RX_HORD_EN bit.

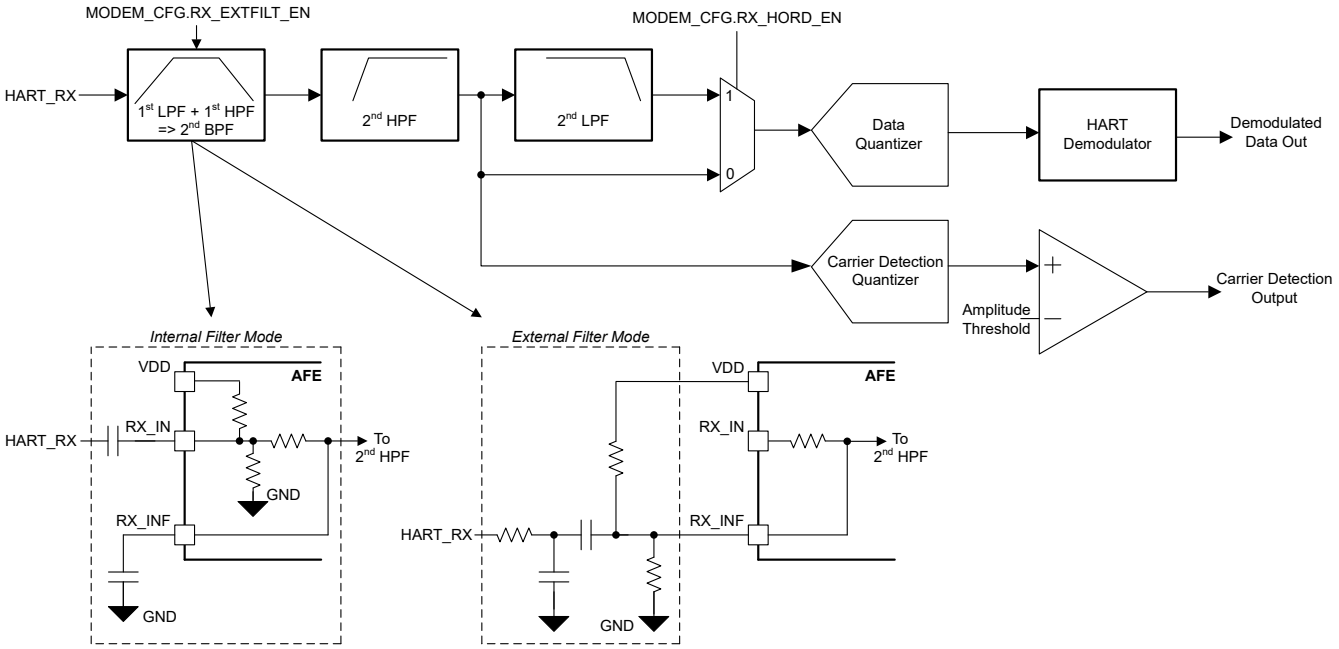


Figure 6-19. HART Demodulator Architecture

The HART demodulator asserts a carrier detect (CD) signal, when a carrier-above-threshold level is detected. Hysteresis is implemented with the carrier-detect feature to prevent erroneous carrier-detection signals. The glitch-free CD signal is available internally to the arbiter and externally to the system controller on the CD pin.

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6.3.5.4 HART Modem Modes

The HART modulator-demodulator operates in either half-duplex or full-duplex mode.

6.3.5.4.1 Half-Duplex Mode

Half-duplex mode is the main functional mode of operation for the AFEx81H1, in conjunction with the half-duplex HART protocol. In half-duplex mode, either the modulator or demodulator is active at any given instant, but never simultaneously enabled. By default, the demodulator is active and the modulator is inactive. When using half-duplex mode, the modem arbitrates when modulator and demodulator are active. For more details, see Section 6.3.5.5.

6.3.5.4.2 Full-Duplex Mode

In full-duplex mode, the modulator and demodulator are simultaneously enabled. This configuration allows a self-test feature to verify functionality of the transmit and receive signal chains to improve system diagnostics. There are internal and external full-duplex modes.

In internal full-duplex mode, the MOD_OUT pin is internally shorted to the RX_INF pin. Set MODEM_CFG.DUPLEX = 1 to enable an internal connection between the HART transmitter and receiver to verify communication.

In external full-duplex mode, the HART modulator and demodulator are enabled, but the MOD_OUT pin is not internally shorted to the RX_IN or RX_INF pins. To enable the external full-duplex mode, short MOD_OUT to RX_IN or RX_INF pins externally, and set MODEM_CFG.DUPLEX_EXT = 1.

6.3.5.5 HART Modulation and Demodulation Arbitration

In half-duplex HART-protocol mode, the device arbitrates when the modulator and demodulator are active, based on activity on the HART bus. The system controller has various means of monitoring and interacting with the AFEx81H1. For the methods used in SPI mode, see Section 6.3.5.9. For the reporting method used in UART mode, see Section 6.3.5.10.

In the default idle state, the $\overline{\text{RTS}}$ pin is high (inactive), and the CD pin is low. The demodulator is active and the modulator is inactive.

6.3.5.5.1 HART Receive Mode

When a carrier is detected, the CD pin toggles high, and data bytes received by the modem are automatically enqueued into FIFO_H2U. This mode is the highest priority, and the device continues to remain in this mode as long as a valid carrier is present. The system controller must timely dequeue the data from the FIFO_H2U as long as CD remains high and the demodulator enqueues new data into FIFO_H2U. CD is deasserted when the level of the incoming carrier is reduced to less than the HART specification. For receive operation timing details, see Section 6.3.5.7.

6.3.5.5.2 HART Transmit Mode

To transmit the HART data, issue a request to send (RTS) either by toggling the $\overline{\text{RTS}}$ pin low or asserting MODEM_CFG.RTS, depending on the selected communication setup. When the HART bus is available for transmission and no carrier is detected, the device deasserts the CD pin, disables the demodulator, asserts the CTS response by setting MODEM_STATUS.CTS_ASSERT = 1, and begins modulating the carrier. If the CD pin is used, wait for the CD pin to be deasserted. Otherwise, unmask CTS_ASSERT and set up the appropriate IRQs for the FIFO_U2H levels and CTS flags to enable the system controller to receive an IRQ when CTS is asserted. See also Section 6.3.5.8. When the CD pin and IRQ are not used, poll the MODEM_STATUS register regularly to detect when the CTS response is asserted.

As long as the CD pin is asserted, the demodulator remains active and the RTS request is held pending by the arbiter. Any HART transmit data bytes received by the AFEx81H1 are enqueued into FIFO_U2H, but not transmitted immediately. The system controller must monitor the FIFO_U2H level to avoid buffer overflow in this condition.

When the CTS response is asserted, the data enqueued into FIFO_U2H are dequeued and transmitted onto the MOD_OUT pin. If no data are enqueued into FIFO_U2H, the modulator starts transmitting the *mark* signal. The

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beginning of the bit stream must meet the minimum bit times requirement to make sure there is enough time for successful detection of the *mark*-to-*space* transition on the receiving side; see also Section 6.3.5.6.

The system controller is then required to maintain adequate an FIFO_U2H buffer level to avoid gap errors and deassert the RTS at the end of bit stream with the correct timing delays; see also Section 6.3.5.6.

6.3.5.6 HART Modulator Timing and Preamble Requirements

The HART modulator starts modulating the carrier as soon as the CTS response is asserted. If data are enqueued into FIFO_U2H before the CTS is asserted, make sure to enqueue the required preamble bytes at the beginning of the data packet in accordance with Table 6-8. The first byte is used by the HART recipient receiver to recognize the carrier and properly detect the *mark*-to-*space* transition of the start bit in the second character. Alternatively, wait for CTS_ASSERT, and give an appropriate delay while the modulator is transmitting the *mark* signal. Then enqueue the preamble bytes followed by the data bytes into FIFO_U2H. Monitor the level of FIFO_U2H and timely enqueue the new data to avoid transmission gap errors.

Table 6-8. Carrier Detect and Preamble

HART REQUIREMENT	FIFO_U2H STATE	AFEx81H1 BEHAVIOR	RECOMMENDED USE CASE
Transmit at least 6 bit times of HART signal of specified amplitude for the carrier to be detected by the receiver.	FIFO_U2H is empty.	HART modulator starts sending *mark* FSK signal as soon as CTS is asserted.	Wait at least 6 bit times from CTS assert before transmitting first preamble byte. Calculate the time to enqueue the data into FIFO_U2H based on the interface mode used.
	FIFO_U2H is preloaded with data.	HART modulator starts sending FIFO_U2H data as soon as CTS is asserted.	Preload FIFO_U2H with one additional preamble byte.

Depending on the interface mode, there is a latency from the UARTIN or $\overline{CS}$ pin to the MOD_OUT pin as a result of using FIFO_U2H in the data path.

In the SPI plus UART and UBM modes, a delay of approximately 1.5 bit times (1.5 × $t_{BAUDUART}$) occurs from the stop bit on the UARTIN pin until the data are enqueued into FIFO_U2H as a result of data decoding and synchronization. Figure 6-20 shows this timing.

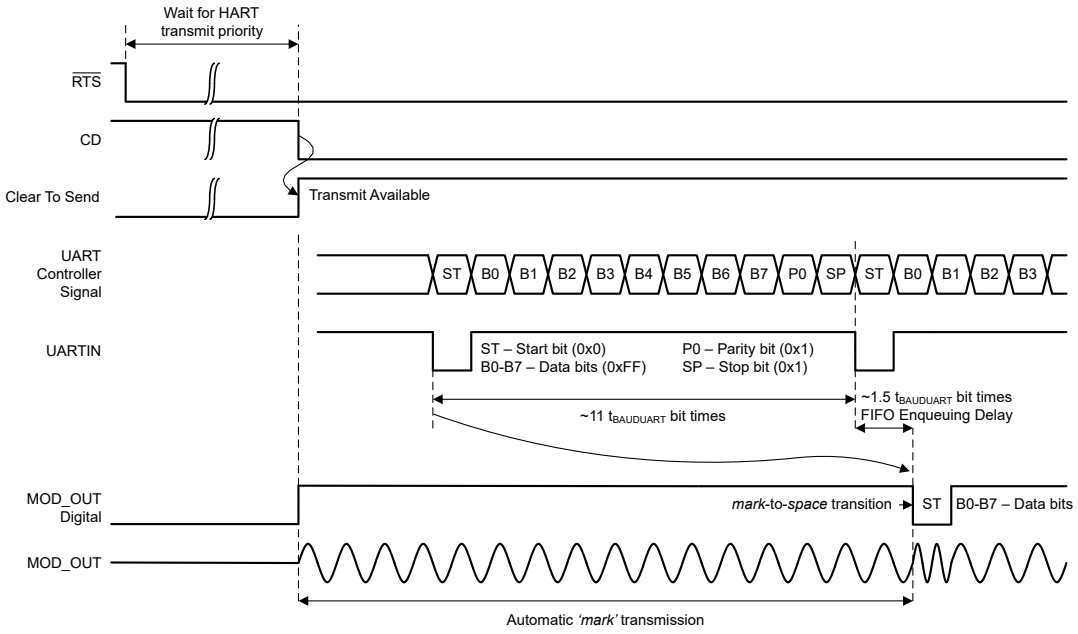


Figure 6-20. HART Transmit Start Timing Diagram (UART Mode)

In SPI only mode, the HART transmit data are enqueued into FIFO_U2H using FIFO_U2H_WR register. Therefore, in this mode, take the standard SPI timing into consideration while calculating the latency of the HART transmit data from the $\overline{CS}$ pin to the MOD_OUT pin. Figure 6-21 shows the HART transmit start timing for SPI mode.

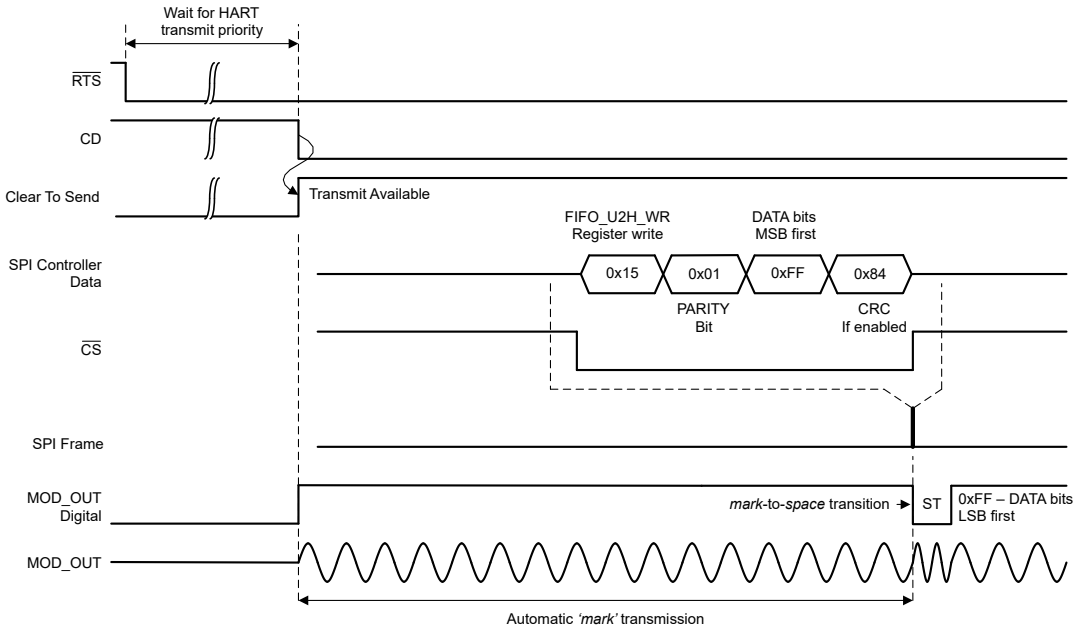


Figure 6-21. HART Transmit Start Timing Diagram (SPI Mode)

The HART character contains 11 bits; therefore, a delay of approximately 11 bit times (11 × $t_{BAUDHART}$) occurs from the moment the data are dequeued from FIFO_U2H until the data are fully transmitted on the MOD_OUT pin (see Figure 6-22).

Additional delay is accumulated when there is a frequency mismatch between the incoming UART_IN data and the HART data transmitted on MOD_OUT. If the UART_IN data frequency is 2% greater compared to the MOD_OUT data frequency, a delay of approximately 1 bit time is accumulated every five HART characters. Add a gap of at least 1 bit time between every five HART characters to account for this latency. Keep the request to send (RTS) asserted until the data are fully transmitted on MOD_OUT.

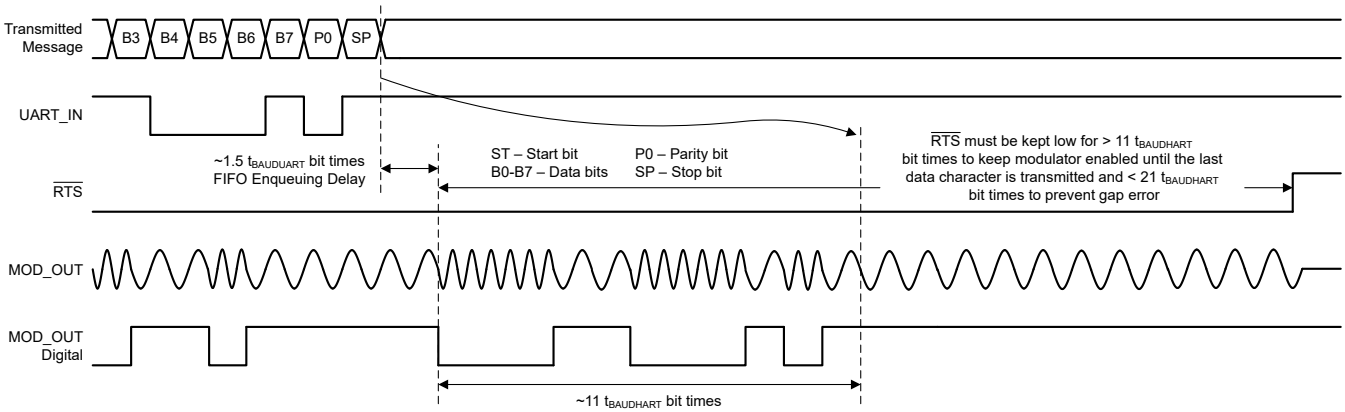


Figure 6-22. HART Transmit End Timing Diagram (UBM, UART Plus SPI Modes)

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6.3.5.7 HART Demodulator Timing and Preamble Requirements

The RX_IN and RX_INF pins are continuously monitored by the HART demodulator when not transmitting. AFEx81H1 requires at least 3 *mark* bits (3 × $t_{BAUDHART}$) of 1200Hz for carrier detection.

For UART-based communication setup, the HART data are automatically dequeued from FIFO_H2U and transmitted on the UARTOUT pin as UART characters. A delay of approximately 1.5 bit times (1.5 × $t_{BAUDHART}$) occurs as a result of data decoding and synchronization from the end of the character on RX_IN or RX_INF pin until the data are enqueued into FIFO_H2U. Thus, when CD deasserts, there is typically still one UART character pending transfer to the system controller on UARTOUT (see Figure 6-24).

FIFO latency is as low as a few microseconds when using the SPI to dequeue the data from FIFO_H2U by reading FIFO_H2U_RD register. Figure 6-23 and Figure 6-24 show the timing diagrams for the start and end of the HART receive character, respectively.

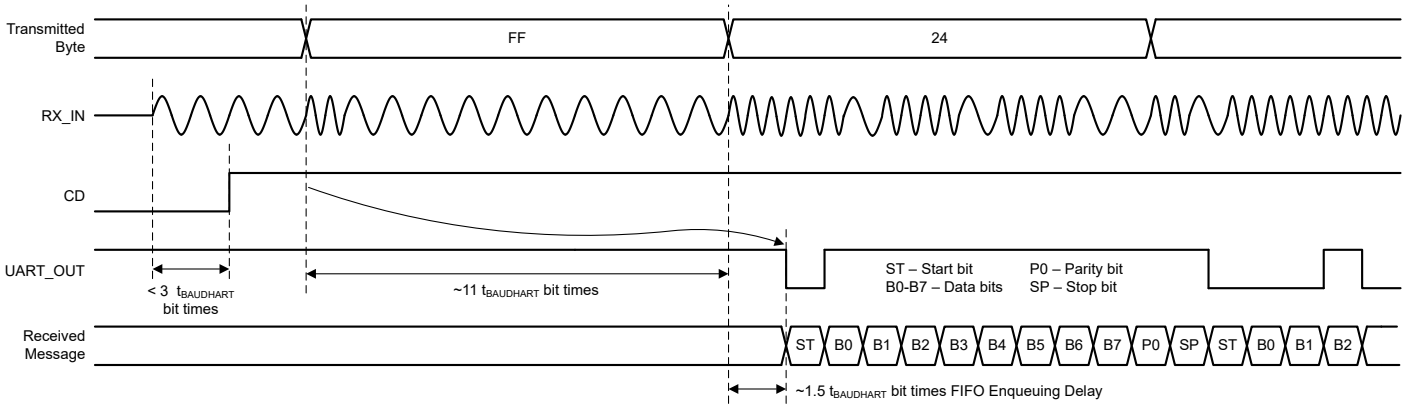


Figure 6-23. HART Receive Start Timing Diagram (SPI and UART Modes)

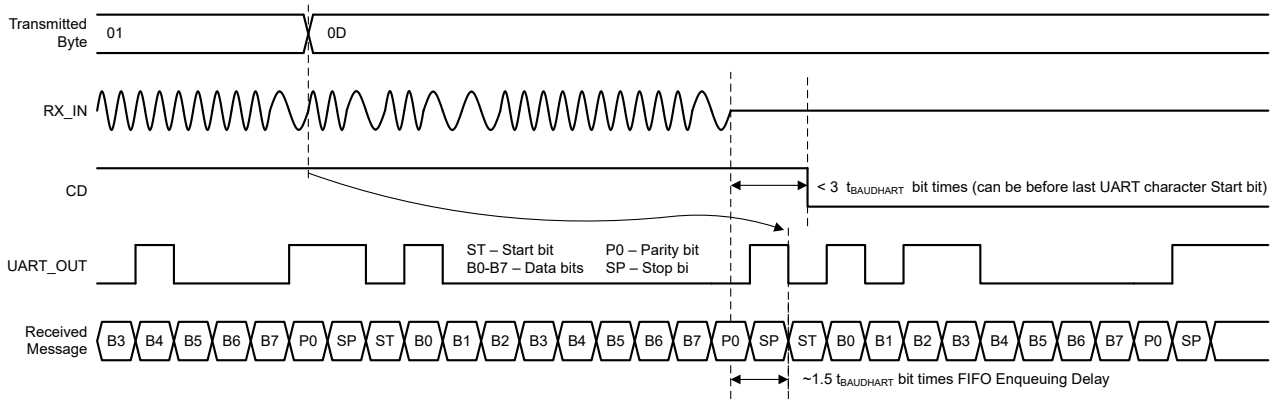


Figure 6-24. HART Receive End Timing Diagram (UART Mode)

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6.3.5.8 IRQ Configuration for HART Communication

To enable robust and error-free communicate on the HART bus, the events listed in Table 6-9 must be detected from the AFEx81H1 by the system controller in a timely manner. If the IRQ signal is not directly connected to the system controller, poll the corresponding status flags. In UART mode, the automatic dequeue of FIFO_H2U simplifies event management significantly, and not all events must be translated to IRQs.

When using the HART modem with the IRQ, the IRQ features help control communication in both directions. Enable IRQ functionality by following these steps:

1. Configure the IRQ to be either edge or level sensitive using CONFIG.IRQ_LVL. See also Section 6.3.4.
2. Configure the IRQ polarity with CONFIG.IRQ_POL, as needed per the respective system. See also Section 6.3.4.
3. For SPI only mode, set CONFIG.IRQ_PIN_EN = 1 to enable IRQ functionality on the UARTOUT pin. Also, set CONFIG.UART_DIS = 1 to disable all UART functionality.
4. For UBM, use one of the two following methods:
   a. Set CONFIG.IRQ_PIN_EN = 1 to enable IRQ functionality on the SDO pin, or
   b. Set CONFIG.UBM_IRQ_EN = 1 to enable interrupts being sent UARTOUT using UBM.
5. After IRQ functionality is enabled, unmask all the required interrupt signals in the MODEM_STATUS_MASK register (set each bit = 0).

Table 6-9. IRQ Sources and Uses

AFEx81H1 HART STATE	EVENT	MODEM_STATUS FLAG	ASSERTION METHOD(1)	ACTION
Receive	RTS deasserted	CTS_DEASSERT	Toggle $\overline{\text{RTS}}$ pin high or set MODEM_CFG.RTS = 0.	Demodulator enabled and ready to receive HART data.
	Carrier detect asserted	CD_ASSERT	Demodulator detects the HART carrier signal of valid amplitude.	Expect to receive HART data. Set desired FIFO_H2U level trigger threshold.
	FIFO_H2U level threshold trigger	FIFO_H2U_LEVEL_FLAG	Automatic enqueue of FIFO_H2U by HART demodulator.	Dequeue data from FIFO_H2U when level exceeds the set threshold. Prevent FIFO_H2U from being full to avoid the loss of incoming data.
	FIFO_H2U full	FIFO_H2U_FULL_FLAG	Automatic enqueue of FIFO_H2U by HART demodulator. System controller has not dequeued FIFO_H2U.	Critical flag. Dequeue FIFO_H2U immediately to avoid the loss of incoming data.
	Carrier detect deasserted	CD_DEASSERT	Demodulator stops detecting the HART carrier signal of valid amplitude.	Dequeue remaining data from FIFO_H2U. Monitor the empty flag to make sure that all data have been received.
	FIFO_H2U empty	FIFO_H2U_EMPTY_FLAG	Dequeue of FIFO_H2U by system controller.	If using UART, wait to make sure the last character is received on UARTOUT.
Transmit	RTS asserted	NA	Toggle $\overline{\text{RTS}}$ pin low or write set MODEM_CFG.RTS = 1.	Wait for clear-to-send confirmation flag.
	Clear to send (CTS)	CTS_ASSERT	RTS asserted and CD deasserted.	Modulator enabled. Device starts modulating the carrier on MOD_OUT. Set desired FIFO_U2H level trigger threshold. Enqueue data into FIFO_U2H. Modulator automatically dequeues FIFO_U2H and transmits the HART data.
	FIFO_U2H level threshold trigger	FIFO_U2H_LEVEL_FLAG	Automatic dequeue of FIFO_U2H by HART modulator.	Enqueue new data into FIFO_U2H when the level drops below the set threshold. Prevent FIFO_U2H from being empty to avoid a gap in transmission.
	FIFO_U2H full	FIFO_U2H_FULL_FLAG	System controller enqueue of the new data into FIFO_U2H.	Critical flag. Stop enqueue of data into FIFO_U2H immediately to avoid loss of HART data.
	FIFO_U2H empty	FIFO_U2H_EMPTY_FLAG	Automatic dequeue of FIFO_U2H by HART modulator. System controller has not enqueued new data into FIFO_U2H.	Critical flag in the middle of the data packet. Enqueue new data into FIFO_U2H immediately to avoid a gap in transmission. When the last character is dequeued from FIFO_U2H, wait until the character is fully transmitted on MOD_OUT before deasserting RTS.

