Design Guide: TIDA-010935
Solar Power Line Communication Reference Design

TEXAS INSTRUMENTS

Description

Power Line Communication (PLC) is now used in multiple end-equipment applications. A good example are grid applications, where the necessary data is communicated from one device to another using the power cable as transmission lines. Hence the name; Power line communication. This is achieved by modulating the data at a higher frequency band (typically in the kHz and MHz band) on top of the power line. This reference design features a simple approach for PLC, using an On-Off-Keying modulator in combination with a line driver and passive filtering, to transmit data over a Universal Asynchronous Receiver, Transmitter (UART) interface.

Resources

TIDA-010935	Design Folder
TPS26624DRCR, TPS560430X3FDBVR	Product Folder
LM5164QDDARQ1, THVD8000DDFR	Product Folder
THS6222IRGTR, TMUX1204DGSR	Product Folder
LP-MSPM0G307	Product Folder

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Features

- 4 selectable modulating frequencies: 125 kHz, 500 kHz, 2 MHz, 5 MHz
- Built-in current limit protection, and reverse polarity protection using TI eFuse
- Space reduction using the same communication line for both receiving and transmitting
- BoosterPack™ Plug-in Module compatible with multiple microcontroller families like MSPM0 and the C2000™

Applications

- Micro inverter
- String inverter
- Solar power optimizer
- Central inverter
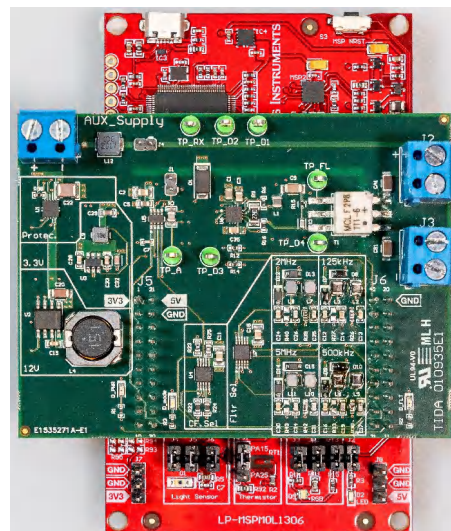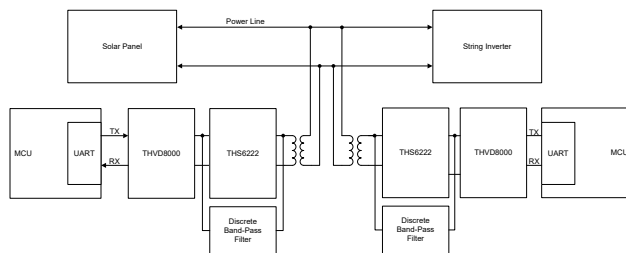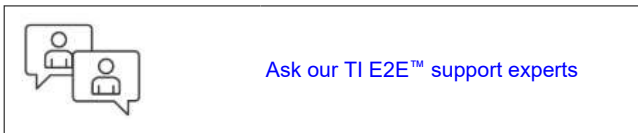
1 System Description

The TIDA-010935 reference design is a low-cost, flexible PLC module compatible with an MSPM0 microcontroller, designed for solar applications. The design can be powered directly from the solar panel or from an auxiliary power supply by means of screw terminals. The TIDA-010935 comes with built-in current limit protection, and reverse polarity protection. Multiple carrier frequencies can be selected in this design ranging from 125 kHz up to 5 MHz. Engineers can utilize this feature when trying to avoid the switching frequency from the string inverter which can interfere with the carrier frequency from the THVD8000. In addition, the BIAS setting of the THS6222 line driver can be adjusted to improve overall power efficiency.

1.1 Key System Specifications

Table 1-1. System Specifications for PLC

PARAMETER	SPECIFICATION
Input voltage	13.5 V–50 V
Current limit protection	500 mA
Output voltage	12 V
Maximum driver current	338 mA
Selectable carrier frequencies	125 kHz, 500 kHz, 2 MHz, 5 MHz
Baud rate	9600
Board size	80 mm × 60 mm

	CAUTION
	Do not leave the design powered when unattended.

	WARNING
	External Connections: All external connections to the hardware must stay within the recommended operating conditions and intended usage for all hardware and components connected in the system.

	WARNING
	High voltage! *Accessible high voltages are present on the board.* Electric shock is possible. The board operates at voltages and currents that can cause shock, fire, or injury if not properly handled. Use the equipment with necessary caution and appropriate safeguards to avoid injuring yourself or damaging property. For safety, use of isolated test equipment with overvoltage and overcurrent protection is highly recommended. TI considers it the user's responsibility to confirm that the voltages and isolation requirements are identified and understood before energizing the board or simulation. *When energized, do not touch the design or components connected to the design*.

WARNING

TI intends this reference design to be operated in a *lab environment only and does not consider the board to be a finished product* for general consumer use. The design is intended to be run at ambient room temperature and is not tested for operation under other ambient temperatures.