(1) For CD, $\overline{\text{RTS}}$, $\overline{\text{ALARM}}$, and IRQ connection choices, see Section 6.5.1.

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6.3.5.9 HART Communication Using the SPI

HART bus communication activity is reported to the host controller through the IRQ signal routed to the UARTOUT pin and MODEM_STATUS register. Read the MODEM_STATUS register to determine the source of the IRQ when an IRQ is received. If the UARTOUT pin is not connected, poll the status registers regularly through the SPI.

To transmit data, set up the desired FIFO_U2H level thresholds using FIFO_CFG.U2H_LEVEL_SET. Assert the RTS. After CTS_ASSERT is set, begin to fill FIFO_U2H. Enqueue enough data into FIFO_U2H to fill the FIFO above the set threshold level. The HART modulator automatically dequeues the data from FIFO_U2H and transmits the data on MOD_OUT. When FIFO_U2H level drops below the set threshold, an IRQ triggers, indicating that new data bytes can be enqueued without losing any data. After the last set of data have been enqueued into FIFO_U2H, an IRQ event triggered by the level flag can be ignored. Wait for the IRQ event triggered by FIFO_U2H_EMPTY_FLAG. Deassert the RTS after required delay; see also Section 6.3.5.6. When the RTS is deasserted, the CTS_DEASSERT bit is set. CTS_DEASSERT is an informational bit.

To receive data, set up an IRQ event based on CD_ASSERT to know when the carrier is detected and the new data bytes are expected. Also, set up the additional IRQ events to trigger each time FIFO_H2U_LEVEL_FLAG is set. Select the desired level of FIFO_H2U. Dequeue the data from FIFO_H2U every time the level exceeds the set threshold. Also, set up IRQ event trigger based on CD_DEASSERT to know when all the data have been received. At this point, monitor FIFO_H2U.EMPTY_FLAG when dequeuing each character to know when FIFO_H2U is empty and all the data bytes have been dequeued and transmitted to the microcontroller.

Alternatively, the CD pin can be directly connected to the microcontroller to monitor the status of the HART bus. In this configuration, mask CD_ASSERT flag by setting MODEM_STATUS_MASK.CD_ASSERT bit = 1 to prevent CD_ASSERT from generating an IRQ event.

6.3.5.10 HART Communication Using UART

In SPI plus UART mode, the UART data are transmitted and received at 1200 baud, which is matched to the HART FSK input and output signals. Both SDO and UARTOUT pins are used; therefore, the IRQ functionality is not available in SPI plus UART mode. FIFO_H2U level monitoring is not required because any HART data received by the demodulator and enqueued into FIFO_H2U are automatically dequeued and transmitted on UARTOUT. FIFO_U2H level monitoring is also not required if HART bus communication activity is interfaced to the host controller through the CD and $\overline{\text{RTS}}$ pins. The host controller can properly time the $\overline{\text{RTS}}$ pin to transmit the HART data when no carrier is detected on the bus. If the CD and $\overline{\text{RTS}}$ pins are not used in SPI plus UART mode, the host controller can periodically poll the MODEM_STATUS register through the SPI to detect when the carrier is not present on the HART bus, and assert the request to send by setting MODEM_CFG.RTS bit = 1.

In UBM, the UART data are transmitted and received at 9600 baud. The HART data characters are interleaved with break commands for register map access or interrupt reporting; see also Section 6.5.3.1.1. Similar to SPI plus UART mode, monitoring of FIFO_H2U and FIFO_U2H levels is not required. The CD and $\overline{\text{RTS}}$ pins are available to interface the HART bus activity with the microcontroller. IRQ functionality is also available on the SDO pin. If the SDO pin is connected to the microcontroller, the IRQ event based on CD_ASSERT can be set to report when the carrier is detected. In this case, CD pin connection to the microcontroller is not required. Similarly, $\overline{\text{RTS}}$ pin connection is not required if MODEM_CFG.RTS is used to issue a request to send. The SDO pin connection to the microcontroller is also not required if the microcontroller can periodically poll the MODEM_STATUS register using break commands, and monitor all the required flags.

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6.3.5.11 Memory Built-In Self-Test (MBIST)

Memory built-in self-test (MBIST) verifies the validity of the static random-access memory (SRAM) used for the FIFO buffers. When initiated, the MBIST takes control of the SRAM module until completion.

Disable HART communication while the MBIST is running. Communication with the FIFO buffers during the MBIST produces unreliable results. Two status bits, GEN_STATUS.MBIST_DONE and GEN_STATUS.MBIST_FAIL, can be monitored for completion or failure, or used to create IRQ events.

Do not try to read back the GEN_STATUS register while the MBIST is running. The MBIST control logic generates narrow pulses for the MBIST_DONE and MBIST_FAIL status flags. The status flags can be missed if these pulses occur during the readback of the GEN_STATUS register. To avoid missing the MBIST_DONE flag, mask all the status bits except GEN_STATUS_MASK.MBIST_DONE and then either:

1. monitor for an IRQ event, or
2. periodically send a NOP and check the GEN_IRQ status bit.

Wait until MBIST_DONE is reported, verify the status of the MBIST_FAIL flag, and then resume normal operation.

6.3.6 Internal Reference

The AFEx81H1 family of devices includes a 1.25V precision band-gap reference. The internal reference is externally available at the VREFIO pin and sources up to 2.5mA. For noise filtering, use a 100nF capacitor between the reference output and GND.

The internal reference circuit is enabled or disabled by using the REF_EN pin. A logic high on this pin enables the internal reference, and the VREFIO pin outputs 1.25V. A logic low on this pin disables the internal reference, and the device expects to have 1.25V from external VREF at the VREFIO pin.

An invalid reference voltage asserts an alarm condition. The DAC response depends on the VREF_FLT setting in the ALARM_ACT register (10h).

6.3.7 Integrated Precision Oscillator

The internal time base of the device is provided by an internal oscillator that is trimmed to less than 0.5% tolerance at room temperature. The precision oscillator is the timing source for ADC conversions. At power up, the internal oscillator and ADC take roughly 300µs to reach < 1% error stability. After the clock stabilizes, the ADC data output is accurate to the electrical specifications provided in Section 5.

6.3.8 One-Time Programmable (OTP) Memory

One-time programmable (OTP) memory in the device is used to store the device trim settings and is not accessible to users. The OTP memory data are loaded to the memory (OTP shadow load) at power up. The OTP memory CRC is performed to verify the correct data are loaded. The TRIGGER.SHADOWLOAD bit is available to initiate a reload of the OTP memory data if a CRC error is detected. The SPECIAL_CFG.OTP_LOAD_SW_RST bit controls whether the OTP memory data are reloaded with a software reset.

6.4 Device Functional Modes

6.4.1 DAC Power-Down Mode

Power-down mode facilitates rapid turn-off of the voltage at the DAC output. The DAC can be set to enter and exit power-down mode through hardware, software, or automatically in response to an alarm event. The DAC output is specified for glitch-free performance when going into and out of power-down mode.

Power-down mode is also be enabled by setting DAC_CFG.PD to 1. In power-down mode, the DAC output amplifier powers down and the DAC output pin is put into the Hi-Z configuration. The DAC output remains in power-down mode until the DAC output is re-enabled.

Alarm control of the power-down mode is enabled by setting the alarm events as DAC power-down sources. The alarm events that trigger the DAC output power-down state must be specified in the ALARM_ACT register. After

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the alarm bit is cleared, the DAC returns to normal operation, as long as no other power-down controlling alarm event has been triggered.

The DAC register does not change when the DAC enters power-down mode, which enables the device to return to the original operating point after return from the power-down mode. Additionally, the DAC register can be updated while the DAC is in power-down mode, thus allowing the DAC to output a new value upon return to normal operation.

6.4.2 Reset

There are three reset mechanisms in the device: a power-on reset (POR), a $\overline{\text{RESET}}$ pin, and the SW_RST command that can be sent through the either the SPI or by UBM.

When power is first applied to the device, a POR circuit holds the device in reset until all supplies reach the specified operating voltages. The power-on reset returns the device to a known operating state in case a brownout event occurs (when the supplies have dipped below the minimum operating voltages). The POR starts all digital circuits in reset as the supply settles, and releases them to make sure that the device starts in the default condition and loads the OTP memory. After the OTP memory has been loaded, the $\overline{\text{ALARM}}$ pin is released. At this time, communication with the device is safe. This t_{POR} time is less than 100µs.

The devices also have a $\overline{\text{RESET}}$ pin that is used as a hardware reset to the device. Send the $\overline{\text{RESET}}$ pin low for a minimum of 100ns (t_{RESET}) to reset the device. A delay time of 10µs ($t_{RESETWAIT}$) is required before sending the first serial interface command as the device latches and releases the reset. The release of the internal reset state is synchronized to the internal clock. The $\overline{\text{RESET}}$ pin resets the SPI and the UART interfaces, the HART FIFO buffer, the watchdog timer, the internal oscillator, and the device registers. $\overline{\text{RESET}}$ does not reload the OTP memory.

The command to RESET.SW_RST = 0xAD resets the device as a software reset. The command is decoded at the rising edge of $\overline{\text{CS}}$ with an SPI command or during the stop bit of the last character of a UBM frame. Set UBM.REG_MODE again to put the device back into UBM when resetting the device in UBM. After sending the RESET command, no delay time is required before sending the first serial interface command as the device latches and releases the reset. The reset is synchronized to the falling edge of the internal clock and is released well before the next rising edge. The $\overline{\text{ALARM}}$ pin pulses low for the width of the internal reset. This pulse duration is less than 20ns. This command resets the SPI and the UART interface, the HART FIFO, and the watchdog timer, but does not reset the internal oscillator. The software reset also reloads internal factory trim registers if properly configured in the SPECIAL_CFG register. The SPECIAL_CFG register is only reset with a POR.

The POR and hardware reset place the internal oscillator into a reset condition, which holds the clock low. When these two signals are released, there is a delay of a few microseconds before the first rising edge of the clock. The hardware reset, $\overline{\text{RESET}}$, pulse width must be at least 100ns to allow the oscillator to properly reset. The SW_RST command is a short pulse. This pulse is not long enough to adequately reset the oscillator. The SW_RST is asserted with a falling edge of the clock. As a result of the long oscillator period, the design architecture provides that all devices are out of reset by the next rising edge.

Figure 6-25 shows the reset tree.

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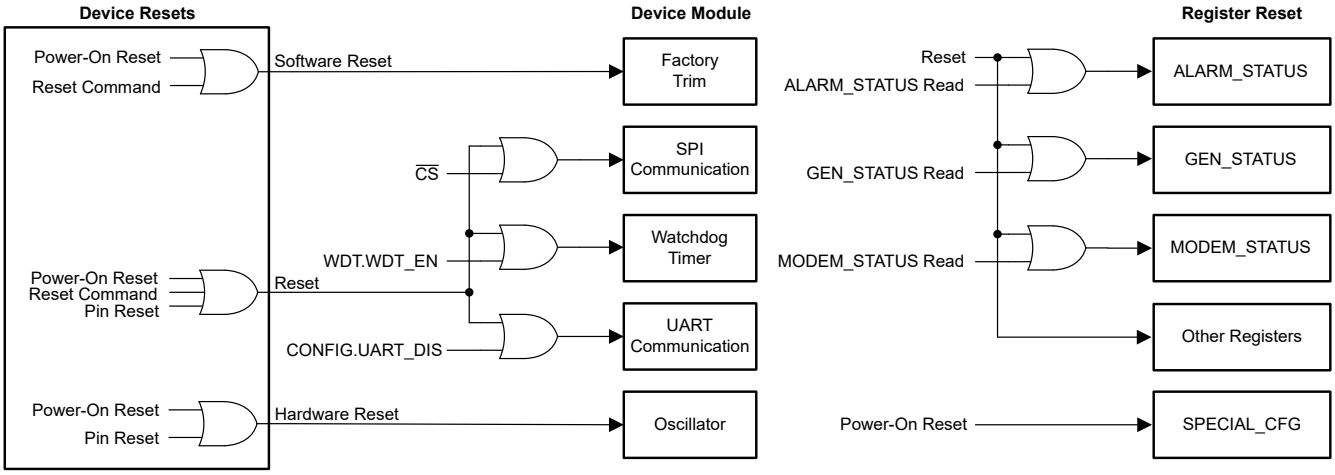


Figure 6-25. Reset Conditions

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6.5 Programming

The AFEx81H1 communicate with the system controller through a serial interface that supports either a UART-compatible two-wire bus or an SPI-compatible bus. Based on the hardware configuration, either interface can be enabled. Figure 6-26 and Figure 6-27 show the configurations to enable SPI mode and UART break mode (UBM), respectively. The SPI supports an 8-bit frame-by-frame CRC that is enabled by default, but can be disabled by the user. UBM does not support CRC, but does support the UART protocol parity bit.

The AFEx81H1 are designed to leverage the existing firmware for communication with DACs or HART modems. A special SPI- and UART-capable dual mode of communication that is available to enable firmware reuse from discrete HART architecture is shown in Figure 6-28. See Section 6.5.1.3 for more details.

6.5.1 Communication Setup

After any reset or power up, the AFEx81H1 wake up able to use the SPI or UART break mode (UBM). The devices include a robust mechanism that configures the interface between either an SPI-compatible or UART-compatible protocol based system, thus preventing protocol change during normal operation. The selection is based on initial conditions from the respective hardware configurations (see Figure 6-26 and Figure 6-27) and any subsequent user configuration.

In SPI plus UART mode, all communication pins on the system microcontroller are connected to the AFEx81H1, as shown in Figure 6-28.

6.5.1.1 SPI Mode

By default, the AFEx81H1 can be fully accessed with the SPI (except UBM.REG_MODE). To set up the device in SPI mode:

1. Set CONFIG.UART_DIS = 1 (disables the UART communication).
2. Optionally, set CONFIG.DSDO, CONFIG.FSDO, and CONFIG.IRQ_PIN_EN.

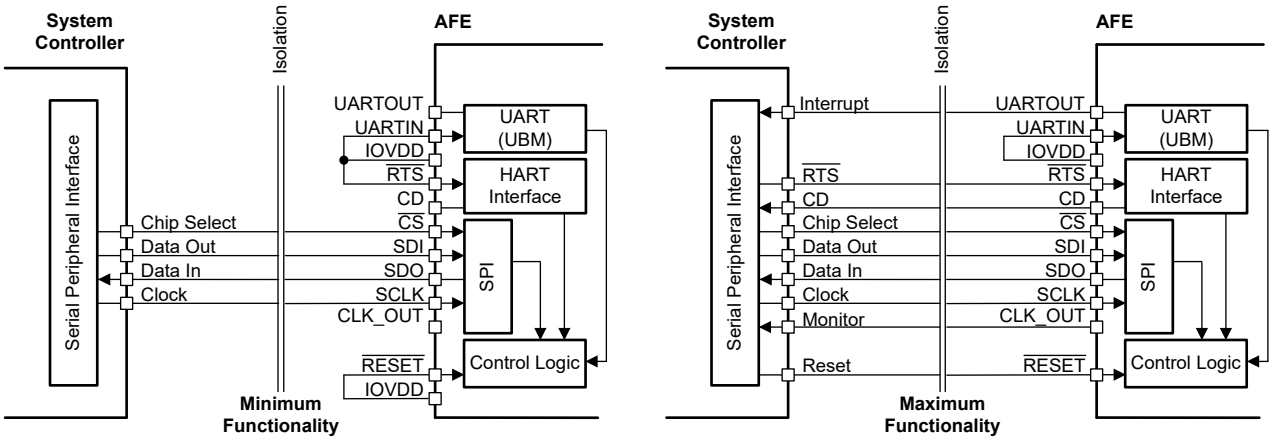


Figure 6-26. SPI Mode Connections

Figure 6-26 shows the SPI mode logical connections (through the isolation barrier, if used) for both minimum functionality (all optional pins disconnected) and maximum functionality (all pins connected). If CONFIG.IRQ_PIN_EN = 1 is set, then the UARTOUT pin functions as the IRQ output. In SPI mode, set CONFIG.SDO_DSDO = 0 to enable the readback function. This function is disabled by default to save power. If the readback function not enabled, SDO remains in Hi-Z mode even during the subsequent frame after a read request.

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6.5.1.2 UART Mode

At power up, the UART interface is set to 9600 baud with UBM enabled. Any reset clears the UBM register, and the register must be set again to use UBM. To set up the device in UBM:

1. Using UBM, set UBM.REG_MODE = 1 at 9600 baud. This setting blocks the SPI from accessing the device and enables the UART interface access to the entire register map.
2. Optionally, set CONFIG.CLR_PIN_EN and CONFIG.IRQ_PIN_EN.

Figure 6-27 shows the UBM logical connections (through the isolation barrier, if used) for both minimum functionality (all optional pins disconnected) and maximum functionality (all pins connected). If CONFIG.IRQ_PIN_EN = 1 is set, then the SDO pin functions as the IRQ output. If CONFIG.CLR_PIN_EN = 1 is set, then the SDI pin controls the clear pin function.

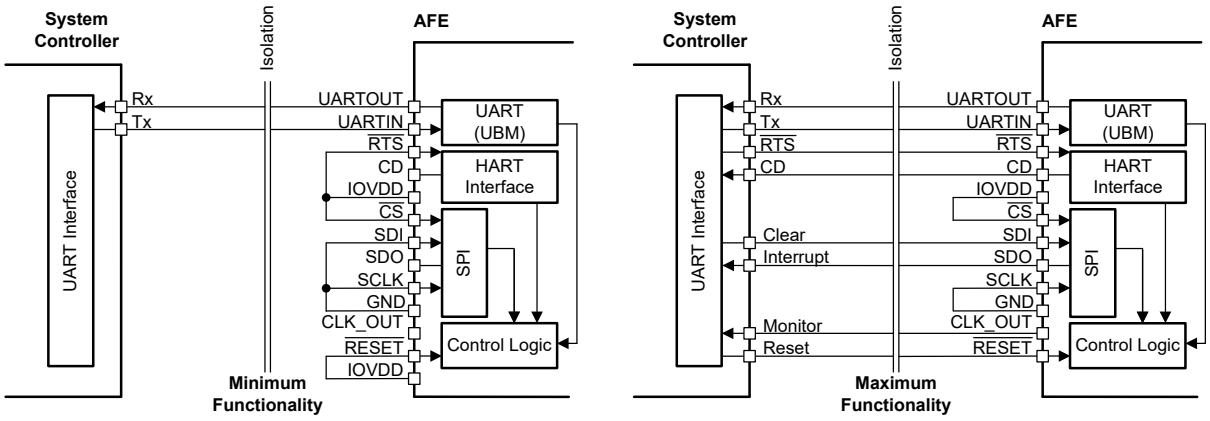


Figure 6-27. UBM (UART Interface) Connections

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6.5.1.3 SPI Plus UART Mode

In this mode, communicate with the integrated HART modem using the UART while communicating with the DAC using the SPI. Many discrete DACs use SPI communication, whereas HART modems use UART communication, but this special communication interface enables easy transition from discrete to integrated HART architecture. Figure 6-28 shows the UBM logical connections (through the isolation barrier, if used) for both minimum functionality (all optional pins disconnected) and maximum functionality (all pins connected).

To setup the device in SPI plus UART mode using the SPI, set CONFIG.UART_BAUD = 0 to set the baud rate to 1200 for the UART, and to track the HART baud rate of 1200. The UART also works at a 9600 baud, but the 1200 baud rate of HART must be considered, and the FIFO STATUS must be monitored through the SPI.

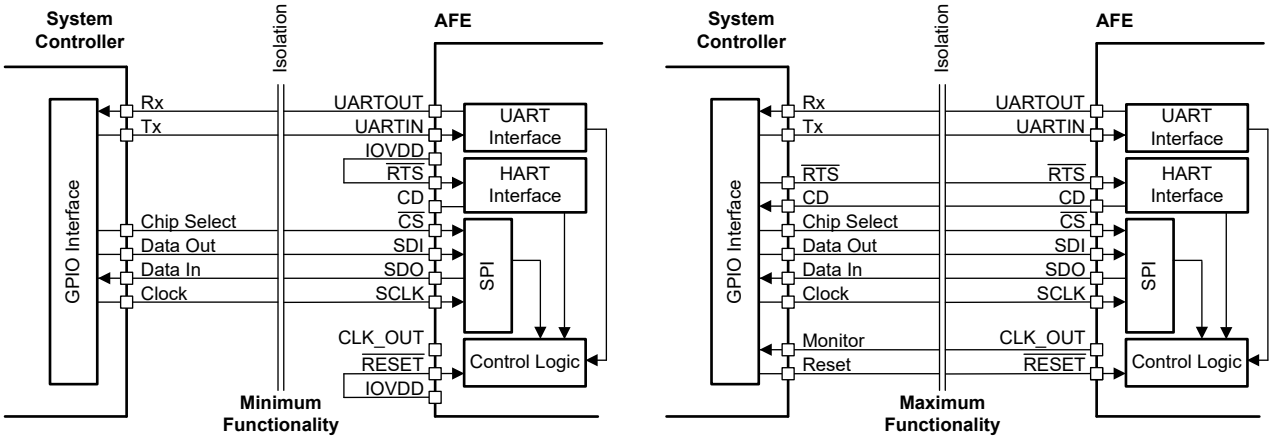


Figure 6-28. SPI Plus UART Mode Connections

6.5.1.4 HART Functionality Setup Options

Table 6-10 shows the various options to set up HART functionality based on communication options by connected pin.

Table 6-10. HART Function Setup Options by Communication Pins Used

FUNCTION	INTERFACE MODE[1]	PIN NAME	HARDWARE METHOD (PIN CONNECTED)	ALTERNATE METHOD (PIN NOT CONNECTED)
Request to send (RTS)	Any	$\overline{\text{RTS}}$ (input)	L: RTS asserted. H: RTS deasserted.	Write to MODEM_CFG.RTS bit 1: RTS asserted. 0: RTS deasserted.
Carrier detect (CD)	Any	CD (output)	L: CD deasserted. H: CD asserted.	Connect and setup interrupt request or Poll CD_ASSERT / CD_DEASSERT
Clear to send (CTS)	Any	None	Not available	Connect and setup interrupt request or Poll CTS_ASSERT
Alarm	Any	$\overline{\text{ALARM}}$ (output)	Multiple alarm based interrupt sources for system controller; see also Section 6.3.3.	Connect and setup interrupt request or Poll ALARM_STATUS register
Interrupt request (IRQ)[2]	UART	SDO (output)	Level- and polarity-configurable interrupt pin (see Section 6.3.4). Multiple interrupt sources for system controller; see also Section 6.3.5.8.	Set CONFIG.UBM_IRQ_EN = 1 to generate soft IRQ as break command followed by data on UARTOUT. See Section 6.5.3.1 for details.
	SPI only	UARTOUT (Output)		Poll status registers
	SPI plus UART	None	Not available	Poll status registers

1. For option details, see Section 6.5.1.
2. For IRQ configuration details, see Table 6-9.

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6.5.2 Serial Peripheral Interface (SPI)

The AFEx81H1 are controlled over a versatile four-wire serial interface (SDIN, SDO, SCLK, and $\overline{CS}$). The interface operates at clock rates of up to 12.5MHz and is compatible with SPI, QSPI, Microwire, and digital signal processing (DSP) standards. The SPI communication command consists of a read or write address, a data word, and an optional CRC byte.

The SPI can access all register addresses except for the UBM register. Read-only and read-write capability is defined by register (see Table 6-13). The SPI supports both SPI Mode 1 (CPOL = 0, CPHA = 1) and SPI Mode 2 (CPOL = 1, CPHA = 0). The default SCLK value is low for SPI Mode 1 and high for SPI Mode 2. See Section 5.7 for timing diagrams in each mode. The serial clock, SCLK, can be continuous or gated.

6.5.2.1 SPI Frame Definition

Subject to the timing requirements listed in the *Timing Requirements*, the first SCLK falling edge immediately following the falling edge of $\overline{CS}$ captures the first frame bit. Subject to the same requirements, the last SCLK falling edge before the rising edge of $\overline{CS}$ captures the last bit of the frame. Figure 6-29 shows that the SPI shift register frame is 32-bits wide, and consists of an R/W bit, followed by a 7-bit address, and a 16-bit data word. The 8-bit CRC is optional (enabled by default) and is disabled by setting CONFIG.CRC_EN = 0 (see also Section 6.5.2.3). Figure 6-30 shows that when the CRC is disabled, the frame is 24-bits wide.

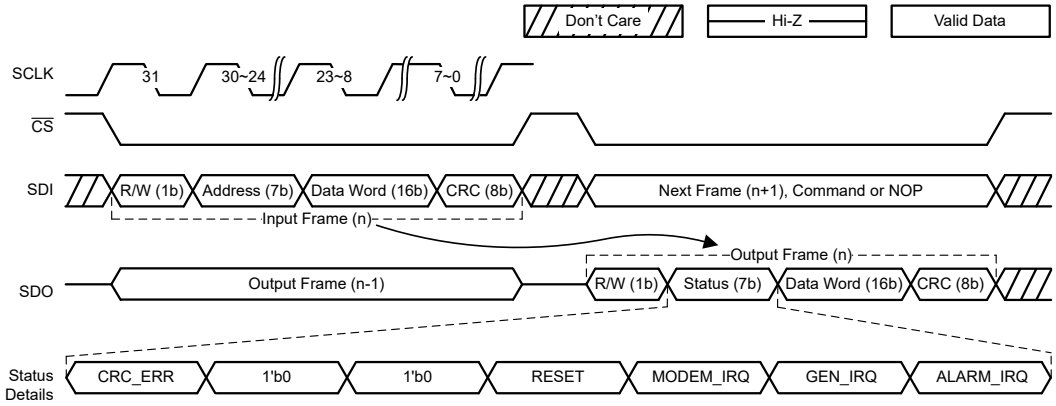


Figure 6-29. SPI Frame Details (Default, CRC Enabled)

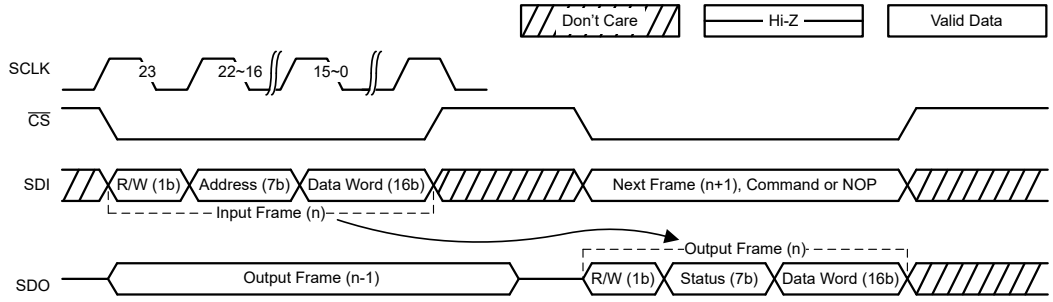


Figure 6-30. SPI Frame Details (CRC Disabled)

For a valid frame, a full frame length of data (24 bits if CRC is disabled or 32 bits if CRC is enabled) must be transmitted before $\overline{CS}$ is brought high. If $\overline{CS}$ is brought high before the last falling SCLK edge of a full frame, then the data word is not transferred into the internal registers. If more than a full frame length of falling SCLK edges are applied before $\overline{CS}$ is brought high, then the last full frame length number of bits are used. In other words, if the number of falling SCLK edges while $\overline{CS}$ = 0 is 34, then the last 32 SCLK cycles (or 24 if CRC is disabled) are treated as the valid frame. The device internal registers are updated from the SPI shift register on the rising edge of $\overline{CS}$. To start another serial transfer, bring $\overline{CS}$ low again. When $\overline{CS}$ is high, the SCLK and SDI signals are blocked and the SDO pin is high impedance.

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6.5.2.2 SPI Read and Write

The SDI input bit is latched on the SCLK falling edge. The SDI pin receives right-justified data. At the rising edge of $\overline{CS}$, the right-most (last) bits are evaluated as a frame. Extra clock cycles (exceeding frame length) during the frame begin to output on SDO the SDI data delayed by one frame length.

A read operation is started when R/W bit is 1. The data word input for SDI is ignored in the read command frame. Send the subsequent read or write command frame into SDI to clock out the data of the addressed register on SDO. If no other read or write commands are needed, then issue a NOP command to retrieve the requested data. The read register value is output most significant bit first on SDO on successive edges (rising or falling based on CONFIG.FSDO setting) of SCLK.

A write operation starts when R/W bit is 0. The SDO output to a write command, delivered in the next frame, contains status bits, data described in Table 6-11, and if the CRC is enabled, an 8-bit CRC for the output frame.

Table 6-11. Command Functions

COMMAND BIT	SDI INPUT DATA WORD	SDO RESPONSE DATA WORD(1)
Write (R/W = 0)	Data to be written (16b)	0x0000
Read (R/W = 1)	Ignored(2)	Register output data (16b)

(1) Response data portion in next frame output.
(2) The input bits are included in the calculation for CRC, if enabled (see Section 6.5.2.3).

Valid SDO output is driven only when $\overline{CS}$ = 0 and CONFIG.DSDO = 0; otherwise, the SDO pin remains Hi-Z to save power. The SDO data bits are left-justified within the frame, meaning the most significant bit is produced on the line (subject to timing details) when $\overline{CS}$ is asserted low (bit is driven by falling edge of $\overline{CS}$). The subsequent bits in the frame are driven by the rising SCLK edge when CONFIG.FSDO = 0 (default). To drive the SDO data on the falling edge of SCLK, set CONFIG.FSDO = 1. This setting effectively gives the SDO data an additional ½ clock period for setup time, but at the expense of hold time.

The frame output on SDO contains the command bit of the input that generated the frame (previous input frame), followed by seven status bits (see Figure 6-29). When an input frame CRC error is detected, the status bit CRC_ERR = 1. If there is no input frame CRC error, then CRC_ERR = 0. See Table 6-12 for details.

6.5.2.3 Frame Error Checking

If the AFEx81H1 are used in a noisy environment, use the CRC to check the integrity of the SPI data communication between the device and the system controller. This feature is enabled by default and is controlled by the CONFIG.CRC_EN bit. If the CRC is not required in the system, disable frame error checking through the CRC_EN bit, and switch from the default 32-bit frame to the 24-bit frame.

Frame error checking is based on the CRC-8-ATM (HEC) polynomial: $x^8 + x^2 + x + 1$ (*9'b100000111*).

For the output register readback, the AFEx81H1 supply the calculated 8-bit CRC for the 24 bits of data provided, as part of the 32-bit frame.

The AFEx81H1 decodes 24-bits of the input frame data and the 8-bit CRC to compute the CRC remainder. If no error exists in the frame, the CRC remainder is zero. When the remainder is nonzero (that is, the input frame has single-bit or multiple-bit errors) the ALARM_STATUS.CRC_ERR_CNT bits are incremented. A bad CRC value prevents execution of commands to the device, which prevents FIFO data from being lost as a result of an invalid read command.

When the CRC error counter reaches the limit programmed in CONFIG.CRC_ERR_CNT, the CRC_FLT status bit is set in the ALARM_STATUS register. The fault is reported (as long as the corresponding mask is not set) as an ALARM_IRQ on SDO during the next frame. The $\overline{ALARM}$ pin asserts low if enabled by the alarm action configuration (see Section 6.3.3.2).

The CRC_ERR status bit (see Figure 6-29) in the SDO frame is not sticky and is only reported for the previous frame. The ALARM_STATUS.CRC_FLT bit is sticky and is only cleared after a successful read of the

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ALARM_STATUS register. Read the GEN_STATUS, MODEM_STATUS or ALARM_STATUS registers to clear any sticky bits that are set.

The sticky status bits are cleared at the start of the readback frame and are latched again at the end of the readback frame. Therefore, if the fault condition previously reported in the status register is no longer present at the end of the readback frame, and the data are received by the microcontroller with the CRC error, the fault information is lost. If a robust monitoring of the status bits is required in a noisy environment, use the IRQ pin in combination with the status mask bits to find out the status of each fault before clearing the status bits. Set the CONFIG.IRQ_LVL bit to monitor the signal level on the IRQ pin, and unmask each status bit one at a time to retrieve the information from the status registers.

6.5.2.4 Synchronization

The AFEx81H1 register map runs on the internal clock domain. Both the SPI and UBM packets are synchronized to this domain. This synchronization adds a latency of 0.4µs to 1.22µs (1.5 internal clocks), with respect to the rising edge of $\overline{CS}$ or the STOP bit of the last byte of the UBM packet.

The effect of clock synchronization on UBM communication is not evident because of the lower speed and asynchronous nature of UBM communication.

In SPI mode, if changing register bits CONFIG.DSDO, CONFIG.FSDO, or CONFIG.CRC_EN, keep $\overline{CS}$ high for at least two clock cycles before issuing the next frame. Frame data corruption can occur if the two extra cycles are not used. The following are examples of frame corruption:

- Setting CONFIG.DSDO = 0: SDO begins to drive in the middle of the next frame.
- Changing CONFIG.FSDO: The launching edge of SDO changes in the middle of the next frame.
- Setting CONFIG.CRC_EN = 1: The next frame has a CRC error because the CRC is enabled in the middle of the frame.

Send a NOP command (SDI = 0x00_0000) after setting the DSDO, FSDO, and CRC_EN bits to prevent the corrupted frames from impacting communication. Sending a NOP after CONFIG.CRC_EN is set still generates a CRC error, and is reported in the STATUS portion of SDO. To avoid false errors, wait approximately 2 µs after setting CONFIG.CRC_EN before sending the next frame.

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6.5.3 UART Interface

In UART mode, the device expects 1 start bit, 8 data bits, 1 odd parity bit, and 1 stop bit, or an 8O1 UART character format.

When using SPI to communicate with the registers, and only using UART for HART communication, use 1200 baud. The baud must have ±1% accuracy.

6.5.3.1 UART Break Mode (UBM)

In UART break mode (UBM), the microcontroller issues a UART break to start communication. The device interprets the UART break as the start to receive commands from the UART. A communication UART character consists of one start bit, eight data bits, one odd parity bit, and at least one stop bit. A UART break character is all 11 bits (including start, data, parity and stop bit) held low by the microcontroller on the UARTIN pin and by the AFEx81H1 on the UARTOUT pin. When a valid break character is detected on UARTIN by the AFEx81H1, no parity (even though parity is odd) or stop bit errors are flagged for this character. The parity and stop bit differences between valid UBM break and communication characters must be managed by the system microcontroller when receiving these characters from the UARTOUT pin of the AFEx81H1. See Figure 5-2 for UBM break character, communication timing details, and bit order.

Two baud rates are supported for UART communication: 9600 and 1200. The 9600 baud rate is default for UBM. The 1200 baud rate is supported to maintain backward compatibility and requires the use of SPI to communicate with the register map; whereas, the UART pins are used only for HART communication. The baud rates are selected by register bit CONFIG.UART_BAUD. When CONFIG.UART_BAUD = 1 (default), the UART operates at 9600 baud. When CONFIG.UART_BAUD = 0, the UART operates at 1200 baud. The break function of the UART protocol is enabled only for 9600 baud. This configuration allows interleaving of HART data with register communication and enables the access to all registers of the device, when configured correctly.

Set UBM.REG_MODE = 1 to enable register map access through the UART. By default, this bit is set to 0. The entire register map can only be accessed with SPI, except for the UBM register. The UBM register can only be accessed with UBM. After UBM.REG_MODE is set to 1, the SPI does not have access to the register map, and the full register map is accessible by UBM.

A UBM data output packet is initiated by AFEx81H1 on UARTOUT in two cases. See Figure 6-33 for packet structure details. If the R/IRQn status bit is 0 an IRQ event initiated the break command. If the R/IRQn status bit is 1, the break command is a response to the prior read request. For details on HART data see Section 6.5.3.1.1.

To enable IRQ events, set CONFIG.UBM_IRQ_EN = 1. When IRQ is enabled, the AFEx81H1 triggers a break command followed by data on UARTOUT (see Figure 6-33).

The contents of the data are listed in order of priority below.

1. If ALARM_IRQ bit is set, then the contents of the ALARM_STATUS register are output.
2. If GEN_IRQ is set, then the contents of the GEN_STATUS register are output.
3. If MODEM_IRQ bit is set, then the contents of the MODEM_STATUS register are output.
4. If none of the previous bits are set, then an IRQ is not generated.

A break byte is followed by three bytes. These three bytes have information identical to the SPI frame without the CRC (see Figure 6-30). The CRC cannot be enabled for UBM. All communication characters on the UART bus are transmitted least significant data bit (D0) first.

Figure 6-31 shows the data structure of the UBM write command, and Figure 6-32 shows the data structure of the UBM read command.

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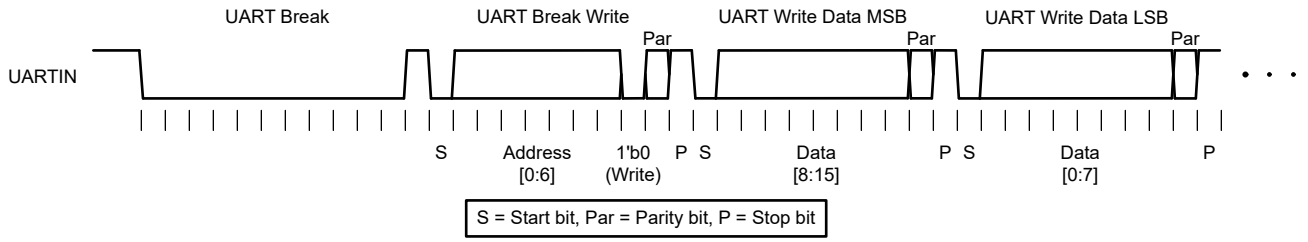


Figure 6-31. UARTIN Break Write Data Format

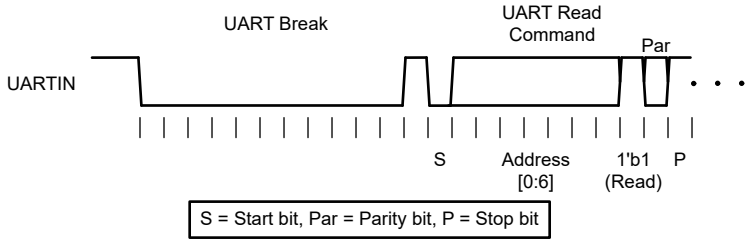


Figure 6-32. UARTIN Break Read Data Format

Figure 6-33 shows the UARTOUT data frame with details of the status bits produced by the AFEx81H1. See Table 6-12 for details.

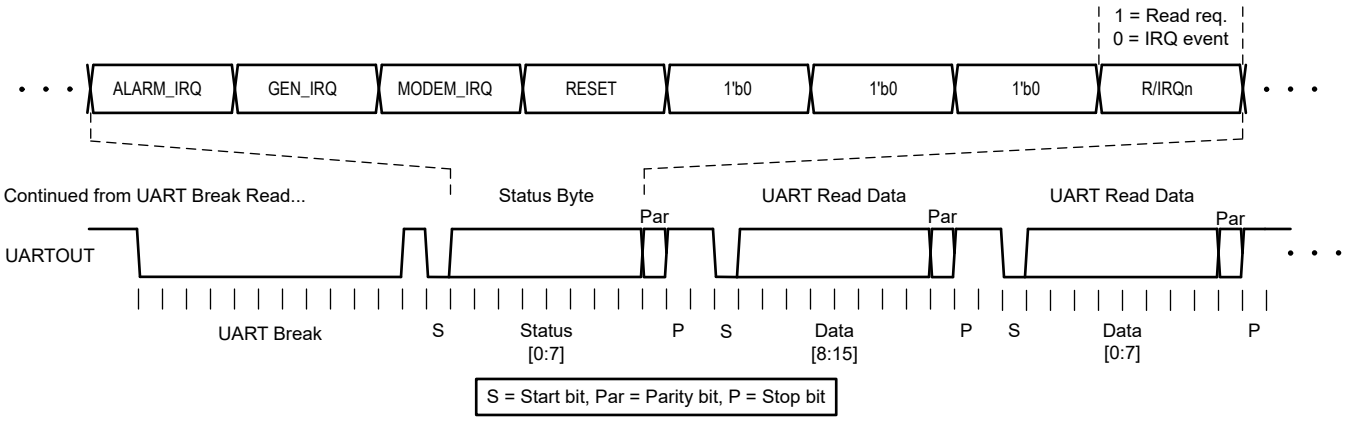


Figure 6-33. UARTOUT Break Data Format

6.5.3.1.1 Interface With FIFO Buffers and Register Map

In UBM, the HART data characters are interleaved with break commands for register map access or interrupt reporting.

The device reports parity and frame errors received on UARTIN. These status bits can be found in the GEN_STATUS register and are maskable to create IRQ events.

Avoid the large gaps between the HART bytes. The HART standard has a gap specification of 11 bit times (11 × $t_{BAUDHART}$ ms); therefore, gaps longer than 10.5 HART bit times (10.5 × $t_{BAUDHART}$ ms) can cause a gap error in the HART modem.

The following timing diagrams illustrate examples of microcontroller communication with the device registers, as well as HART transmit and receive data transfers.

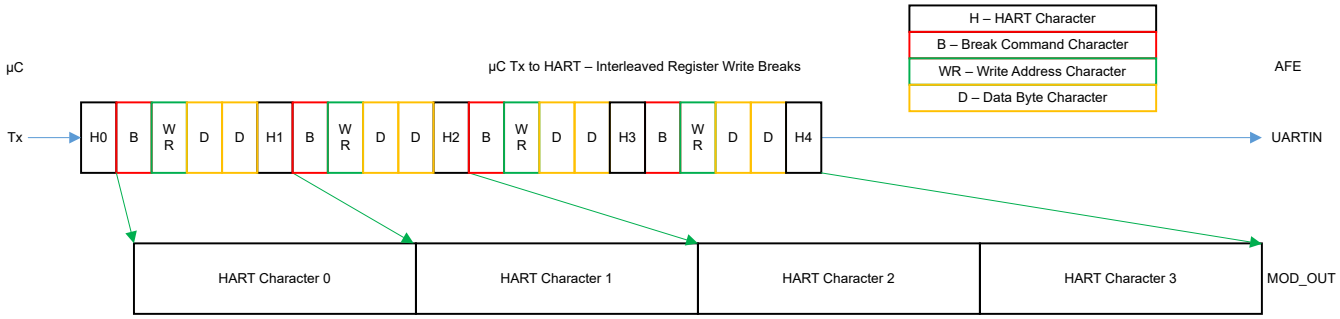


Figure 6-34. Interleaved HART Transmit With UBM Register Writes

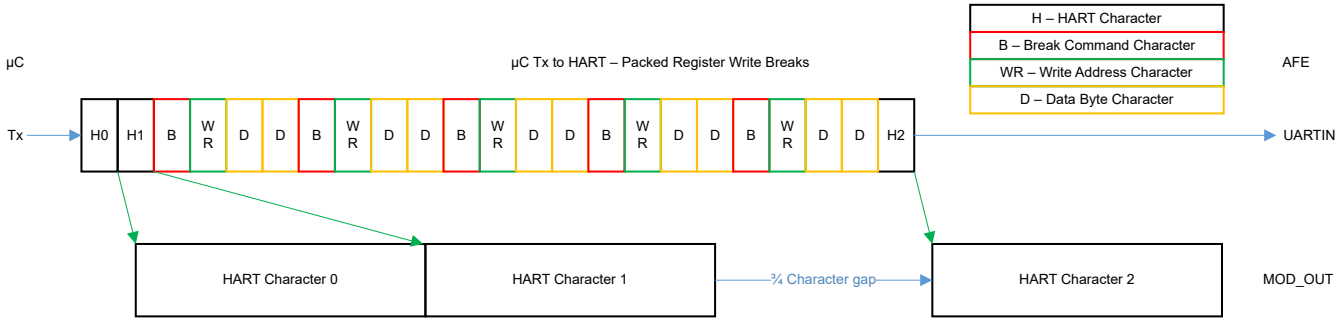


Figure 6-35. Packed HART Transmit With UBM Register Writes

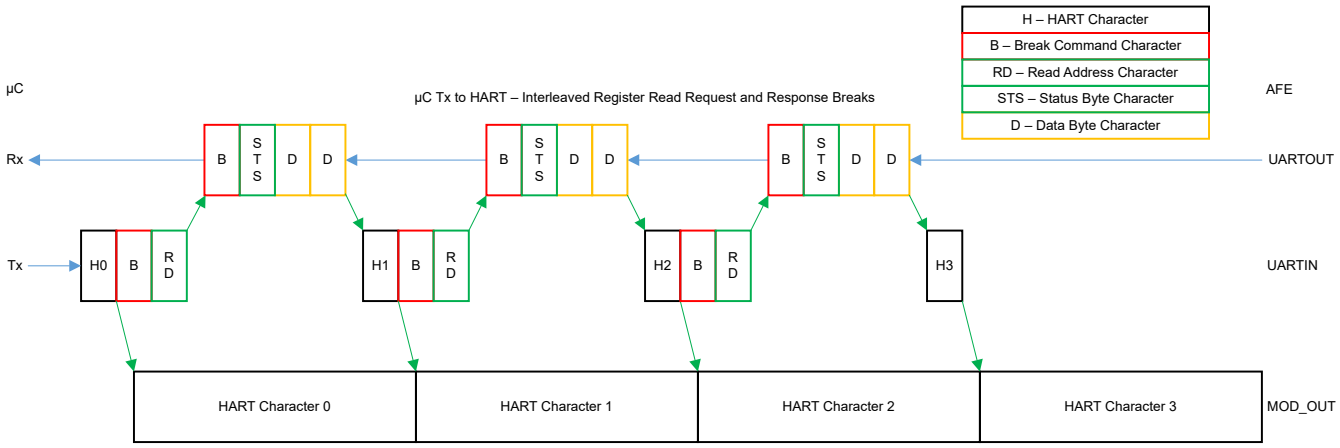


Figure 6-36. Interleaved HART Transmit With UBM Register Read Requests and Responses

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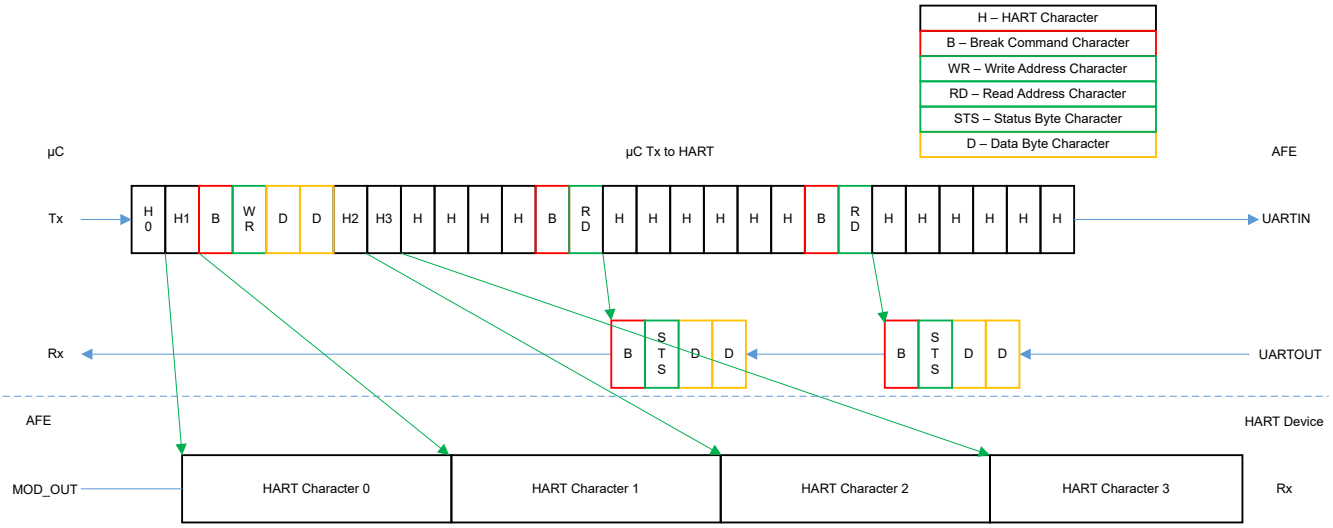


Figure 6-37. Packed HART Transmit With UBM Register Write and Read Requests and Responses

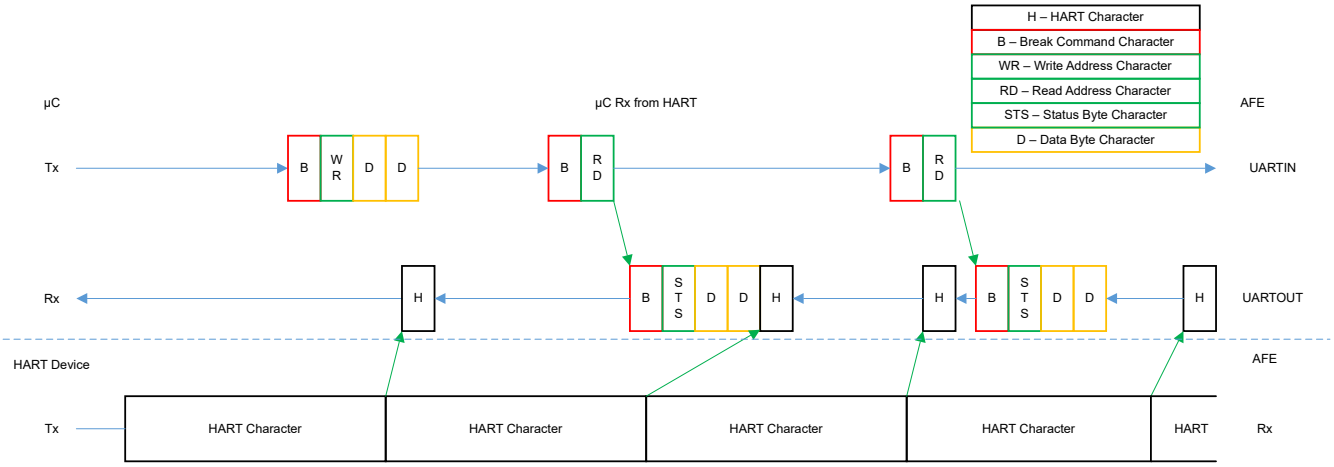


Figure 6-38. Interleaved HART Receive With UBM Register Write and Read Requests and Responses

6.5.4 Status Bits

In SPI mode and UBM, every response from the AFEx81H1 includes a set of status bits. For SPI mode bit order, see Section 6.5.2.1. For UBM bit order, Section 6.5.3.1.

Table 6-12. Status Bits

STATUS BIT	DESCRIPTION	NOTES / REFERENCE
ALARM_IRQ	1h = ALARM_IRQ asserted 0h = Normal operation	From the GEN_STATUS(1) register. See also Section 6.3.4.
CRC_ERR (CRC enabled SPI only)	1h = CRC error detect in input frame 0h = No CRC error detected	Generated by the SPI on a frame by frame basis. See Section 6.5.2.3.
GEN_IRQ	1h = GEN_IRQ asserted 0h = Normal Operation	From the ALARM_STATUS(1) register. See also Section 6.3.4.
MODEM_IRQ	1h = MODEM_IRQ asserted 0h = Normal operation	From the GEN_STATUS(1) register. See also Section 6.3.4.
R/IRQn (UBM only)	1h = Read request 0h = IRQ event	Generated by the UART interface on a frame by frame basis. See Section 6.5.3.1 for details.
RESET	1h = First readback after RESET 0h = All other readbacks	From the GEN_STATUS register. See also Section 6.4.2.

(1) ALARM_STATUS, MODEM_STATUS, and GEN_STATUS registers contain cross-readable IRQ flags for the other registers. The ALARM_STATUS register has the GEN_IRQ and MODEM_IRQ bits. MODEM_STATUS has the GEN_IRQ and ALARM_IRQ bits. GEN_STATUS has the ALARM_IRQ and MODEM_IRQ bits. This functionality enables the system microcontroller to always get full status information by reading only one register, and thus save power.

6.5.5 Watchdog Timer

The AFEx81H1 include a watchdog timer (WDT) that is used to make sure that communication between the system controller and the device is not lost. The WDT checks that the device received a communication from the system controller within a programmable period of time. To enable this feature, set WDT.WDT_EN to 1. The WDT monitors both SPI and UBM communications.

The WDT has two limit fields: WDT.WDT_UP and WDT.WDT_LO. The WDT_UP field sets the upper time limit for the WDT. The WDT_LO field sets the lower time limit. If the WDT_LO is set to a value other than 2’b00, then the WDT acts as a window comparator. If the write occurs too quickly (less than the WDT_LO time), or too slowly (greater than the WDT_UP time), then a WDT error is asserted. When acting as a window comparator, in the event of a WDT error, the WDT resets only when a write to the WDT register occurs. If the WDT_LO is set to 2'b00, then a write to any register resets the WDT time counter. In this mode, the WDT error is asserted when the timer expires.

If enabled, the chip must have any SPI or UBM write to the device within the programmed timeout window. Otherwise, the $\overline{\text{ALARM}}$ pin asserts low, and the ALARM_STATUS.WD_FLT bit is set to 1. The WD_FLT bit is sticky. After a WD_FLT has been asserted, WDT.WDT_EN must be set to 0 to clear the WDT condition. Then the WDT can be re-enabled. The WDT condition is also cleared by issuing a software or hardware reset. After the WDT condition is clear, WD_FLT is cleared by reading the ALARM_STATUS register.

The watchdog timeout period is based on a 1200Hz clock (1.2288MHz / 1024).

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6.6 Register Maps

Table 6-13 lists the memory-mapped registers for the AFEx81H1 registers. Consider all register offset addresses not listed in Table 6-13 as reserved locations; do not modify these register contents.

Table 6-13. Register Map

ADDR (HEX)	REGISTER	BIT DESCRIPTION																
		15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
00h	NOP	NOP [15:0]																
01h	DAC_DATA	DATA [15:0]																
02h	CONFIG	RESERVED	CRC_ERR_CNT [1:0]		CLKO_DIV	CLKO_EN	RESERVED	UBM_IRQ_EN	IRQ_PIN_EN	CLR_PIN_EN	UART_DIS	UART_BAUD	CRC_EN	IRQ_POL	IRQ_LVL	DSDO	FSDO	
03h	DAC_CFG	RESERVED			PD	SR_CLK [2:0]			SR_STEP [2:0]			SR_EN	SR_MODE	RESERVED	CLR	CLR_RANGE	RANGE	
04h	DAC_GAIN	GAIN [15:0]																
05h	DAC_OFFSET	OFFSET [15:0]																
06h	DAC_CLR_CODE	CODE [15:0]																
07h	RESET	RESERVED								SW_RST [7:0]								
08h	ADC_CFG	BUF_PD	HYST [6:0]							FLT_CNT [2:0]			AIN_RANGE	EOC_PER_CH	CONV_RATE [1:0]		DIRECT_MODE	
09h	ADC_INDEX_CFG	RESERVED								STOP [3:0]				START [3:0]				
0Ah	TRIGGER	RESERVED													MBIST	SHADOW LOAD	ADC	
0Bh	SPECIAL_CFG(1)	RESERVED													OTP_LOAD_SW_RST	ALMV_POL	AIN1_ENB	
0Eh	MODEM_CFG	Tx2200Hz	RESERVED		DUPLEX_EXT	RX_HORD_EN	RX_EXT FILT_EN	TxRES	TxAMP [4:0]					HART_EN	DUPLEX	TxHPD	RTS	
0Fh	FIFO_CFG	RESERVED						FIFO_H2U_FLUSH	FIFO_U2H_FLUSH	H2U_LEVEL_SET [3:0]				U2H_LEVEL_SET [3:0]				
10h	ALARM_ACT	SD_FLT [1:0]		TEMP_FLT [1:0]		AIN1_FLT [1:0]		AIN0_FLT [1:0]		CRC_WDT_FLT [1:0]		VREF_FLT [1:0]		THERM_ERR_FLT [1:0]		THERM_WARN_FLT [1:0]		
11h	WDT	RESERVED										WDT_UP [2:0]			WDT_LO [1:0]		WDT_EN	
12h	AIN0_THRESHOLD	Hi [7:0]								Lo [7:0]								
13h	AIN1_THRESHOLD	Hi [7:0]								Lo [7:0]								
14h	TEMP_THRESHOLD	Hi [7:0]								Lo [7:0]								
15h	FIFO_U2H_WR	RESERVED							PARITY	DATA [7:0]								
16h	UBM(2)	RESERVED															REG_MODE	
1Dh	ALARM_STATUS_MASK	RESERVED		SD_FLT	OSC_FAIL	RESERVED			OTP_CRC_ERR	CRC_FLT	WD_FLT	VREF_FLT	ADC_AIN1_FLT	ADC_AIN0_FLT	ADC_TEMP_FLT	THERM_ERR_FLT	THERM_WARN_FLT	
1Eh	GEN_STATUS_MASK	RESERVED					MBIST_DONE	MBIST_FAIL	RESERVED	SR_BUSYn	ADC_EOC	RESERVED		BREAK_FRAME_ERR	BREAK_PARITY_ERR	UART_FRAME_ERR	UART_PARITY_ERR	

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Table 6-13. Register Map (continued)

ADDR (HEX)	REGISTER	BIT DESCRIPTION															
		15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1Fh	MODEM_STATUS_MASK	RESERVED			GAP_ERR	FRAME_ERR	PARITY_ERR	FIFO_H2U_LEVEL_FLAG	FIFO_H2U_FULL_FLAG	FIFO_H2U_EMPTY_FLAG	FIFO_U2H_LEVEL_FLAG	FIFO_U2H_FULL_FLAG	FIFO_U2H_EMPTY_FLAG	CD_DE ASSERT	CD_ ASSERT	CTS_DE ASSERT	CTS_ ASSERT
20h	ALARM_STATUS	GEN_IRQ	MODEM_IRQ	SD_FLT	OSC_FAIL	CRC_CNT [1:0]		OTP_LOADEDn	OTP_CRC_ERR	CRC_FLT	WD_FLT	VREF_FLT	ADC_AIN1_FLT	ADC_AIN0_FLT	ADC_TEMP_FLT	THERM_ERR_FLT	THERM_WARN_FLT
21h	GEN_STATUS	ALARM_IRQ	MODEM_IRQ	RESERVED	OTP_BUSY	RESERVED	MBIST_DONE	MBIST_FAIL	RESET	SR_BUSYn	ADC_EOC	ADC_BUSY	PVDD_HI	BREAK_FRAME_ERR	BREAK_PARITY_ERR	UART_FRAME_ERR	UART_PARITY_ERR
22h	MODEM_STATUS	ALARM_IRQ	GEN_IRQ	RESERVED	GAP_ERR	FRAME_ERR	PARITY_ERR	FIFO_H2U_LEVEL_FLAG	FIFO_H2U_FULL_FLAG	FIFO_H2U_EMPTY_FLAG	FIFO_U2H_LEVEL_FLAG	FIFO_U2H_FULL_FLAG	FIFO_U2H_EMPTY_FLAG	CD_DE ASSERT	CD_ ASSERT	CTS_DE ASSERT	CTS_ ASSERT
23h	ADC_FLAGS	RESERVED							SD4_FAIL	SD3_FAIL	SD2_FAIL	SD1_FAIL	SD0_FAIL	TEMP_FAIL	AIN1_FAIL	AIN0_FAIL	RESERVED
24h	ADC_AIN0	RESERVED				DATA [11:0]											
25h	ADC_AIN1	RESERVED				DATA [11:0]											
26h	ADC_TEMP	RESERVED				DATA [11:0]											
27h	ADC_SD_MUX	RESERVED				DATA [11:0]											
28h	ADC_OFFSET	RESERVED				DATA [11:0]											
2Ah	FIFO_H2U_RD	LEVEL [3:0]				LEVEL_FLAG	FULL_FLAG	EMPTY_FLAG	PARITY	DATA [7:0]							
2Bh	FIFO_STATUS	H2U_LEVEL [3:0]				H2U_LEVEL_FLAG	H2U_FULL_FLAG	H2U_EMPTY_FLAG	RESERVED	U2H_LEVEL [3:0]				U2H_LEVEL_FLAG	U2H_FULL_FLAG	U2H_EMPTY_FLAG	RESERVED
2Ch	DAC_OUT	DATA [15:0]															
2Dh	ADC_OUT	RESERVED				DATA [11:0]											
2Eh	ADC_BYP	DATA_BYP_EN	OFST_BYP_EN	DIS_GND_SAMP	RESERVED	DATA [11:0]											
2Fh	FORCE_FAIL	CRC_FLT	VREF_FLT	THERM_ERR_FLT	THERM_WARN_FLT	RESERVED		SD4_HI_FLT	SD4_LO_FLT	SD3_HI_FLT	SD3_LO_FLT	SD2_HI_FLT	SD2_LO_FLT	SD1_HI_FLT	SD1_LO_FLT	SD0_HI_FLT	SD0_LO_FLT

(1) The SPECIAL_CFG register can only be reset with POR, and does not respond to the $\overline{\text{RESET}}$ pin or SW_RST command.
(2) The UBM register can only be accessed with a UBM command.

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6.6.1 AFEx81H1 Registers

Complex bit access types are encoded to fit into small table cells. The following table shows the codes that are used for access types in this section.

Table 6-14. AFEx81H1 Access-Type Codes

Access Type	Code	Description
Read Type		
R	R	Read
Write Type		
W	W	Write
W	WO	Write only
W	WSC	Write self clear
Reset or Default Value		
-n		Value after reset or the default value
Register Array Variables		
i,j,k,l,m,n		When used in a register name, an offset, or an address, these variables refer to the value of a register array where the register is part of a group of repeating registers. The register groups form a hierarchical structure and the array is represented with a formula.
y		When used in a register name, an offset, or an address, this variable refers to the value of a register array.

6.6.1.1 NOP Register (Offset = 0h) [Reset = 0000h]

Return to the Register Map.

Table 6-15. NOP Register Field Descriptions

Bit	Field	Type	Reset	Description
15-0	NOP	WO	0h	No operation. Data written to this field have no effect. Always reads zeros.

6.6.1.2 DAC_DATA Register (Offset = 1h) [Reset = 0000h]

Return to the Register Map.

DAC code for VOUT.

Table 6-16. DAC_DATA Register Field Descriptions

Bit	Field	Type	Reset	Description
15-0	DATA	R/W	0h	Data. DAC code for VOUT.

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6.6.1.3 CONFIG Register (Offset = 2h) [Reset = 0036h]

Return to the Register Map.

Table 6-17. CONFIG Register Field Descriptions

Bit	Field	Type	Reset	Description
15	RESERVED	R	0h	
14-13	CRC_ERR_CNT	R/W	0h	CRC Errors Count Limit Sets the numbers of consecutive SPI CRC frames that must have errors before the status bits is set. 0h = 1 (default); 1h = 2; 2h = 4; 3h = 8
12	CLKO_DIV	R/W	0h	CLKO Divider Divide the clock by 128 to output to CLKO. 0h = Divider disabled, output 1.2288MHz (default) 1h = Divider enabled, output 9600Hz
11	CLKO_EN	R/W	0h	CLKO Enable Enable the internal oscillator to be driven on CLKO pin. 0h = Disabled (default); 1h = Enabled
10	RESERVED	R	0h	
9	UBM_IRQ_EN	R/W	0h	UBM IRQ Enable Enable IRQ to be sent on UARTOUT through UBM. 0h = Disabled (default); 1h = Enabled
8	IRQ_PIN_EN	R/W	0h	IRQ Pin Enable Enable IRQ pin functionality. 0h = Disabled (default); 1h = Enabled
7	CLR_PIN_EN	R/W	0h	Clear Input Pin Enable Enable pin-based transition to the CLEAR state in UBM. 0h = Disabled (default); 1h = SDI pin configured as clear input pin
6	UART_DIS	R/W	0h	UART Disable Disable UART functionality. 0h = UART Enabled (default); 1h = UART Disabled
5	UART_BAUD	R/W	1h	UART Baud Configure BAUD rate for UART. 0h = 1200 baud (no break); 1h = 9600 baud (Break mode) (default)
4	CRC_EN	R/W	1h	CRC Enable Enable CRC for SPI. 0h = Disabled; 1h = Enabled (default)
3	IRQ_POL	R/W	0h	IRQ Polarity 0h = Active low (default); 1h = Active high
2	IRQ_LVL	R/W	1h	IRQ Level 0h = Edge sensitive; 1h = Level sensitive (default)
1	DSDO	R/W	1h	SDO Hi-Z 0h = Drive SDO during $\overline{CS}$ = 0; 1h = SDO always Hi-Z (default)
0	FSDO	R/W	0h	Fast SDO SDO is driven on negative edge of SCLK. 0h = drive SDO on rising edge of SCLK (launching edge) (default) 1h = drive SDO on falling edge of SCLK (capture edge 1/2 clock early)

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6.6.1.4 DAC_CFG Register (Offset = 3h) [Reset = 0B00h]

Return to the Register Map.

Table 6-18. DAC_CFG Register Field Descriptions

Bit	Field	Type	Reset	Description
15-13	RESERVED	R/W	0h	
12	PD	R/W	0h	DAC Output Buffer Power-down DAC output set to Hi-Z in power-down. 0h = DAC output buffer enabled (default) 1h = DAC output buffer disabled
11-9	SR_CLK	R/W	5h	Slew Clock Rate 0h = 307.2kHz 1h = 153.6kHz 2h = 76.8kHz 3h = 38.4kHz 4h = 19.2kHz 5h = 9600Hz (default) 6h = 4800Hz 7h = 2400Hz
8-6	SR_STEP	R/W	4h	Slew Step Size 0h = 1 code 1h = 2 codes 2h = 4 codes 3h = 8 codes 4h = 16 codes (default) 5h = 32 codes 6h = 64 codes 7h = 128 codes
5	SR_EN	R/W	0h	Slew Enable Enables slew on the output voltage. 0h = Disabled (default) 1h = Enabled
4	SR_MODE	R/W	0h	Slew Mode Output slew rate mode select. 0h = Linear Slew (default) 1h = Sinusoidal Slew
3	RESERVED	R	0h	
2	CLR	R/W	0h	CLEAR State 0h = Normal operation (default) 1h = Force the DAC to the CLEAR state
1	CLR_RANGE	R/W	0h	Clear Range Sets DAC CLEAR state output range. 0h = 0.15V to 1.25V (default) 1h = 0.2V to 1.0V
0	RANGE	R/W	0h	Range Sets DAC output range during normal operation. 0h = 0.15V to 1.25V (default) 1h = 0.2V to 1.0V

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6.6.1.5 DAC_GAIN Register (Offset = 4h) [Reset = 8000h]

Return to the Register Map.

Table 6-19. DAC_GAIN Register Field Descriptions

Bit	Field	Type	Reset	Description
15-0	GAIN	R/W	8000h	Gain Set the gain of the DAC output from 0.5 – 1.499985. For example: 0000h = 0.5 8000h = 1.0 (default) FFFFh = 1.499985

6.6.1.6 DAC_OFFSET Register (Offset = 5h) [Reset = 0000h]

Return to the Register Map.

Table 6-20. DAC_OFFSET Register Field Descriptions

Bit	Field	Type	Reset	Description
15-0	OFFSET	R/W	0h	Offset Adjust the offset of the DAC output, 2's complement number. For example: 0000h = 0 (default) FFFFh = –1

6.6.1.7 DAC_CLR_CODE Register (Offset = 6h) [Reset = 0000h]

Return to the Register Map.

Table 6-21. DAC_CLR_CODE Register Field Descriptions

Bit	Field	Type	Reset	Description
15-0	CODE	R/W	0h	CLEAR State DAC Code DAC code applied in the CLEAR state. See *DAC Register Structure and CLEAR State*.

6.6.1.8 RESET Register (Offset = 7h) [Reset = 0000h]

Return to the Register Map.

Table 6-22. RESET Register Field Descriptions

Bit	Field	Type	Reset	Description
15-8	RESERVED	R	0h	
7-0	SW_RST	WSC	0h	Software Reset Write ADh to initiate software reset.

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6.6.1.9 ADC_CFG Register (Offset = 8h) [Reset = 8810h]

Return to the Register Map.

Table 6-23. ADC_CFG Register Field Descriptions

Bit	Field	Type	Reset	Description
15	BUF_PD	R/W	1h	ADC Buffer Power-Down 0h = ADC buffer enabled; 1h = ADC buffer powered down (default)
14-8	HYST	R/W	8h	Hysteresis The number of codes of hysteresis used when a threshold is exceeded for an ADC measurement of AIN0/AIN1/TEMP.
7-5	FLT_CNT	R/W	0h	Fault Count Number of successive faults to trip an alarm. Number of successive faults is programmed value + 1 (1-8 faults).
4	AIN_RANGE	R/W	1h	ADC Analog Input Range Can only be set if PVDD ≥ 2.7V to use 2.5V range for AIN0 and AIN1 inputs. 0h = 2 × VREF; 1h = 1 × VREF (default)
3	EOC_PER_CH	R/W	0h	ADC End-of-Conversion for Every Channel Sends an EOC pulse at the end of each channel instead of at the end of all the channels. 0h = EOC after last channel (default); 1h = EOC for every channel
2-1	CONV_RATE	R/W	0h	ADC Conversion Rate This setting only affects the conversion rate for channels AIN0 and AIN1. Rates are based on a 76.8kHz ADC clock. All other channels use 2560Hz. 0h = 3840Hz (default) 1h = 2560Hz 2h = 1280Hz 3h = 640Hz
0	DIRECT_MODE	R/W	0h	Direct Mode Enable 0h = Auto mode (default); 1h = Direct mode

6.6.1.10 ADC_INDEX_CFG Register (Offset = 9h) [Reset = 0080h]

Return to the Register Map.

The ADC custom channel sequencing configuration is shown in Table 6-24.

Table 6-24. ADC_INDEX_CFG Register Field Descriptions

Bit	Field	Type	Reset	Description
15-8	RESERVED	R	0h	
7-4	STOP	R/W	8h	Custom Channel Sequencer Stop Index CCS index to stop ADC sequence. Must be ≥ START. If not, STOP is forced to = START. 0h = OFFSET 1h = AIN0 2h = AIN1 3h = TEMP 4h = SD0 (VREF) 5h = SD1 (PVDD) 6h = SD2 (VDD) 7h = SD3 (ZTAT) 8h = SD4 (VOUT) (default) 9h through Fh = GND
3-0	START	R/W	0h	Custom Channel Sequencer Start Index CCS index to start ADC sequence. 0h through Fh = Same as STOP field (0h is default)

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6.6.1.11 TRIGGER Register (Offset = Ah) [Reset = 0000h]

Return to the Register Map.

Table 6-25. TRIGGER Register Field Descriptions

Bit	Field	Type	Reset	Description
15-3	RESERVED	R	0h	
2	MBIST	WSC	0h	Memory Built-In Self-Test Trigger This trigger initiates an MBIST on the SRAM that is used for the FIFO. During this time communication to/from HART does not work as MBIST takes over the control of the SRAM.
1	SHADOWLOAD	WSC	0h	Shadow Load Trigger This trigger initiates the loading of the OTP array into the parallel latches. If an OTP CRC error is detected, assert this trigger to try and reload the OTP into the memory locations.
0	ADC	WSC	0h	ADC Trigger In auto mode, this bit enables or disables the conversions. Manually set to 1 (enable) or 0 (disable). In direct mode, set this bit to start a conversion sequence. The bit is cleared at the end of the sequence. To stop a sequence prematurely, manually clear this bit.

6.6.1.12 SPECIAL_CFG Register (Offset = Bh) [Reset = 0000h]

Return to the Register Map.

Table 6-26. SPECIAL_CFG Register Field Descriptions

Bit	Field	Type	Reset	Description
15-3	RESERVED	R	0h	
2	OTP_LOAD_SW_RST	R/W	0h	OTP (One Time Programmable Factory Trimmed Registers) LOAD with SW RESET OTP reloads with the assertion of a software reset (SW_RST). 0h = No reload with SW_RST 1h = Reload with SW_RST
1	ALMV_POL	R/W	0h	Alarm Voltage Polarity This register bit is ORed with the POL_SEL/AIN1 pin (if AIN1_ENB bit is low) to control the VOUT during a hardware reset condition or if alarm is active and alarm action is set appropriately. The following Boolean function is implemented for the internal signal ALMV_POL_o that sets the VOUT voltage: ALMV_POL_o = ALMV_POL OR (POL_SEL/AIN1 AND NOT AIN1_ENB) 0h = Low (0V) 1h = High (2.5V)
0	AIN1_ENB	R/W	0h	AIN1 Pin Enable This bit determines whether the POL_SEL/AIN1 pin acts as alarm voltage polarity control bit or an input channel to the ADC. 0h = AIN1 pin acts as alarm voltage polarity bit and ADC converts GND 1h = AIN1 pin is an active channel to the ADC

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6.6.1.13 MODEM_CFG Register (Offset = Eh) [Reset = 0040h]

Return to the Register Map.

Table 6-27. MODEM_CFG Register Field Descriptions

Bit	Field	Type	Reset	Description
15	Tx2200Hz	R/W	0h	Transmit 2200Hz Only By not sending data to the FIFO buffer and asserting RTS, the user can transmit multiples of 1200Hz as long as RTS is asserted. By setting this bit the user can transmit multiples of 2200Hz. Setting this bit prevents data in the FIFO buffer from being correctly transmitted. If using this bit there is no need to use the FIFO buffer. 0h = Transmit 1200Hz and 2200Hz (default) 1h = Transmit only 2200Hz
14-13	RESERVED	R	0h	
12	DUPLEX_EXT	R/W	0h	Duplex External Mode Allows full duplex mode but expects the connection of MOD_OUT to RX_IN to be made externally. 0h = Internal duplex connection (default) 1h = External duplex connection
11	RX_HORD_EN	R/W	0h	High Order Filter Enable Enables a higher order filter on HART_RX. 0h = Disable (default); 1h = Enable
10	RX_EXTFILT_EN	R/W	0h	External Filter Enable Enables the use of an external filter for HART_RX. If enabled, then connect the HART signal to RX_INF. 0h = Use internal filter (default); 1h = Use external filter
9	TxRES	R/W	0h	HART Transmit Resolution 0h = 32 steps per period (default) at 38.4kHz update rate for 1200 baud 1h = 128 steps per period at 153.6kHz update rate for 1200 baud 128-step per period waveform consumes more power.
8-4	TxAMP	R/W	4h	Transmit Amplitude HART Tx amplitude. 00h = 400mV$_{PP}$; 01h = 425mV$_{PP}$ 02h = 450mV$_{PP}$; 03h = 475mV$_{PP}$ 04h = 500mV$_{PP}$ (default); 05h = 525mV$_{PP}$ 06h = 550mV$_{PP}$; 07h = 575mV$_{PP}$ 08h = 600mV$_{PP}$; 09h = 625mV$_{PP}$ 0Ah = 650mV$_{PP}$; 0Bh = 675mV$_{PP}$ 0Ch = 700mV$_{PP}$; 0Dh = 725mV$_{PP}$ 0Eh = 750mV$_{PP}$; 0Fh = 775mV$_{PP}$ 10h through 1Fh = 800mV$_{PP}$
3	HART_EN	R/W	0h	HART Enable Enable the HART Tx and Rx. 0h = Disable (default); 1h = Enable
2	DUPLEX	R/W	0h	Duplex Mode Enable internal connection of Tx to Rx for debug and testing. 0h = Normal operation (default); 1h = Duplex enabled
1	TxHPD	R/W	0h	HART Tx DAC Output Buffer Hi-Z in Rx Mode or When Disabled 0h = HART Tx DAC output is set to midcode with 50kΩ output impedance (default) 1h = HART Tx DAC is Hi-Z in Rx mode or when disabled. Users can set the default voltage level with an external circuit.
0	RTS	R/W	0h	Request To Send Starts transmitting a carrier on MOD_OUT pin. 0h = No action (default) 1h = Request to send. Device starts modulating the MOD_OUT pin if CD = 0.

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6.6.1.14 FIFO_CFG Register (Offset = Fh) [Reset = 00F0h]

Return to the Register Map.

Table 6-28. FIFO_CFG Register Field Descriptions

Bit	Field	Type	Reset	Description
15-10	RESERVED	R	0h	
9	FIFO_H2U_FLUSH	WSC	0h	Flush HART-to-µC FIFO (FIFO_H2U) Clear the pointers for the FIFO_H2U.
8	FIFO_U2H_FLUSH	WSC	0h	Flush µC-to-HART FIFO (FIFO_U2H) Clear the pointers for the FIFO_U2H.
7-4	H2U_LEVEL_SET	R/W	Fh	FIFO_H2U FIFO Level Flag Trip Set Sets the level for FIFO_H2U at which the Level Flag trips. This is a (>) comparison. Because the FIFO size is 5 bits wide, the LSB is not used with this 4-bit setting. Only change this field while MODEM_CFG.HART_EN = 0.
3-0	U2H_LEVEL_SET	R/W	0h	FIFO_U2H FIFO Level Flag Trip Set Sets the level for FIFO_U2H at which the Level Flag trips. This is a (<) comparison. Because the FIFO size is 5 bits wide, the LSB is not used with this 4-bit setting. Only change this field while MODEM_CFG.HART_EN = 0.

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6.6.1.15 ALARM_ACT Register (Offset = 10h) [Reset = 8020h]

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Table 6-29. ALARM_ACT Register Field Descriptions

Bit	Field	Type	Reset	Description
15-14	SD_FLT	R/W	2h	Self-Diagnostic Fault Action These bits set the device action after a self-diagnostic fault. 0h = No Action 1h = Set DAC to CLEAR state 2h = Switch to alarm voltage determined by ALMV_POL (default) 3h = Place DAC into Hi-Z (power-down)
13-12	TEMP_FLT	R/W	0h	TEMP Fault Action These bits set the device action if the ADC temperature is outside the TEMP_THRESHOLD Hi or Lo thresholds. 0h through 3h = Same as SD_FLT field (default 0h)
11-10	AIN1_FLT	R/W	0h	AIN1 Fault Action These bits set the device action if the ADC AIN1 channel is outside the AIN1_THRESHOLD Hi or Lo thresholds. 0h through 3h = Same as SD_FLT field (default 0h)
9-8	AIN0_FLT	R/W	0h	AIN0 Fault Action These bits set the device action if the ADC AIN0 channel is outside the AIN0_THRESHOLD Hi or Lo thresholds. 0h through 3h = Same as SD_FLT field (default 0h)
7-6	CRC_WDT_FLT	R/W	0h	CRC and WDT Fault Action These bits set the device action when a SPI CRC or SPI Watchdog Timeout error occurs. 0h through 3h = Same as SD_FLT field (default 0h)
5-4	VREF_FLT	R/W	2h	VREF Fault Action These bits set the device action when a fault is detected on VREF. 0h through 3h = Same as SD_FLT field a
3-2	THERM_ERR_FLT	R/W	0h	Thermal Error Fault Action These bits set the device action when a high temperature error occurs (> 130°C). 0h through 3h = Same as SD_FLT field (default 0h)
1-0	THERM_WARN_FLT	R/W	0h	Thermal Warning Fault Action These bits set the device action when a high temperature warning occurs (> 85°C). 0h through 3h = Same as SD_FLT field (default 0h)

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6.6.1.16 WDT Register (Offset = 11h) [Reset = 0018h]

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Table 6-30. WDT Register Field Descriptions

Bit	Field	Type	Reset	Description
15-6	RESERVED	R	0h	
5-3	WDT_UP	R/W	3h	Watchdog Timer (WDT) Upper Limit If the WDT is enabled and the timer exceeds the programmed value, a WDT error is asserted. All times are based on 1200Hz clock (1.2288MHz / 1024). 0h = 53ms (64 clocks) 1h = 106ms (128 clocks) 2h = 427ms (512 clocks) 3h = 853ms (1024 clocks, default) 4h = 1.7s (2048 clocks) 5h = 2.56s (3072 clocks) 6h = 3.41s (4096 clocks) 7h = 5.12s (6144 clocks)
2-1	WDT_LO	R/W	0h	WDT Lower Limit If the WDT is enabled and the WDT Lower Limit is enabled, then only a write to this register resets the WDT timer. If the write occurs before the WDT Lower Limit time, or after the WDT Upper Limit time, then a WDT error is asserted. If WDT Lower Limit is disabled, then a write to any register resets the timer. This is true for both SPI and UART Break modes. All times are based on 1200Hz clock (1.2288MHz / 1024). 0h = Disabled (default) 1h = 53ms (64 clocks) 2h = 106ms (128 clocks) 3h = 427ms (512 clocks)
0	WDT_EN	R/W	0h	WDT Enable 0h = Disabled (default); 1h = Enabled

6.6.1.17 AIN0_THRESHOLD Register (Offset = 12h) [Reset = FF00h]

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Table 6-31. AIN0_THRESHOLD Register Field Descriptions

Bit	Field	Type	Reset	Description
15-8	Hi	R/W	FFh	High Threshold for Channel AIN0 {[11:4],4b1111} This value is compared (>) against AIN0 data bits[11:0].
7-0	Lo	R/W	0h	Low Threshold for Channel AIN0 {[11:4],4b0000} This value is compared (<) against AIN0 data bits[11:0].

6.6.1.18 AIN1_THRESHOLD Register (Offset = 13h) [Reset = FF00h]

Return to the Register Map.

Table 6-32. AIN1_THRESHOLD Register Field Descriptions

Bit	Field	Type	Reset	Description
15-8	Hi	R/W	FFh	High Threshold for Channel AIN1 {[11:4],4b1111} This value is compared (>) against AIN1 data bits[11:0].
7-0	Lo	R/W	0h	Low Threshold for Channel AIN1 {[11:4],4b0000} This value is compared (<) against AIN1 data bits[11:0].

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6.6.1.19 TEMP_THRESHOLD Register (Offset = 14h) [Reset = FF00h]

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Table 6-33. TEMP_THRESHOLD Register Field Descriptions

Bit	Field	Type	Reset	Description
15-8	Hi	R/W	FFh	High Threshold for Channel TEMP {[11:4],4b1111} This value is compared (>) against TEMP data bits[11:0].
7-0	Lo	R/W	0h	Low Threshold for Channel TEMP {[11:4],4b0000} This value is compared (<) against TEMP data bits[11:0].

6.6.1.20 FIFO_U2H_WR Register (Offset = 15h) [Reset = 0000h]

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This register controls the HART to microcontroller FIFO buffer.

Table 6-34. FIFO_U2H_WR Register Field Descriptions

Bit	Field	Type	Reset	Description
15-9	RESERVED	R	0h	
8	PARITY	WO	0h	Parity Odd parity bit to be transmitted with data. This field can only be written by SPI and affects the FIFO when CONFIG.UART_DIS = 1. Otherwise writes to this register are ignored.
7-0	DATA	WO	0h	Data Byte This field can only be written by SPI and affects the FIFO when CONFIG.UART_DIS = 1. Otherwise writes to this register are ignored.

6.6.1.21 UBM Register (Offset = 16h) [Reset = 0000h]

Return to the Register Map.

Table 6-35. UBM Register Field Descriptions

Bit	Field	Type	Reset	Description
15-1	RESERVED	R	0h	
0	REG_MODE	R/W	0h	Register Mode Configure the rest of the Register Map to be accessed by UART break mode (UBM) or SPI. This register can only be written by the UART Break communication. 0h = SPI Mode (default) 1h = UART Break Mode

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6.6.1.22 ALARM_STATUS_MASK Register (Offset = 1Dh) [Reset = EFDFh]

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Table 6-36. ALARM_STATUS_MASK Register Field Descriptions

Bit	Field	Type	Reset	Description
15-14	RESERVED	R	3h	
13	SD_FLT	R/W	1h	SD Fault Mask 0h = Fault asserts IRQ 1h = The mask prevents IRQ or Alarm being triggered (default). The status is always set if the condition exists.
12	OSC_FAIL	R/W	0h	OSC_FAIL Fault Mask Same as SD Fault Mask (default 0h).
11-9	RESERVED	R	7h	
8	OTP_CRC_ERR	R/W	1h	OTP CRC Error Mask Same as SD Fault Mask (default 1h).
7	CRC_FLT	R/W	1h	SPI CRC Fault Mask Same as SD Fault Mask (default 1h).
6	WD_FLT	R/W	1h	Watchdog Fault Mask Same as SD Fault Mask (default 1h).
5	VREF_FLT	R/W	0h	VREF Fault Mask Same as SD Fault Mask (default 0h).
4	ADC_AIN1_FLT	R/W	1h	ADC AIN1 Fault Mask Same as SD Fault Mask (default 1h).
3	ADC_AIN0_FLT	R/W	1h	ADC AIN0 Fault Mask Same as SD Fault Mask (default 1h).
2	ADC_TEMP_FLT	R/W	1h	ADC TEMP Fault Mask Same as SD Fault Mask (default 1h).
1	THERM_ERR_FLT	R/W	1h	Temperature > 130°C Error Mask Same as SD Fault Mask (default 1h).
0	THERM_WARN_FLT	R/W	1h	Temperature > 85°C Warning Mask Same as SD Fault Mask (default 1h).

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6.6.1.23 GEN_STATUS_MASK Register (Offset = 1Eh) [Reset = FFFFh]

Return to the Register Map.

Table 6-37. GEN_STATUS_MASK Register Field Descriptions

Bit	Field	Type	Reset	Description
15-11	RESERVED	R	1Fh	
10	MBIST_DONE	R/W	1h	MBIST Done Mask 0h = Fault asserts IRQ 1h = The mask prevents IRQ or Alarm being triggered (default). The status is always set if the condition exists.
9	MBIST_FAIL	R/W	1h	MBIST Failed Fault Mask Same as MBIST Done Mask (default 1h).
8	RESERVED	R	1h	
7	SR_BUSYn	R/W	1h	Slew Rate Not Busy Mask Same as MBIST Done Mask (default 1h).
6	ADC_EOC	R/W	1h	ADC End Of Conversion Mask Same as MBIST Done Mask (default 1h).
5-4	RESERVED	R	3h	
3	BREAK_FRAME_ERR	R/W	1h	Break Frame Error Fault Mask Same as MBIST Done Mask (default 1h).
2	BREAK_PARITY_ERR	R/W	1h	Break Parity Error Fault Mask Same as MBIST Done Mask (default 1h).
1	UART_FRAME_ERR	R/W	1h	UART Frame Error Fault Mask Same as MBIST Done Mask (default 1h).
0	UART_PARITY_ERR	R/W	1h	UART Parity Error Fault Mask Same as MBIST Done Mask (default 1h).

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6.6.1.24 MODEM_STATUS_MASK Register (Offset = 1Fh) [Reset = FFFFh]

Return to the Register Map.

Table 6-38. MODEM_STATUS_MASK Register Field Descriptions

Bit	Field	Type	Reset	Description
15-13	RESERVED	R	7h	
12	GAP_ERR	R/W	1h	HART Gap Error Fault Mask 0h = Fault asserts IRQ 1h = The mask prevents IRQ or Alarm being triggered (default). The status is always set if the condition exists.
11	FRAME_ERR	R/W	1h	HART Frame Error Fault Mask Same as HART Gap Error Fault Mask (default 1h).
10	PARITY_ERR	R/W	1h	HART Parity (ODD) Error Fault Mask Same as HART Gap Error Fault Mask (default 1h).
9	FIFO_H2U_LEVEL_FLAG	R/W	1h	FIFO_H2U Level Flag Mask Same as HART Gap Error Fault Mask (default 1h).
8	FIFO_H2U_FULL_FLAG	R/W	1h	FIFO_H2U Full Flag Mask Same as HART Gap Error Fault Mask (default 1h).
7	FIFO_H2U_EMPTY_FLAG	R/W	1h	FIFO_H2U Empty Flag Mask Same as HART Gap Error Fault Mask (default 1h).
6	FIFO_U2H_LEVEL_FLAG	R/W	1h	FIFO_U2H Level Flag Mask Same as HART Gap Error Fault Mask (default 1h).
5	FIFO_U2H_FULL_FLAG	R/W	1h	FIFO_U2H Full Flag Mask Same as HART Gap Error Fault Mask (default 1h).
4	FIFO_U2H_EMPTY_FLAG	R/W	1h	FIFO_U2H Empty Flag Mask Same as HART Gap Error Fault Mask (default 1h).
3	CD_DEASSERT	R/W	1h	CD Deasserted Flag Mask Same as HART Gap Error Fault Mask (default 1h).
2	CD_ASSERT	R/W	1h	CD Asserted Flag Mask Same as HART Gap Error Fault Mask (default 1h).
1	CTS_DEASSERT	R/W	1h	CTS Deasserted Flag Mask Same as HART Gap Error Fault Mask (default 1h).
0	CTS_ASSERT	R/W	1h	CTS Asserted Flag Mask Same as HART Gap Error Fault Mask (default 1h).

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6.6.1.25 ALARM_STATUS Register (Offset = 20h) [Reset = 0200h]

Return to the Register Map.

Table 6-39. ALARM_STATUS Register Field Descriptions

Bit	Field	Type	Reset	Description
15	GEN_IRQ	R	0h	General IRQ OR of all the unmasked bits in the GEN_STATUS register. 0h = All of the unmasked bits of the GEN_STATUS register are low 1h = At least one of the unmasked bits in the GEN_STATUS register is high
14	MODEM_IRQ	R	0h	Modem IRQ OR of all the unmasked bits in the MODEM_STATUS register. 0h = All of the unmasked bits of the MODEM_STATUS register are low 1h = At least one of the unmasked bits in the MODEM_STATUS register is high
13	SD_FLT	R	0h	Self Diagnostic (SD) Fault 0h = All self diagnostic channels are within threshold limits 1h = At least one of the self diagnostic channels has failed
12	OSC_FAIL	R	0h	Oscillator Fault This bit holds $\overline{\text{ALARM}}$ low and does not feed IRQ. VOUT follows the alarm voltage setting. 0h = Oscillator is toggling; 1h = Oscillator is not toggling
11-10	CRC_CNT	R	0h	CRC Fault Counter If counter limit ≤ 4 then bits[1:0] of the counter are shown here. If the counter limit = 8 then bits[2:1] of the counter are shown.
9	OTP_LOADEDn	R	1h	OTP NOT Loaded Clears when OTP has loaded at least once. Keeps $\overline{\text{ALARM}}$ asserted until OTP finishes loading. Does not feed IRQ. 0h = OTP has loaded at least once; 1h = OTP has not finished loading
8	OTP_CRC_ERR	R	0h	OTP CRC Error Maskable fault. An error occurred with the OTP CRC calculation. Sticky, cleared by reading register, unless condition still persist. 0h = No OTP CRC fault; 1h = OTP CRC fault
7	CRC_FLT	R	0h	CRC Fault Maskable fault. Invalid CRC value transmitted during SPI frame. Sticky, cleared by reading register, unless condition still persist. 0h = No CRC fault; 1h = CRC fault
6	WD_FLT	R	0h	Watchdog Timer Fault Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = No watchdog fault; 1h = Watchdog fault
5	VREF_FLT	R	0h	Invalid Reference Voltage Maskable fault. OR with FORCE_FAIL.VREF_FLT bit. Active signal, set as long as condition is true. Direct input from analog circuit. 0h = Valid VREF voltage; 1h = Invalid VREF voltage
4	ADC_AIN1_FLT	R	0h	ADC AIN1 Fault. Maskable fault. 0h = AIN1 ADC measurement within threshold limits 1h = AIN1 ADC measurement outside threshold limits
3	ADC_AIN0_FLT	R	0h	ADC AIN0 Fault. Maskable fault. 0h = AIN0 ADC measurement within threshold limits 1h = AIN0 ADC measurement outside threshold limits
2	ADC_TEMP_FLT	R	0h	ADC Temp Fault. Maskable fault. 0h = TEMP ADC measurement within threshold limits 1h = TEMP ADC measurement outside threshold limits
1	THERM_ERR_FLT	R	0h	Temperature > 130°C error. Maskable fault. OR with FORCE_FAIL.THERM_ERR_FLT bit. Active signal, set as long as condition is true. Direct input from analog circuit. 0h = Temperature ≤ 130°C; 1h = Temperature > 130°C
0	THERM_WARN_FLT	R	0h	Temperature > 85°C warning. Maskable fault. OR with FORCE_FAIL.THERM_WARN_FLT bit. Active signal, set as long as condition is true. Direct input from analog circuit. 0h = Temperature ≤ 85°C; 1h = Temperature > 85°C

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6.6.1.26 GEN_STATUS Register (Offset = 21h) [Reset = 1180h]

Return to the Register Map.

Table 6-40. GEN_STATUS Register Field Descriptions

Bit	Field	Type	Reset	Description
15	ALARM_IRQ	R	0h	Alarm IRQ OR of all the unmasked bits in the ALARM_STATUS register. 0h = All of the unmasked bits of the ALARM_STATUS register are low 1h = At least one of the unmasked bits in the ALARM_STATUS register is high
14	MODEM_IRQ	R	0h	Modem IRQ OR of all the unmasked bits in the MODEM_STATUS register. 0h = All of the unmasked bits of the MODEM_STATUS register are low 1h = At least one of the unmasked bits in the MODEM_STATUS register is high
13	RESERVED	R	0h	
12	OTP_BUSY	R	1h	OTP Busy Status = 1h at power up while the OTP is being loaded into the trim latches. 0h = OTP has completed loading into the device 1h = OTP is being loaded into the device
11	RESERVED	R	0h	
10	MBIST_DONE	R	0h	MBIST Completed. Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = MBIST has not completed; 1h = MBIST has completed
9	MBIST_FAIL	R	0h	MBIST Failed. Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = MBIST has passed; 1h = MBIST has failed
8	RESET	R	1h	Device Reset Occurred. Status only. Does not feed IRQ. Sticky, cleared by reading register, unless condition still persist. 0h = Device has not reset since last read of register 1h = Device has reset since last read of register
7	SR_BUSYn	R	1h	Slew Rate Not Busy. Maskable fault. 0h = DAC is slewing to the target code 1h = DAC_OUT has reached the DAC_DATA. If slew rate is disabled, then this signal produces a rising edge within 3 internal clock cycles. If slew rate is enabled, this signal creates an IRQ event when the DAC_OUT has reached the DAC_DATA. At this time, slew rate can be safely disabled. If slew rate is disabled prior to DAC_OUT = DAC_DATA then a jump of DAC_OUT occurs. This can cause an unwanted fast transition on VOUT.
6	ADC_EOC	R	0h	ADC End of Conversion (EOC). Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = No EOC since last read of register; 1h = ADC end of conversion
5	ADC_BUSY	R	0h	ADC Busy. Status only. Does not feed IRQ. Active signal, set as long as condition is true. 0h = No ADC activity; 1h = ADC is actively converting
4	PVDD_HI	R	0h	PVDD High. Status only. Does not feed IRQ. Set as long as condition is true. 0h = PVDD < 2.7V; 1h = PVDD ≥ 2.7V
3	BREAK_ FRAME_ERR	R	0h	Incorrect Stop Bit During Break Character. Maskable fault. Applies to UARTIN. Sticky, cleared by reading register, unless condition still persist. 0h = No break frame error; 1h = Break frame error
2	BREAK_ PARITY_ERR	R	0h	Incorrect parity (ODD) bit during break character. Maskable fault. Applies to UARTIN. Sticky, cleared by reading register, unless condition still persist. 0h = No break parity error; 1h = Break parity error
1	UART_ FRAME_ERR	R	0h	Incorrect Stop Bit During UART Character. Maskable fault. Applies to UARTIN. Sticky, cleared by reading register, unless condition still persist. 0h = No UART frame error; 1h = UART frame error
0	UART_ PARITY_ERR	R	0h	Incorrect Parity (ODD) Bit During UART Character. Maskable fault. Applies to UARTIN. Sticky, cleared by reading register, unless condition still persist. 0h = No UART parity error; 1h = UART parity error

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6.6.1.27 MODEM_STATUS Register (Offset = 22h) [Reset = 009Ah]

Return to the Register Map.

Table 6-41. MODEM_STATUS Register Field Descriptions

Bit	Field	Type	Reset	Description
15	ALARM_IRQ	R	0h	Alarm IRQ OR of all the unmasked bits in the ALARM_STATUS register. 0h = All of the unmasked bits of the ALARM_STATUS register are low 1h = At least one of the unmasked bits in the ALARM_STATUS register is high
14	GEN_IRQ	R	0h	General IRQ OR of all the unmasked bits in the GEN_STATUS register. 0h = All of the unmasked bits of the GEN_STATUS register are low 1h = At least one of the unmasked bits in the GEN_STATUS register is high
13	RESERVED	R	0h	
12	GAP_ERR	R	0h	HART Gap Error. Maskable fault. Applies to RX_IN/RX_INF. Too much time (11 bit times) between HART characters. Sticky, cleared by reading register, unless condition still persist. Fatal Fault. 0h = No HART gap error; 1h = HART gap error
11	FRAME_ERR	R	0h	Incorrect Stop Bit in HART Character. Maskable fault. Applies to RX_IN/RX_INF. Sticky, cleared by reading register, unless condition still persist. Fatal Fault. 0h = No HART frame error; 1h = HART frame error
10	PARITY_ERR	R	0h	Incorrect Parity (ODD) Bit in HART Character. Maskable fault. Applies to RX_IN/RX_INF. Sticky, cleared by reading register, unless condition still persist. 0h = No HART parity error; 1h = HART parity error
9	FIFO_H2U_ LEVEL_FLAG	R	0h	FIFO HART-to-µC Level Flag. Maskable fault. If the level of the FIFO_H2U is full, then the level flag is not asserted, but the full flag is, so no information is lost. 0h = FIFO_H2U level ≤ {FIFO_CFG.H2U_LEVEL_SET[3:0], 1b1} 1h = FIFO_H2U level > {FIFO_CFG.H2U_LEVEL_SET[3:0], 1b1}
8	FIFO_H2U_ FULL_FLAG	R	0h	FIFO HART-to-µC Full Flag. Maskable fault. 0h = FIFO_H2U is not full; 1h = FIFO_H2U is full
7	FIFO_H2U_ EMPTY_FLAG	R	1h	FIFO HART-to-µC Empty Flag. Maskable fault. 0h = FIFO_H2U is not empty; 1h = FIFO_H2U is empty
6	FIFO_U2H_ LEVEL_FLAG	R	0h	FIFO µC-to-HART Level Flag. Maskable fault. FIFO_U2H < {FIFO_CFG.U2H_LEVEL_SET[3:0], 1b0}. When the FIFO_U2H is empty, this flag is set unless FIFO_CFG.U2H_LEVEL_SET = 0. This flag and the empty flag can be set at the same time. 0h = FIFO_U2H level ≥ {FIFO_CFG.U2H_LEVEL_SET[3:0], 1b0} 1h = FIFO_U2H level < {FIFO_CFG.U2H_LEVEL_SET[3:0], 1b0}
5	FIFO_U2H_ FULL_FLAG	R	0h	FIFO µC-to-HART Full Flag. Maskable fault. 0h = FIFO_U2H is not full; 1h = FIFO_U2H is full
4	FIFO_U2H_ EMPTY_FLAG	R	1h	FIFO µC-to-HART Empty Flag. Maskable fault. 0h = FIFO_U2H is not empty; 1h = FIFO_U2H is empty
3	CD_DEASSERT	R	1h	Carrier Detect Deasserted. Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = Carrier detect is asserted; 1h = Carrier detect is deasserted
2	CD_ASSERT	R	0h	Carrier Detect Asserted. Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = Carrier detect is deasserted; 1h = Carrier detect is asserted
1	CTS_DEASSERT	R	1h	Clear To Send Deasserted. Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = Clear to send is asserted; 1h = Clear to send is deasserted
0	CTS_ASSERT	R	0h	Clear To Send Asserted. Maskable fault. Sticky, cleared by reading register, unless condition still persist. 0h = Clear to send is deasserted; 1h = Clear to send is asserted

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6.6.1.28 ADC_FLAGS Register (Offset = 23h) [Reset = 0000h]

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The limits for Self Diagnostic (SD) Alarm ADC Thresholds are shown in Table 6-7.

Table 6-42. ADC_FLAGS Register Field Descriptions

Bit	Field	Type	Reset	Description
15-9	RESERVED	R	0h	
8	SD4_FAIL	R	0h	SD4 (VOUT) Limit Fail
7	SD3_FAIL	R	0h	SD3 (ZTAT) Limit Fail
6	SD2_FAIL	R	0h	SD2 (VDD) Limit Fail
5	SD1_FAIL	R	0h	SD1 (PVDD) Limit Fail
4	SD0_FAIL	R	0h	SD0 (VREF) Limit Fail
3	TEMP_FAIL	R	0h	TEMP Limit Fail
2	AIN1_FAIL	R	0h	AIN1 Limit Fail
1	AIN0_FAIL	R	0h	AIN0 Limit Fail
0	RESERVED	R	0h	

6.6.1.29 ADC_AIN0 Register (Offset = 24h) [Reset = 0000h]

Return to the Register Map.

Table 6-43. ADC_AIN0 Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	RESERVED	R	0h	
11-0	DATA	R	0h	Converted Value of Voltage on Pin AIN0

6.6.1.30 ADC_AIN1 Register (Offset = 25h) [Reset = 0000h]

Return to the Register Map.

Table 6-44. ADC_AIN1 Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	RESERVED	R	0h	
11-0	DATA	R	0h	Converted Value of Voltage on Pin AIN1

6.6.1.31 ADC_TEMP Register (Offset = 26h) [Reset = 0000h]

Return to the Register Map.

Table 6-45. ADC_TEMP Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	RESERVED	R	0h	
11-0	DATA	R	0h	Converted Value of Temperature

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6.6.1.32 ADC_SD_MUX Register (Offset = 27h) [Reset = 0000h]

Return to the Register Map.

Table 6-46. ADC_SD_MUX Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	RESERVED	R	0h	
11-0	DATA	R	0h	Converted Value of Voltage on Self-Diagnostic (SD) MUX Input

6.6.1.33 ADC_OFFSET Register (Offset = 28h) [Reset = 0000h]

Return to the Register Map.

Table 6-47. ADC_OFFSET Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	RESERVED	R	0h	
11-0	DATA	R	0h	ADC Comparator Offset This value reports the offset measured in the device, and can be used to adjust each conversion value. If ADC_BYP.OFST_BYP_EN is set, then the value in ADC_BYP.DATA is used as the offset. This value is not affected by ADC_BYP.

6.6.1.34 FIFO_H2U_RD Register (Offset = 2Ah) [Reset = 0200h]

Return to the Register Map.

Table 6-48. FIFO_H2U_RD Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	LEVEL	R	0h	Level Current Level of FIFO_H2U, bits [4:1] represented as Level[3:0]. Pre-dequeue.
11	LEVEL_FLAG	R	0h	HART-to-µC FIFO Level Flag Set when FIFO_H2U Level > {Level,1b1}. Pre-dequeue. 0h = FIFO_H2U level ≤ {Level, 1b1} 1h = FIFO_H2U level > {Level, 1b1}
10	FULL_FLAG	R	0h	HART-to-µC FIFO Full Flag. Pre-dequeue. 0h = FIFO_H2U is not full, pre-dequeue 1h = FIFO_H2U is full, pre-dequeue
9	EMPTY_FLAG	R	1h	HART-to-µC FIFO Empty Flag. Pre-dequeue. 0h = FIFO_H2U is not empty 1h = FIFO_H2U is empty
8	PARITY	R	0h	Parity Bit (ODD) Parity bit received with data on HART. This field can only be read by SPI when CONFIG.UART_DIS = 1. Otherwise reads from this register are ignored and do not dequeue FIFO. The default value is unknown until data are written to the FIFO.
7-0	DATA	R	0h	Data 8-bit data received on HART. This field can only be read by SPI when CONFIG.UART_DIS = 1. Otherwise reads from this register are ignored and do not dequeue FIFO. The default value is unknown until data are written to the FIFO.

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6.6.1.35 FIFO_STATUS Register (Offset = 2Bh) [Reset = 0202h]

Return to the Register Map.

The FIFO_STATUS register is provided to allow the user to view the state of both FIFOs without enqueuing or dequeuing data in the FIFO. This also allows the flags to be viewed without disturbing other status bits in the MODEM_STATUS register. This register is provided to enable users to check the FIFO status register without disturbing other functions within the device.

Table 6-49. FIFO_STATUS Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	H2U_LEVEL	R	0h	HART-to-µC FIFO Level Current level of FIFO_H2U, right shifted 1 bit (>>1) so only even counts are represented.
11	H2U_LEVEL_FLAG	R	0h	HART-to-µC FIFO Level Flag Set when FIFO Level > {Level,1b1}. 0h = FIFO_H2U level ≤ {Level, 1b1} 1h = FIFO_H2U level > {Level, 1b1}
10	H2U_FULL_FLAG	R	0h	HART-to-µC FIFO Full Flag Set when FIFO is full. 0h = FIFO_H2U is not full 1h = FIFO_H2U is full
9	H2U_EMPTY_FLAG	R	1h	HART-to-µC Empty Flag Set when FIFO is empty. 0h = FIFO_H2U is not empty 1h = FIFO_H2U is empty
8	RESERVED	R	0h	
7-4	U2H_LEVEL	R	0h	µC-to-HART FIFO Level Current level of FIFO_U2H, right shifted 1 bit (>>1) so only even counts are represented
3	U2H_LEVEL_FLAG	R	0h	µC-to-HART FIFO Level Flag Set when FIFO_U2H Level < {Level,1b0}. 0h = FIFO_U2H level ≥ {Level, 1b0} 1h = FIFO_U2H level < {Level, 1b0}
2	U2H_FULL_FLAG	R	0h	µC-to-HART Full Flag Set when FIFO_U2H is full. 0h = FIFO_U2H is not full 1h = FIFO_U2H is full
1	U2H_EMPTY_FLAG	R	1h	µC-to-HART Empty Flag Set when FIFO_U2H is empty. 0h = FIFO_U2H is not empty 1h = FIFO_U2H is empty
0	RESERVED	R	0h	

6.6.1.36 DAC_OUT Register (Offset = 2Ch) [Reset = 0000h]

Return to the Register Map.

Table 6-50. DAC_OUT Register Field Descriptions

Bit	Field	Type	Reset	Description
15-0	DATA	R	0h	DAC Code Applied to the Analog Circuit

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6.6.1.37 ADC_OUT Register (Offset = 2Dh) [Reset = 0000h]

Return to the Register Map.

Table 6-51. ADC_OUT Register Field Descriptions

Bit	Field	Type	Reset	Description
15-12	RESERVED	R	0h	
11-0	DATA	R	0h	ADC Data for Each Conversion Does not include ADC_OFFSET.DATA adjustment. Is not affected by ADC_BYP.DATA.

6.6.1.38 ADC_BYP Register (Offset = 2Eh) [Reset = 0000h]

Return to the Register Map.

ADC_BYP is shown in ADC_BYP Register Field Descriptions.

Table 6-52. ADC_BYP Register Field Descriptions

Bit	Field	Type	Reset	Description
15	DATA_BYP_EN	R/W	0h	Data Bypass Enable Applies ADC_BYP.DATA to the ADC channel being converted. ADC_OFFSET is ignored. Do not set OFST_BYP_EN and DATA_BYP_EN at the same time. If OFST_BYP_EN is also set, DATA_BYP_EN takes priority over OFST_BYP_EN. After a channel is converted, the ADC_BYP.DATA value appears in the readback register for the converted channel and is used to calculate faults. 0h = Data bypass disabled (default) 1h = Data bypass enabled
14	OFST_BYP_EN	R/W	0h	Offset Bypass Enable Overrides the offset register with the ADC_BYP.DATA value. When using this bit, the ADC_BYP.DATA field is processed as 2's complement. Do not set OFST_BYP_EN and DATA_BYP_EN at the same time. 0h = Offset bypass disabled (default) 1h = Offset bypass enabled
13	DIS_GND_SAMP	R/W	0h	Disable GND Sampling This bit disables the sampling of GND during SAR activity. The sampling of GND is used to fully discharge the sampling CAP to reduce channel crosstalk. 0h = GND sampling enabled (default) 1h = GND sampling disabled
12	RESERVED	R	0h	
11-0	DATA	R/W	0h	Bypass Data

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6.6.1.39 FORCE_FAIL Register (Offset = 2Fh) [Reset = 0000h]

Return to the Register Map.

Force failures for fault detection.

Table 6-53. FORCE_FAIL Register Field Descriptions

Bit	Field	Type	Reset	Description
15	CRC_FLT	R/W	0h	Force CRC Failure on SDO by Inverting the CRC Byte 0h = No force failure of CRC (default) 1h = Force failure of CRC
14	VREF_FLT	R/W	0h	Force Reference Voltage Failure. Analog signal. 0h = No force failure of VREF (default) 1h = Force failure of VREF
13	THERM_ERR_FLT	R/W	0h	Force Temperature > 130°C Thermal Error. Analog signal. 0h = No force temperature > 130°C error (default) 1h = Force temperature > 130°C error
12	THERM_WARN_FLT	R/W	0h	Force Temperature > 85°C thermal Warning. Analog signal. 0h = No force temperature > 85°C warning (default) 1h = Force temperature > 85°C warning
11-10	RESERVED	R/W	0h	
9	SD4_HI_FLT	R/W	0h	SD4 (VOUT) High Limit Failure. ADC measurement. 0h = No force failure of SD4 (VOUT) (default) 1h = Force failure of SD4 (VOUT)
8	SD4_LO_FLT	R/W	0h	SD4 (VOUT) Low limit failure. ADC measurement. 0h = No force failure of SD4 (VOUT) (default) 1h = Force failure of SD4 (VOUT)
7	SD3_HI_FLT	R/W	0h	SD3 (ZTAT) High Limit Failure. ADC measurement. 0h = No force failure of SD3 (ZTAT) (default) 1h = Force failure of SD3 (ZTAT)
6	SD3_LO_FLT	R/W	0h	SD3 (ZTAT) Low Limit Failure. ADC measurement. 0h = No force failure of SD3 (ZTAT) (default) 1h = Force failure of SD3 (ZTAT)
5	SD2_HI_FLT	R/W	0h	SD2 (VDD) High Limit Failure. ADC measurement. 0h = No force failure of SD2 (VDD) (default) 1h = Force failure of SD2 (VDD)
4	SD2_LO_FLT	R/W	0h	SD2 (VDD) Low Limit Failure. ADC measurement. 0h = No force failure of SD2 (VDD) (default) 1h = Force failure of SD2 (VDD)
3	SD1_HI_FLT	R/W	0h	SD1 (PVDD) High Limit Failure. ADC measurement. 0h = No force failure of SD1 (PVDD) (default) 1h = Force failure of SD1 (PVDD)
2	SD1_LO_FLT	R/W	0h	SD1 (PVDD) Low Limit Failure. ADC measurement. 0h = No force failure of SD1 (PVDD) (default) 1h = Force failure of SD1 (PVDD)
1	SD0_HI_FLT	R/W	0h	SD0 (VREF) High Limit Failure. ADC measurement. 0h = No force failure of SD0 (VREF) (default) 1h = Force failure of SD0 (VREF)
0	SD0_LO_FLT	R/W	0h	SD0 (VREF) Low Limit Failure. ADC measurement. 0h = No force failure of SD0 (VREF) (default) 1h = Force failure of SD0 (VREF)

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7 Application and Implementation

Note

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes, as well as validating and testing their design implementation to confirm system functionality.

7.1 Application Information

The AFEx81H1 are extremely low-power 16-bit and 14-bit voltage output DACs. The DACs support a low output range of 0.15V to 1.25V or a high output range of 0.3V to 2.5V. These devices have an onboard oscillator and an optional precision internal reference. Use these output values with a voltage-to-current (V-to-I) converter stage for 4mA to 20mA, loop-powered applications. These devices also feature a SAR ADC that is used to measure internal and external nodes for making diagnostic measurements with fault detection and alarm actions. Use these diagnostic measurements together with the CRC and watchdog timer monitoring for device and system monitoring for functional safety.

The AFEx81H1 devices support modem functionality with the Highway Addressable Remote Transducer (HART) Protocol through SPI or UART communications. To create a field transmitter, a HART interface is created through modulation and demodulation using the SPI or UART. Demodulate the input through band-pass filtering internal or external to the device.

The AFEx81H1 can operate using extremely low power with 1.8V supplies. For low-voltage operation, use PVDD with a 1.8V nominal supply and an operating range of 1.71V to 1.89V. Run the digital interface supply, IOVDD, from 1.71V to 5.5V. During low-voltage operation, the VDD LDO is automatically disabled and VDD is tied to PVDD. Low-voltage operation allows for both lower power for field transmitter applications and better voltage compliance when there are high resistances in the loop.

With higher-supply operation, the PVDD has an operating range of 2.7V to 5.5V. With this range of operation, the VDD is powered from an onboard LDO.

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7.1.1 Multichannel Configuration

The integration of receive and transmit FIFOs for HART communication enables easy scalability in multichannel configurations using the SPI only interface. Because $\overline{CS}$ low is required for communication and SDO can be set to a tri-state condition, only individual $\overline{CS}$ signals are required from the microcontroller for all the AFEx81H1 devices in the system. The SDI, SDO, and SCLK signals can be combined. All the individual $\overline{ALARM}$ pins can be wired-OR together. This minimizes the number of microcontroller GPIO signals required for communication, as well as the number of isolation channels for isolated systems. The multichannel configuration block diagram is shown in Figure 7-1.

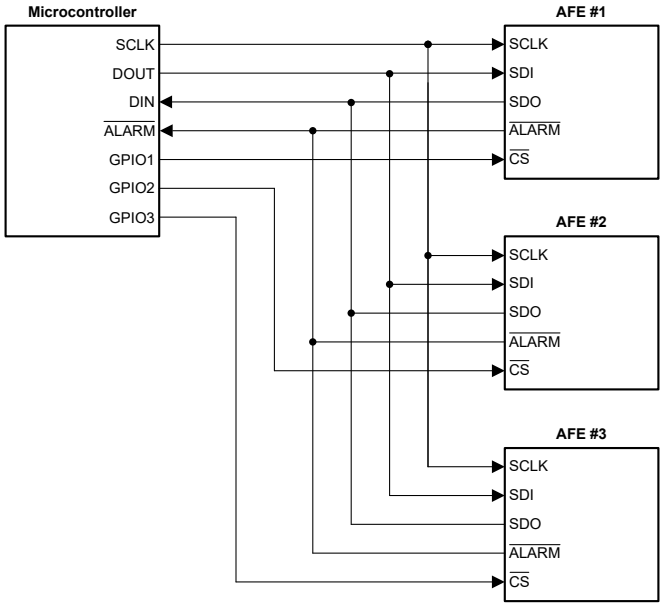


Figure 7-1. Multichannel Configuration

7.2 Typical Application

This design example shows a loop-powered, 4mA to 20mA field transmitter featuring the AFE881H1. The AFE781H1 can also be used in this design for lower-resolution applications.

This design example combines several circuit elements to create a subsystem that can support most field sensors in two-wire, current-loop applications. The design accepts bus voltages from 12V to 36V, while regulating the loop-current representation of a sensor to a post-calibration accuracy of less than 0.1% full-scale range (FSR) of total error at room temperature. The high integration in the system allows for a compact circuit, making this device an excellent choice for field transmitters where space is a concern. In field-transmitter applications, the current-loop transmitter, microcontroller, sensors, and analog front end are all required to consume less than the minimum bus current of 3mA. Use an integrated DC/DC converter in the system to extend the current budget and allow more current for sensors and the AFE.

Figure 7-2 shows the schematic diagram for the loop-powered, 4mA to 20mA field transmitter.

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7.2.1 4mA to 20mA Current Transmitter

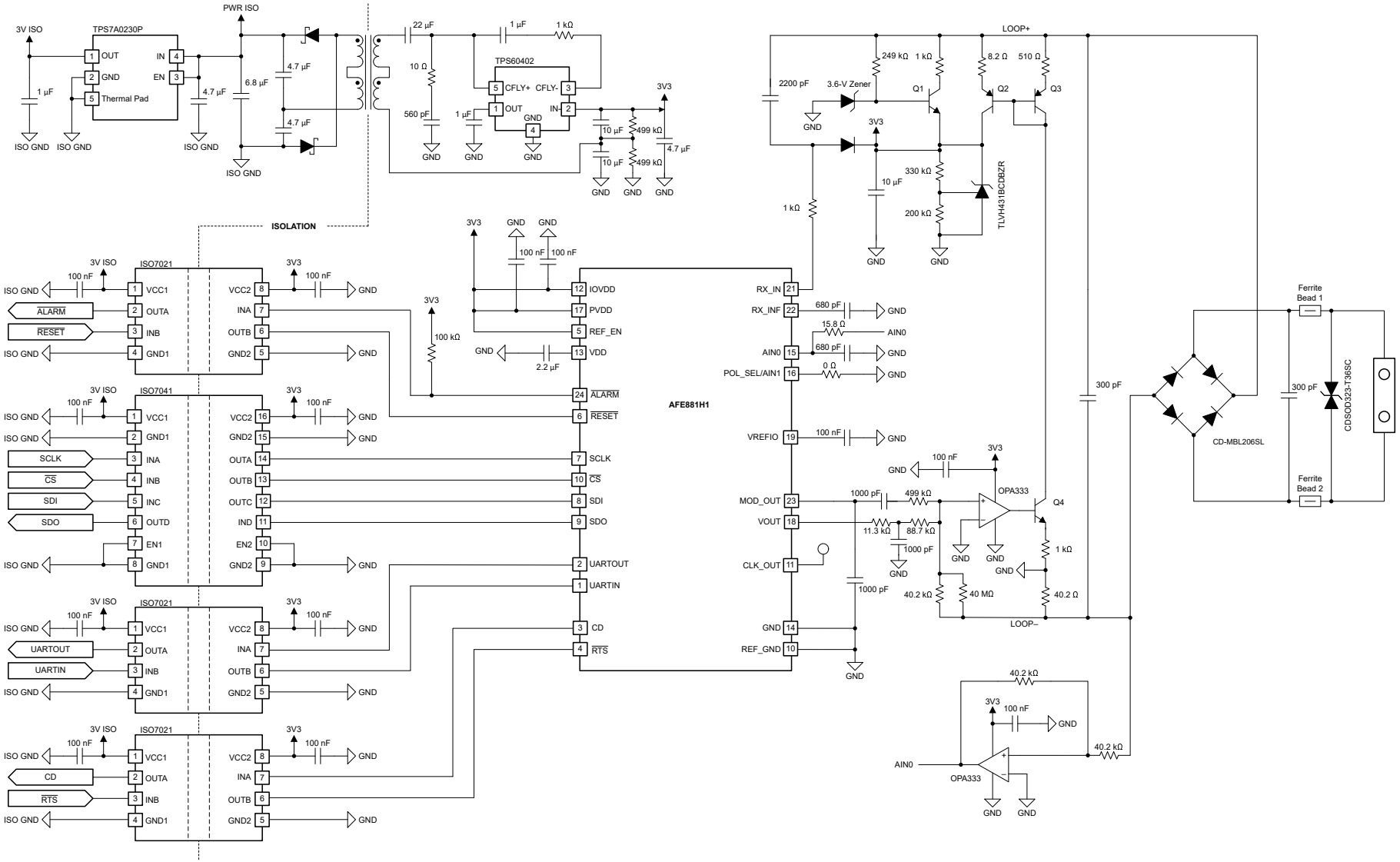


Figure 7-2. AFEx81H1 in a 4mA to 20mA Current Transmitter

7.2.1.1 Design Requirements

The design requirements are:

- Transmitter with a current output range of 4mA to 20mA for a process variable signal
- Out-of-range current output capability from 3mA to 25mA for error or fault signal levels
- Operation with standard industrial automation supply voltages from 12V to 30V
- Current and voltage outputs with TUE less than 0.5% at 25°C
- Total on-board current must be less than or equal to 3mA

7.2.1.2 Detailed Design Procedure

Figure 7-3 shows a block diagram of a loop-powered, 4mA to 20mA current transmitter.

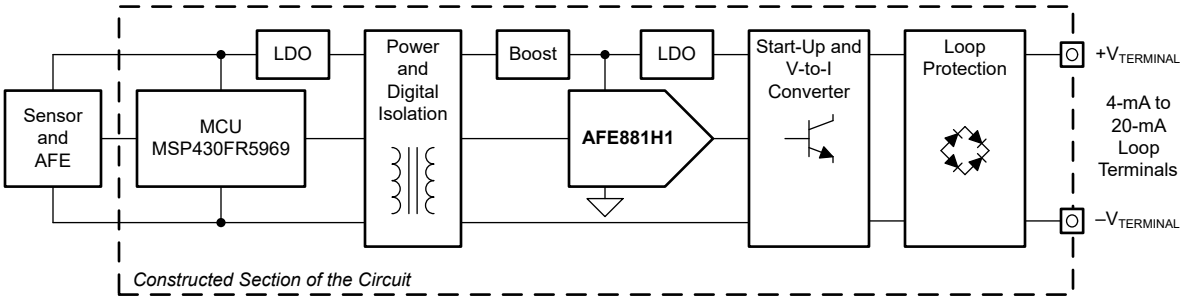


Figure 7-3. Block Diagram of a Loop-Powered, 4mA to 20mA Current Transmitter

The terminals connected to the loop are shown on the right side of the block diagram. This connection to the loop powers the entire transmitter. A bridge rectifier at the input protects against reverse connection to the loop. The rectified loop voltage powers a start-up circuit that provides power to an LDO, that in turn powers the AFE881H1. The LDO powers a flyback converter acting as a boost and supplies power across an isolation barrier. On the other side of the isolation barrier, another LDO powers the MCU and any sensor connected to the transmitter. The LDOs also power the digital signal isolation on each side of the barrier.

The AFE881H1 controls the loop current through the voltage-to-current (V-to-I) converter block. The DAC voltage sets the output from 0.3 V to 2.5 V. The output is sent through a V-to-I converter block using an OPA333 and an NPN bipolar junction transistor (BJT).

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7.2.1.2.1 Start-Up Circuit

When the loop is applied to the terminals, the loop power starts up the board. Transistor Q4 from Figure 7-2 pulls current from the start-up and current-shunt regulator sections of the transmitter. The start-up circuit is shown in Figure 7-4.

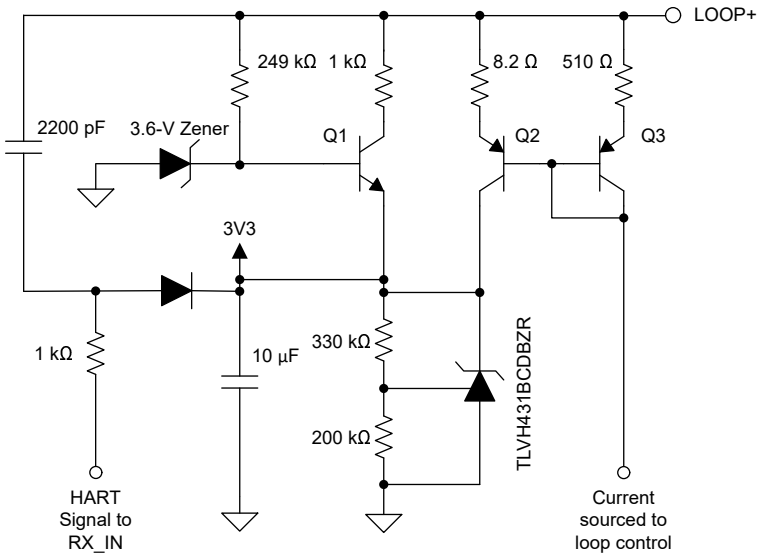


Figure 7-4. Start-Up Circuit

In the start-up circuit, the 3.6V Zener diode sets the voltage at the base of Q1. If the TLVH431B shunt regulator has not started, apply voltage to LOOP+ and LOOP– to turn on Q1 and source current to the shunt regulator. As the shunt regulator turns on and approaches the set voltage of 3.3 V, the base-emitter voltage (V_{BE}) of Q1 becomes smaller. The collector current of Q2 drives the current of the shunt regulator to set the LOOP current going through the 40.2Ω resistor in the current loop control circuit shown in the following section. After the start-up circuit has started, Q1 stops supplying current because the V_{BE} is restricted. Q1 shuts off, leaving several microamps of current flowing through the 3.6V Zener diode.

Take care when selecting the Zener diode. The voltage across the Zener diode varies with the loop voltage and the temperature of the circuit. This variance can change the V_{BE} across Q1 and change the total current going through the start-up circuit. If the voltage is too high, the Zener diode sets Q1 to continue to source current after the circuit starts up. If the voltage is too low, the Zener diode prevents the TLVH431B from turning on. Verify proper start up by checking that the 3.3V supply starts up, and that Q1 turns off when in operation.

When the circuit starts up and the 3V3 line comes up to the desired 3.3V supply level, the current through the TLVH431B is primarily sourced through Q2. The Q2 transistor must be able to dissipate enough power to handle the high current (> 20mA) and the high voltage (> 30V) in the loop. Because the biased transistor, Q2, is responsible for sourcing most of the output current, choose the components in the path of this current flow with appropriate power ratings. In this case, the 8.2Ω resistor is rated to 0.25W.

The current mirror is set up so that the current gain from Q3 to Q2 is approximately a factor of 60 ×. The exact current gain is not important as long as the current through Q3 is low.

In addition to the start-up circuit, the dc-blocking capacitor for the HART input of RX_IN is shown with a series resistance of 1kΩ. A diode clamps the pin to the device supply and the resistance limits the input current. This configuration protects the RX_IN from damage from an overvoltage event at the start up of the circuit.

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7.2.1.2.2 Current Loop Control

The AFE881H1 sets an output voltage from 0.3V to 2.5V if configured in Range 0 with PVDD > 2.7V. Figure 7-5 shows the feedback circuit that sets the loop current from the DAC output voltage.

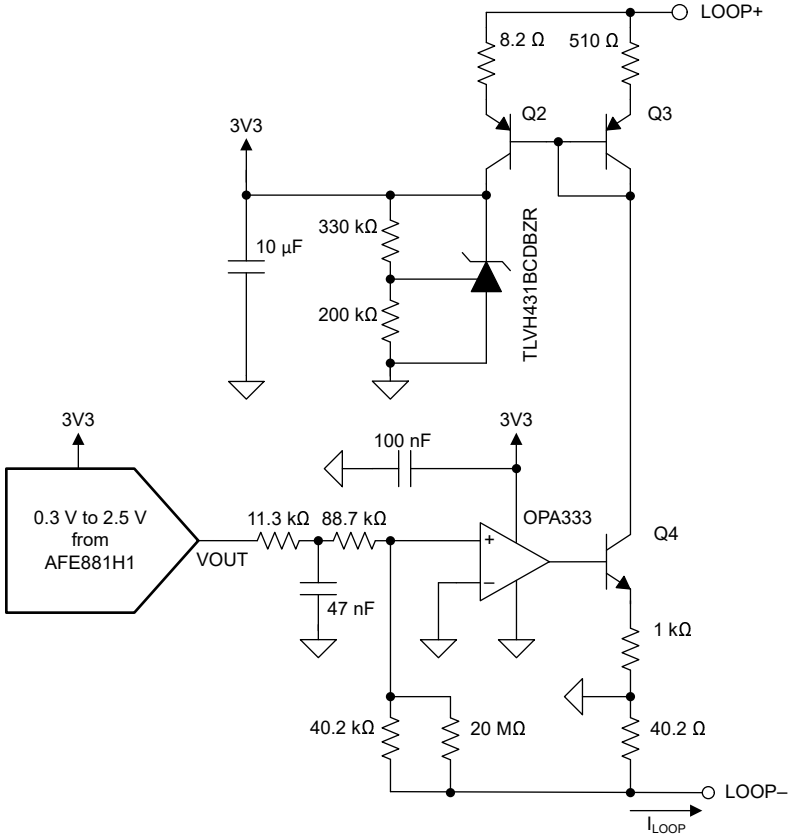


Figure 7-5. Current Loop Control for the AFE881H1 Transmitter

In this circuit, the VOUT voltage is set across 100kΩ of resistance (from the 11.3kΩ plus 88.7 kΩ of series resistance) by the AFE881H1. The opposite end of the 100 kΩ of resistance is set to ground by the feedback of the OPA333. The current across the 100kΩ resistance is VOUT divided by 100kΩ. This current continues through the 40.2kΩ resistor so that the voltage at LOOP– is less than ground. Equation 11 calculates the voltage at LOOP–.

$$V_{LOOP-} = -(VOUT / 100\,k\Omega) \times 40.2\,k\Omega = -VOUT \times 0.402 \quad (11)$$

When the DAC output voltage is set to 0.3V, the voltage at LOOP– is 0.1206V less than ground. When the DAC output voltage is set to 2.5 V, the voltage at LOOP– is 1.005V less than ground. The LOOP– voltage sets the loop current that flows from ground to LOOP– through the 40.2Ω resistor. This current is sourced from ground but controlled by the current sunk from Q4 coming from the start-up circuit. Equation 12 calculates the loop current.

$$I_{LOOP} = -V_{LOOP} / 40.2\,k\Omega \quad (12)$$

Substituting Equation 12 into Equation 11, Equation 13 is obtained.

$$I_{LOOP} = VOUT \times 0.402 / 40.2\,\Omega = VOUT / 100\,\Omega \quad (13)$$

When the DAC output voltage is set to 0.3V, the loop current is 3mA. When the DAC output voltage is set to 2.5 V, the loop current is 25 mA. The OPA333 drives the base of transistor Q4 to pull the correct amount of

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current to set the feedback loop. The current pulled from LOOP+ powers the board. Excess current greater than what is required to power the board is shunted through the TLVH431B regulator.

The AFE881H1 sets the DAC output voltage through an output code. This conversion to output voltage is set through Equation 1; V_{MIN} = 0.3V and FSR = 2.2V, resulting in Equation 14.

$$VOUT = \frac{DAC_CODE}{2^{16}} \times 2.2\ V + 0.3\ V \tag{14}$$

In 4mA to 20mA systems, the nominal output operates from 4mA as the low output and 20 mA as the high output. However, systems sometimes use current outputs that are outside this range to indicate different error conditions. Loop currents of 3.375mA and 21.75mA can be used to indicate different loop errors. Table 7-1 shows different loop output currents, along with the DAC code and voltages used.

Table 7-1. DAC Voltage Output and Loop Current Based on DAC Output Codes

OUTPUT CONDITION	DAC CODE	DAC OUTPUT (V)	LOOP CURRENT (mA)
DAC minimum	0x0000	0.3	3
Error low	0x045D	0.3375	3.375
In-range minimum	0x0BA2	0.4	4
In-range midscale	0x68BA	1.2	12
In-range maximum	0xC5D1	2.0	20
Error high	0xDA2E	2.175	21.75
DAC maximum	0xFFFF	2.5	25

Among the passive devices included in the design, choose gain-setting resistors that exhibit tight tolerances to achieve high accuracy. These resistors are primarily responsible for setting the gain of the current loop, along with primary path of the output current flow.

Similar to converting the VOUT pin voltage to the loop current magnitude, the HART output from the MOD_OUT pin is converted from a voltage to a current. A dc-blocking capacitor of 1000pF is used to couple in the HART signal without the dc output offset from the MOD_OUT pin. From MOD_OUT, the HART sinusoid nominal output is 500 mVpp. Equation 15 shows that this V_{MOD} HART sinusoid voltage is set across a 499kΩ resistor to create signal voltage V_{LOOPAC} superimposed onto $V_{LOOP–}$.

$$\mathrm{V_{LOOPAC}} = (\mathrm{V_{MOD}} / 499\ \mathrm{k\Omega}) \times 40.2\ \mathrm{k\Omega} = \mathrm{V_{MOD}} \times 0.08056 \tag{15}$$

The V_{LOOPAC} voltage sets the HART-modulated loop current that flows from ground to LOOP– through the 40.2Ω resistor. This current is sourced from ground but controlled by the current sunk from Q4 coming from the start-up circuit. Equation 16 calculates the loop current.

$$\mathrm{I_{LOOPAC}} = \mathrm{V_{LOOPAC}} / 40.2\ \mathrm{k\Omega} \tag{16}$$

Substituting Equation 15 into Equation 16, Equation 17 is obtained.

$$\mathrm{I_{LOOPAC}} = \mathrm{V_{MOD}} \times 0.08056/40.2\ \Omega = 500\ \mathrm{mV_{pp}} \times 0.08056/40.2\ \Omega = 1\ \mathrm{mA_{pp}} \tag{17}$$

Using the 1000pF capacitor as a dc-blocking capacitor and the 499kΩ resistor, the 500mVpp MOD_OUT signal is converted to a 1-mApp HART signal on the current loop.

7.2.1.2.3 Input Protection and Rectification

Figure 7-6 shows the simple protection scheme implemented in the design to mitigate issues that arise from voltage and current transients on the bus. These transients have two main components: high-frequency and high-energy. These two components can be leveraged with a strategy of attenuation and diversion by the protection circuitry to deliver robust immunity.

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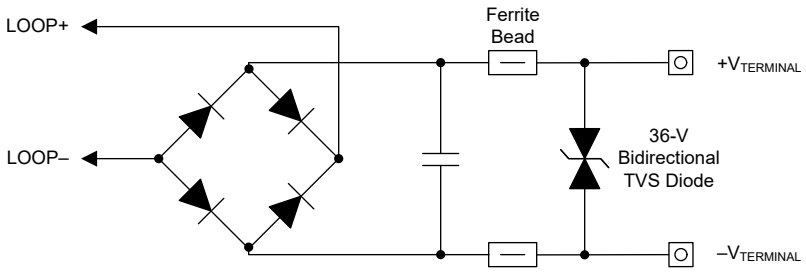


Figure 7-6. Loop Input Protection

Attenuation uses passive components, primarily resistors and capacitors, to attenuate high-frequency transients and to limit series current. Use ferrite beads to maintain dc accuracy while still delivering the ability to limit current from high-frequency transients. This circuit uses a capacitor placed across the input terminals, as well as ferrite beads in series with the terminals.

Diversion capitalizes on the high-voltage properties of the transient signals by using a diode to clamp the transient within supply voltages, or to divert the energy away from the system. Transient voltage suppressor (TVS) diodes help protect against transients because TVS diodes break down very quickly and often feature high power ratings that are critical to survive multiple transient strikes.

A rectifier is also implemented for reverse polarity protection so that the design can be connected to the bus regardless of the pin orientation or polarity without damage to the design.

7.2.1.2.4 System Current Budget

Power consumption is an important consideration when designing two-wire transmitters. Power supplied from the loop must power all the circuitry related to the transmitter and sensor. The minimum loop current in two-wire applications is typically 4mA. However, for error indications, this current is as low as 3.375mA. Therefore, the power budget of all transducer circuitry must be less than the maximum allowable system power budget of 3mA. Table 7-2 lists the specified maximum quiescent current of all included active components (provided from the respective datasheets).

Table 7-2. Typical Component Currents

DEVICE	DESCRIPTION	TYPICAL CURRENT (µA)
TPS7A0230	LDO	0.025
AFE881H1	16-bit DAC	190
OPA333 (2)	Operational amplifier	17
TLVH431B	Shunt regulator	60
MSP430	Microcontroller	Dependent on firmware
ISO7021D (2), ISO7041F	Digital isolation	Dependent on communications

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7.2.1.3 Application Curves

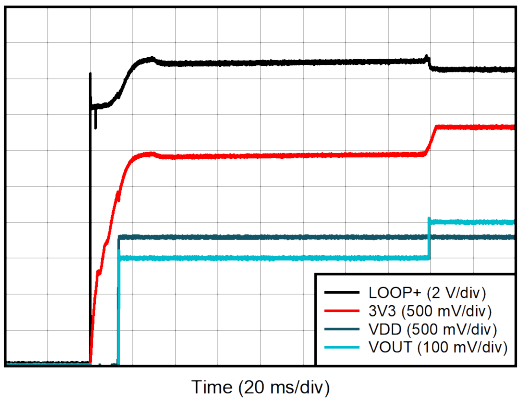


Figure 7-7. Circuit Start-Up

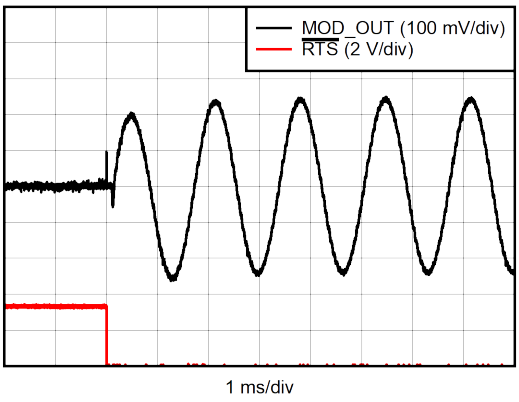


Figure 7-8. $\overline{\text{RTS}}$ Start Timing

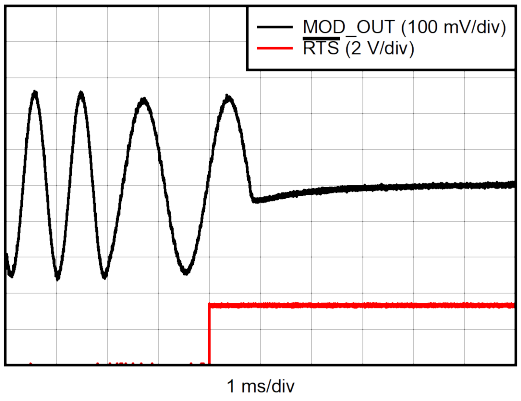


Figure 7-9. $\overline{\text{RTS}}$ Stop Timing

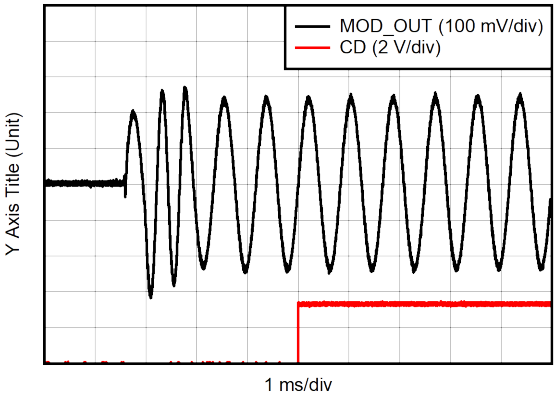


Figure 7-10. CD Start Timing

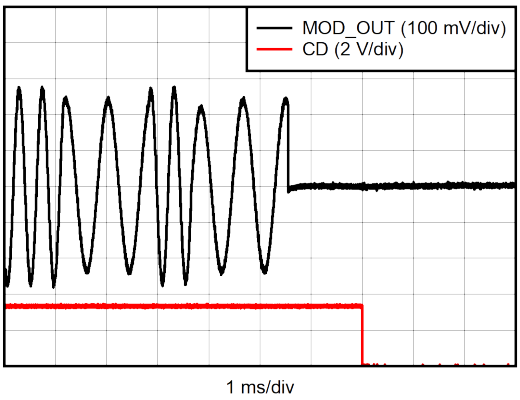


Figure 7-11. CD Stop Timing

7.3 Initialization Set Up

This section describes several recommendations to set up the AFEx81H1.

The AFEx81H1 power up with the CRC enabled. If the device is intended to be run without the CRC, the CRC must be disabled by setting the CRC_EN bit to 0h in the CONFIG register. Be aware that the command to write to this register is first done with the CRC enabled. The CRC byte must be appended to the command for the device to interpret the command correctly. To disable the CRC after start up, write 0x02 0x00 0x26 0x24 to the device. The first three bytes write the command, while the last byte is the CRC byte. For more information on the CRC, see the communication description in Section 6.5.2.3.

The AFEx81H1 also power up with the SDO pin disabled. The SDO is required for reading from any of the device registers, as well as reading any data from the ADC in SPI mode. The SDO is enabled by writing 0h into the DSDO bit in the CONFIG register. See also Section 6.5.2.1 and Section 6.5.2.2.

To enable the ADC, first enable the ADC buffer by writing 0h into the BUF_PD bit in the ADC_CFG register. Information about using the ADC in different modes of operation is in Section 6.3.2.

7.4 Power Supply Recommendations

The AFEx81H1 can operate within a single-supply range of 2.7V to 5.5V applied to the PVDD pin. When 2.7V to 5.5V is provided to PVDD, an internal LDO is enabled that drives VDD internally. VDD pin must have 1µF to 10µF of capacitance for operation.

The AFEx81H1 can also be operated with a lower supply voltage of 1.71V to 1.89V applied to the PVDD pin. When the voltage is within this lower range, the internal LDO is not operational, and the lower external supply on the PVDD pin must be tied to the VDD pin.

The digital interface supply, IOVDD, can operate with a supply range of 1.71V to 5.5V.

Switching power supplies and DC/DC converters often have high-frequency glitches or spikes riding on the output voltage. In addition, digital components can create similar high-frequency spikes. This noise can easily couple into the DAC output voltage or current through various paths between the power connections and analog output. To further reduce noise, include bulk and local decoupling capacitors. The current consumption on the PVDD and IOVDD pins, the short-circuit current limit for the voltage output, and the current ranges for the current output are listed in the *Electrical Characteristics*. The power supply must meet the requirements listed in the *Recommended Operating Conditions*.

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7.5 Layout

7.5.1 Layout Guidelines

To maximize the performance of the AFEx81H1 in any application, follow good layout practices and proper circuit design. The following recommendations are specific to the device:

- For best performance, dedicate an entire PCB layer to a ground plane and do not route any other signal traces on this layer. However, depending on restrictions imposed by specific end equipment, a dedicated ground plane is not always practical. If ground-plane separation is necessary, make a direct connection of the planes at the DAC. Do not connect individual ground planes at multiple locations because this configuration creates ground loops.
- IOVDD and PVDD must have 100nF decoupling capacitors local to the respective pins. VDD must have at least a 1µF decoupling capacitor used for the internal LDO, or for an external 1.8V supply. Use a high-quality ceramic-type NP0 or X7R capacitor for best performance across temperature and a very low dissipation factor.
- Place a 100nF reference capacitor close to the VREFIO pin.
- Avoid routing switching signals near the reference input.
- Maintain proper placement for the digital and analog sections with respect to the digital and analog components. Separate the analog and digital circuitry for less coupling into neighboring blocks and to minimize the interaction between analog and digital return currents.
- For designs that include protection circuits:
  - Place diversion elements, such as TVS diodes or capacitors, close to off-board connectors to make sure that return current from high-energy transients does not cause damage to sensitive devices
  - Use large, wide traces to provide a low-impedance path to divert high-energy transients away from the I/O pins.

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7.5.2 Layout Example

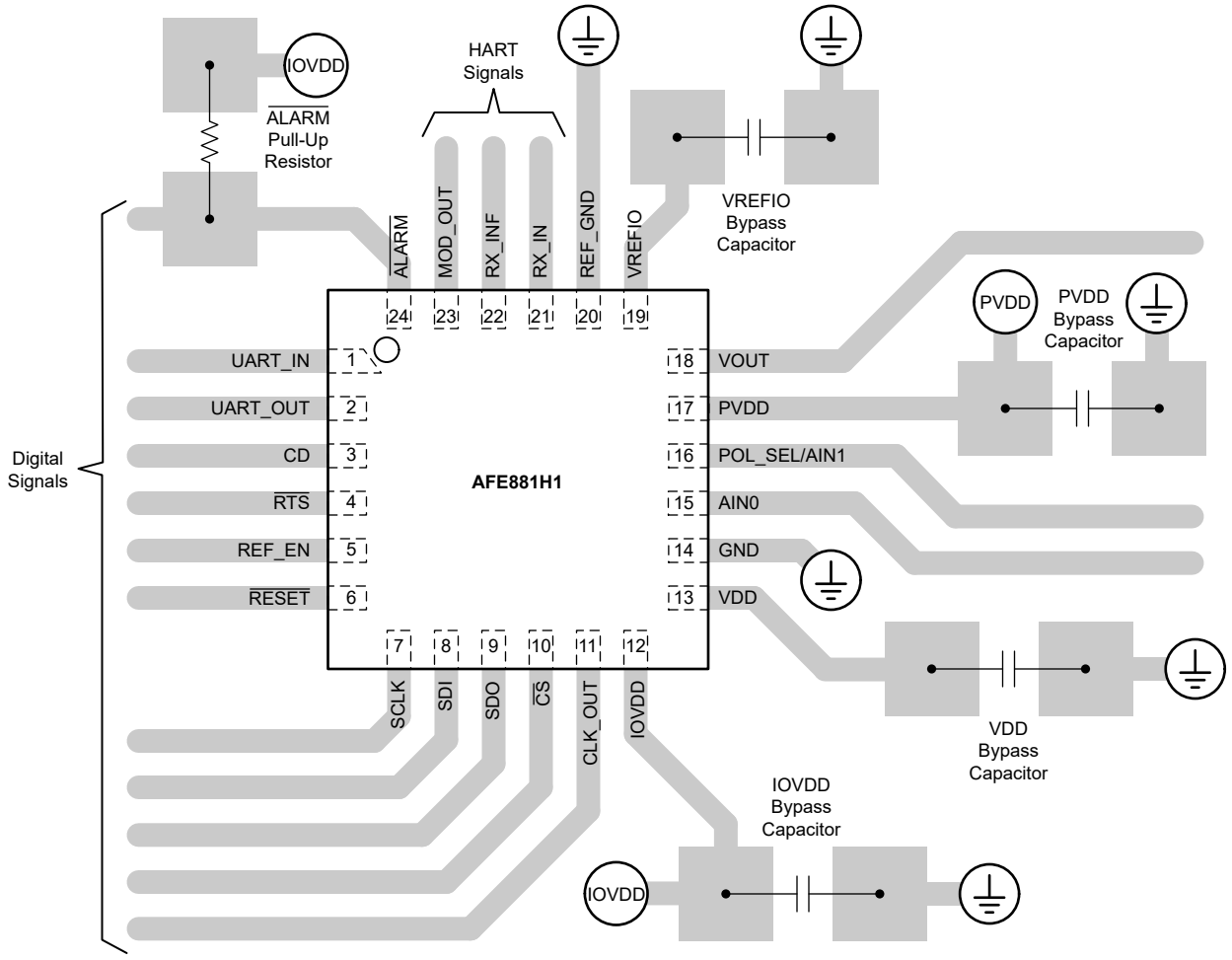


Figure 7-12. Layout Example

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8 Device and Documentation Support

8.1 Documentation Support

8.1.1 Related Documentation

For related documentation see the following:

- Texas Instruments, AFE881H1 Evaluation Module User's Guide
- Texas Instruments, A Basic Guide to the HART Protocol
- Texas Instruments, Design and Test of a HART-Enabled Field Transmitter for 4-20mA Loops
- Texas Instruments, HART-Enabled Transmitter Based on an Evaluation Module Design
- Texas Instruments, REF35 Ultra Low-Power, High-Precision Voltage Reference data sheet
- Texas Instruments, OPA391 Precision, Ultra-Low IQ, Low Offset Voltage, e-trim™ Op Amp datasheet
- Texas Instruments, ADS1220 4-Channel, 2-kSPS, Low-Power, 24-Bit ADC with Integrated PGA and Reference datasheet
- Texas Instruments, TPS7A16 60V, 5-µA IQ, 100mA, Low-Dropout Voltage Regulator With Enable and Power-Good datasheet
- Texas Instruments, TPS7A02 Nanopower IQ, 25nA, 200mA, Low-Dropout Voltage Regulator With Fast Transient Response datasheet
- Texas Instruments, ISO7021 Ultra-Low Power Two-Channel Digital Isolator datasheet
- Texas Instruments, Isolated, Ultra-Low Power Design for 4- to 20mA Loop Powered Transmitters design guide
- Texas Instruments, Isolated Loop Powered Thermocouple Transmitter design guide
- Texas Instruments, Small Form Factor, 2-Wire, 4- to 20mA Current-Loop, RTD Temperature Transmitter design guide
- Texas Instruments, Isolated Power and Data Interface for Low-power Applications reference design
- Texas Instruments, Uniquely Efficient Isolated DC/DC Converter for Ultra-Low Power and Low-Power Applications design guide

8.2 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. Click on *Notifications* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

8.3 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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8.4 Trademarks

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HART® is a registered trademark of FieldComm Group.
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8.5 Electrostatic Discharge Caution



This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

8.6 Glossary

TI Glossary	This glossary lists and explains terms, acronyms, and definitions.

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9 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (March 2023) to Revision A (October 2026)	Page
• Changed description of $\overline{\text{RESET}}$ putting the device in power-down mode to turning off the internal oscillator	3
• Added description of about frame error	46
• Changed 0x8F to 0x84 of SPI Controller Data in Figure 6-21	51
• Added text regarding additional accumulated delay to *HART Modulator Timing and Preamble Requirements*	51
• Deleted text regarding 1200 baud setting	60
• Updated the OSC_FAIL bit description	73
• Added references to new application notes related to device	107

10 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this datasheet, refer to the left-hand navigation.

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PACKAGING INFORMATION

Orderable part number	Status (1)	Material type (2)	Package | Pins	Package qty | Carrier	RoHS (3)	Lead finish/ Ball material (4)	MSL rating/ Peak reflow (5)	Op temp (°C)	Part marking (6)
AFE781H1RRUR	Active	Production	UQFN (RRU) | 24	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 781H1
AFE781H1RRUR.A	Active	Production	UQFN (RRU) | 24	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 781H1
AFE781H1RRUT	Active	Production	UQFN (RRU) | 24	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 781H1
AFE781H1RRUT.A	Active	Production	UQFN (RRU) | 24	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 781H1
AFE881H1RRUR	Active	Production	UQFN (RRU) | 24	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 881H1
AFE881H1RRUR.A	Active	Production	UQFN (RRU) | 24	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 881H1
AFE881H1RRUT	Active	Production	UQFN (RRU) | 24	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 881H1
AFE881H1RRUT.A	Active	Production	UQFN (RRU) | 24	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-55 to 125	AFE 881H1

(1) **Status:** For more details on status, see our product life cycle.

(2) **Material type:** When designated, preproduction parts are prototypes/experimental devices, and are not yet approved or released for full production. Testing and final process, including without limitation quality assurance, reliability performance testing, and/or process qualification, may not yet be complete, and this item is subject to further changes or possible discontinuation. If available for ordering, purchases will be subject to an additional waiver at checkout, and are intended for early internal evaluation purposes only. These items are sold without warranties of any kind.

(3) **RoHS values:** Yes, No, RoHS Exempt. See the TI RoHS Statement for additional information and value definition.

(4) **Lead finish/Ball material:** Parts may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

(5) **MSL rating/Peak reflow:** The moisture sensitivity level ratings and peak solder (reflow) temperatures. In the event that a part has multiple moisture sensitivity ratings, only the lowest level per JEDEC standards is shown. Refer to the shipping label for the actual reflow temperature that will be used to mount the part to the printed circuit board.

(6) **Part marking:** There may be an additional marking, which relates to the logo, the lot trace code information, or the environmental category of the part.

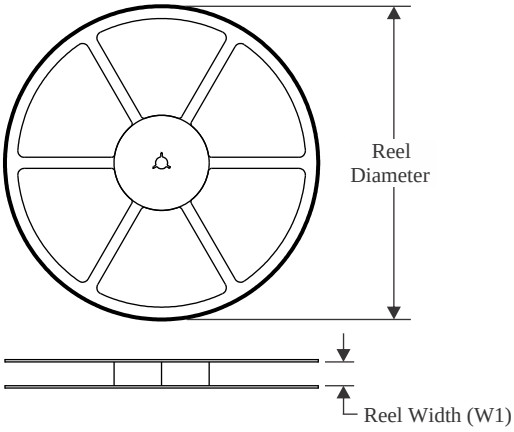
Multiple part markings will be inside parentheses. Only one part marking contained in parentheses and separated by a "~" will appear on a part. If a line is indented then it is a continuation of the previous line and the two combined represent the entire part marking for that device.

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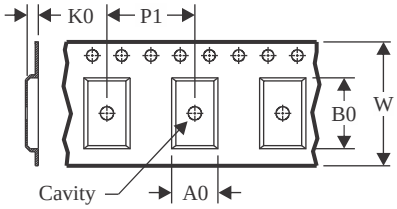
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TAPE AND REEL INFORMATION

REEL DIMENSIONS

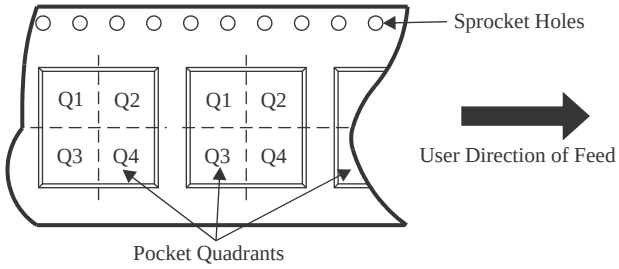


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

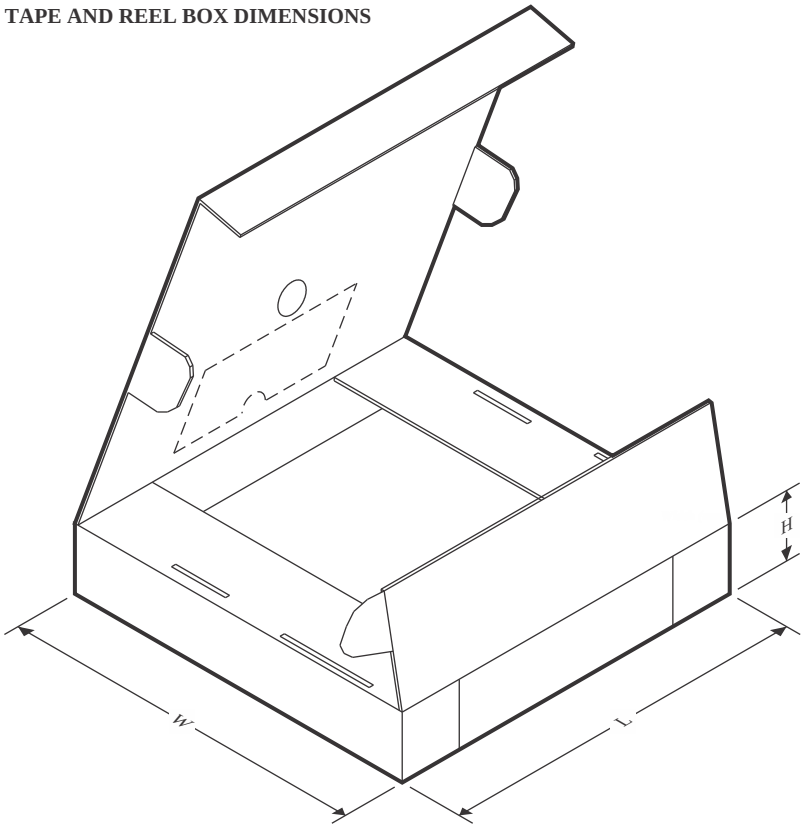
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
AFE781H1RRUR	UQFN	RRU	24	3000	330.0	12.4	4.25	4.25	0.8	8.0	12.0	Q2
AFE781H1RRUT	UQFN	RRU	24	250	180.0	12.4	4.25	4.25	0.8	8.0	12.0	Q2
AFE881H1RRUR	UQFN	RRU	24	3000	330.0	12.4	4.25	4.25	0.8	8.0	12.0	Q2
AFE881H1RRUT	UQFN	RRU	24	250	180.0	12.4	4.25	4.25	0.8	8.0	12.0	Q2

TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

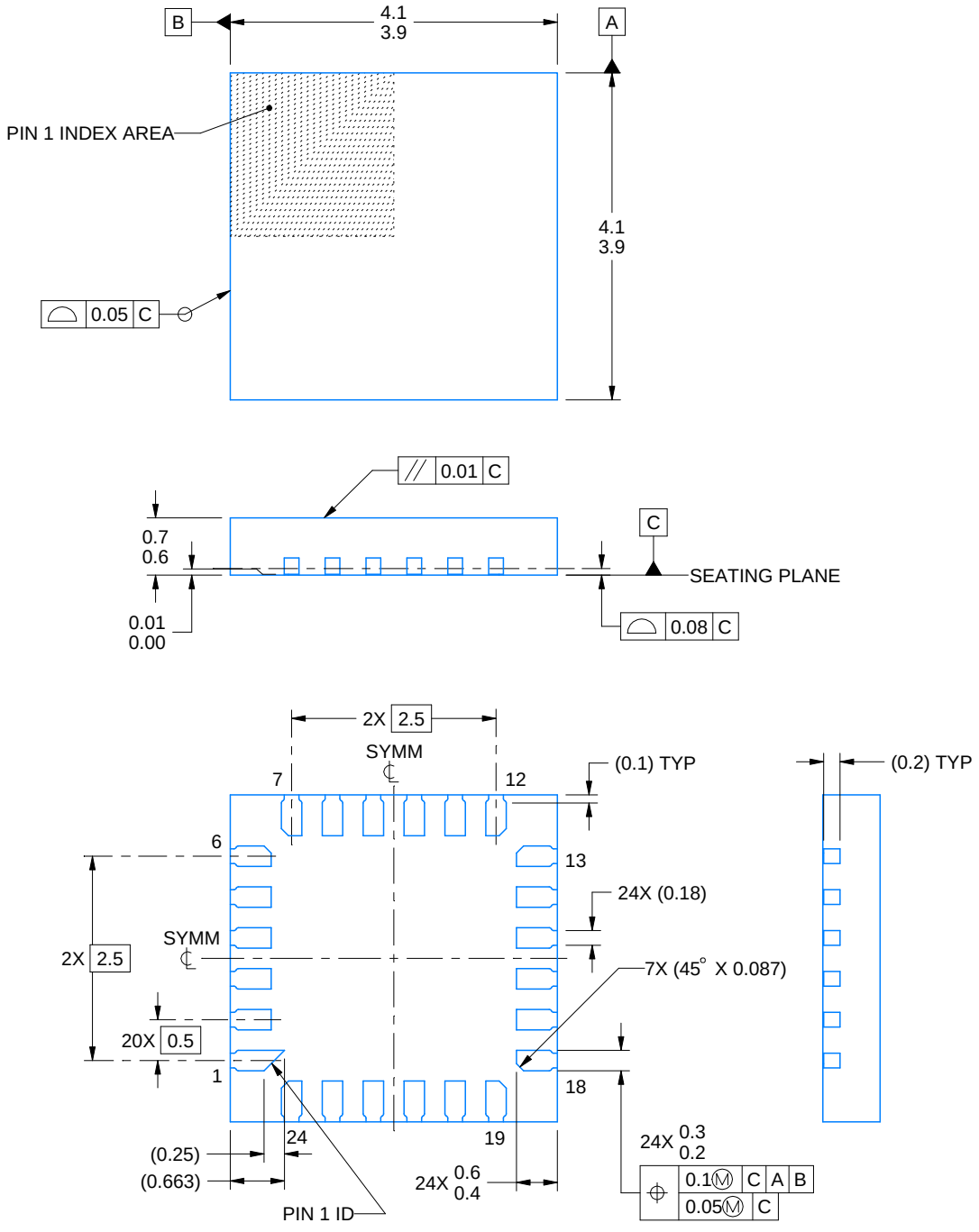
Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
AFE781H1RRUR	UQFN	RRU	24	3000	367.0	367.0	35.0
AFE781H1RRUT	UQFN	RRU	24	250	210.0	185.0	35.0
AFE881H1RRUR	UQFN	RRU	24	3000	360.0	360.0	36.0
AFE881H1RRUT	UQFN	RRU	24	250	210.0	185.0	35.0

PACKAGE OUTLINE

RRU0024A

UQFN - 0.7 mm max height

PLASTIC QUAD FLATPACK - NO LEAD



NOTES:

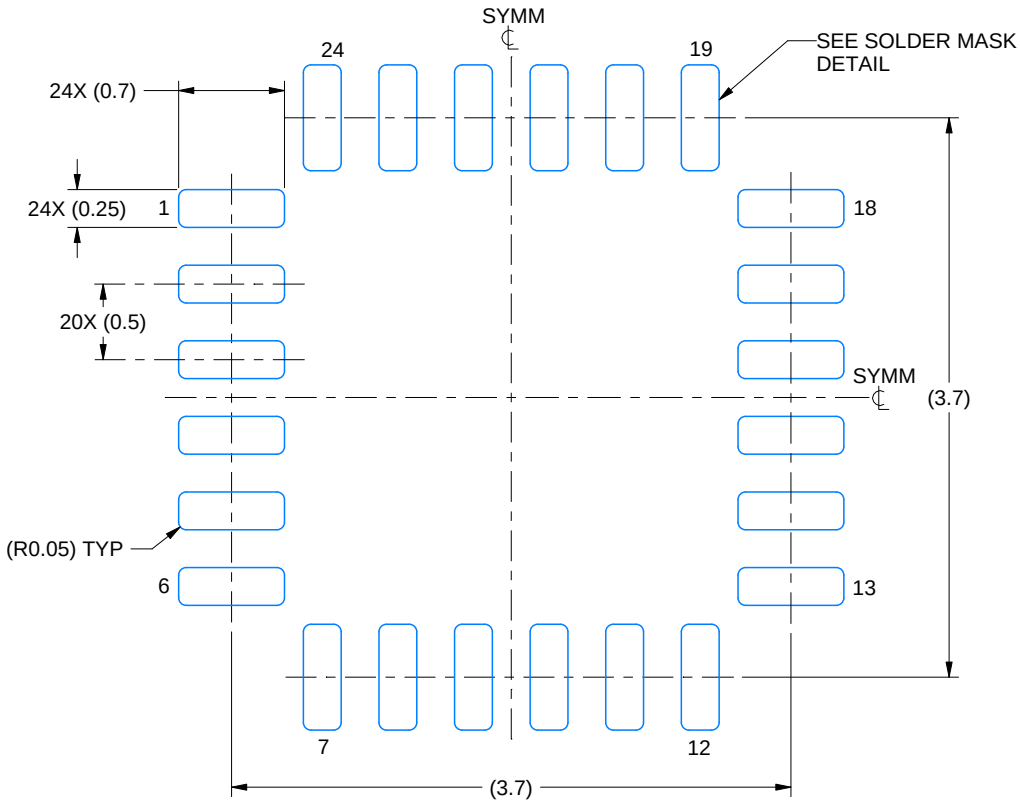
1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. The package thermal pad must be soldered to the printed circuit board for thermal and mechanical performance.

EXAMPLE BOARD LAYOUT

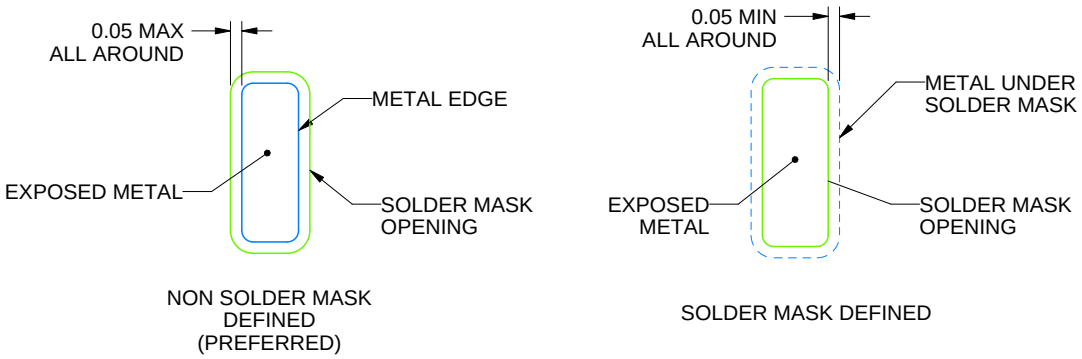
RRU0024A

UQFN - 0.7 mm max height

PLASTIC QUAD FLATPACK - NO LEAD



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 20X

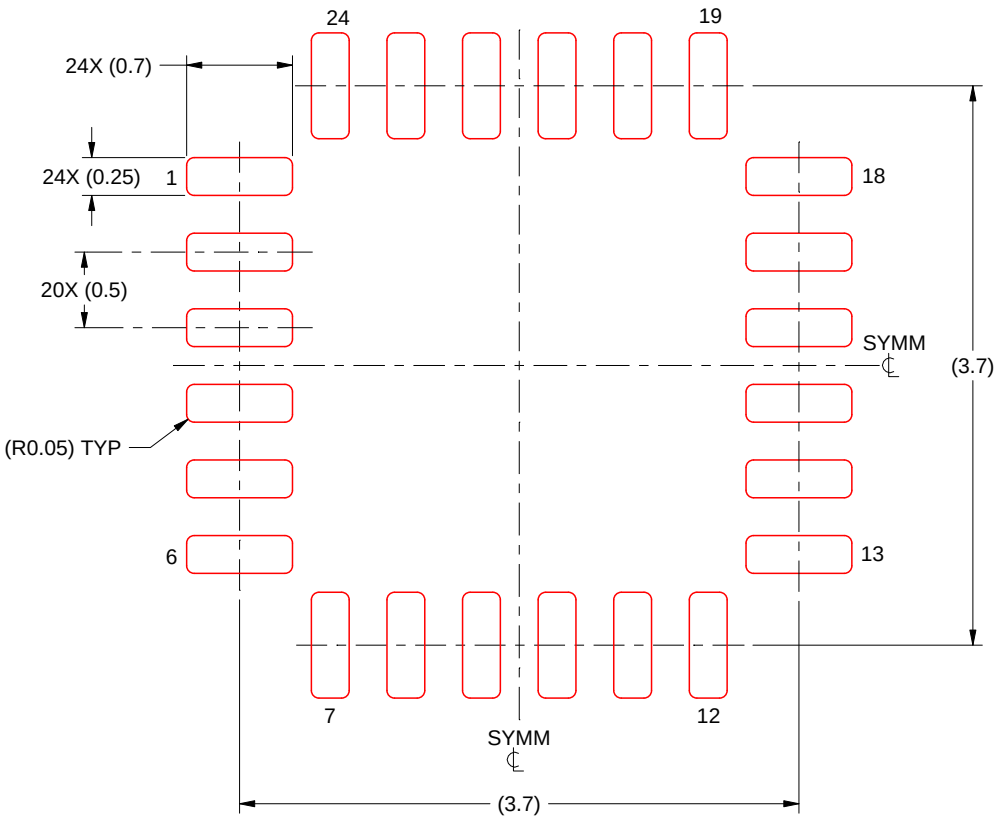


SOLDER MASK DETAILS

4225850/A 04/2020

NOTES: (continued)

4. This package is designed to be soldered to a thermal pad on the board. For more information, see Texas Instruments literature number SLUA271 (www.ti.com/lit/slua271).
5. Vias are optional depending on application, refer to device data sheet. If any vias are implemented, refer to their locations shown on this view. It is recommended that vias under paste be filled, plugged or tented.



SOLDER PASTE EXAMPLE
BASED ON 0.125 MM THICK STENCIL
SCALE: 20X

4225850/A 04/2020

NOTES: (continued)

6. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.

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