TI intends this reference design to be used only by *qualified engineers and technicians* familiar with risks associated with handling high-voltage electrical and mechanical components, systems, and subsystems.

There are *accessible high voltages present on the board*. The board operates at voltages and currents that can cause shock, fire, or injury if not properly handled or applied. Use the equipment with necessary caution and appropriate safeguards to avoid injuring yourself or damaging property.

2 System Overview

2.1 Block Diagram

Figure 2-1 shows a basic overview of the signal front end. The signal being generated from the MCU can be sent over UART into a modulator. From there a line driver is necessary to drive a strong enough signal onto the power line. A discrete filter can filter the necessary band out of the incoming spectrum, which gives the THVD8000 the necessary signal to demodulate.
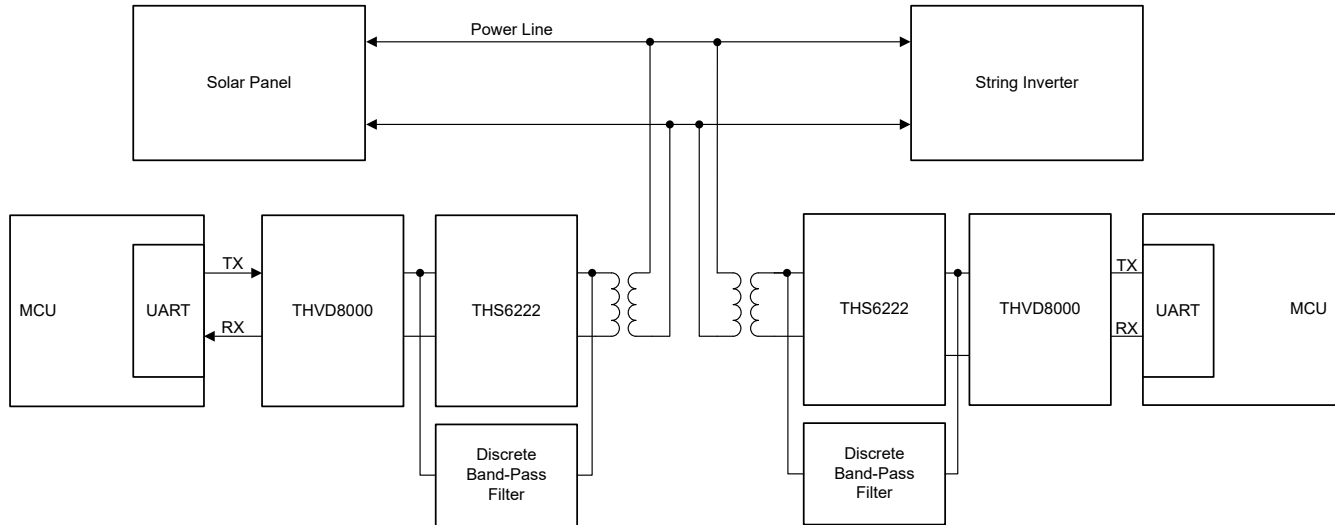

Figure 2-1. TIDA-010935 Block Diagram

2.2 Highlighted Products

2.2.1 THVD8000DDF

The THVD8000DDF is a RS-485 transceiver with On-Off-Keying (OOK) modulation for power line communication. The device has an built-in modulator and demodulator which can be selected with the MODE pin. Carrier frequency can be set by means of tying an external resistor to the F_SET pin, allowing a transmission from 125 kHz up to 5 MHz . Data rates are possible up to 500kbps depending on which carrier frequency was chosen. OOK modulation operates with immunity to data polarity, making this device easy to implement and use.

2.2.2 THS6222RGTT

The THS6222 is a differential line driver amplifier with a current feedback architecture using Texas Instruments' proprietary high-speed silicon-germanium process. The device is targeted for use in broadband, high-speed, power line communications line driver applications that require high linearity when driving heavy line loads.

The unique architecture of the THS6222 uses minimal quiescent current by help of the BIAS pins, while achieving very high linearity. The amplifier has an adjustable current pin that sets the nominal current consumption along with multiple bias modes that allow for enhanced power savings where the full performance of the amplifier is not required. Shutdown bias mode provides further power savings during a receive mode.

The wide output swing of 57 V_{PP} (100-Ω load) with 32-V power supplies, coupled with over 650-mA current drive (25 Ω) allows for wide dynamic range that keeps distortion minimal.

2.2.3 MSPM0G350x

MSPM0G350x microcontrollers are part of TI's highly-integrated, ultra-low-power 32-bit MSPM0 MCU family based on the enhanced Arm Cotrex-M0+ core platform operating at up to 80-MHZ frequency. These cost-optimized MCUs offer high-performance analog peripheral integration, support extended temperature ranges from –40°C to 125°C, and operate with supply voltages ranging from 1.62 V to 3.6 V.

The MSPM0G devices provide up to 128KB embedded flash program memory with up to 32KB SRAM. These MCUs incorporate a high-speed on-chip oscillator with an accuracy up to ±1.2%, eliminating the need for an external crystal. Additional features include a 3-channel DMA, 16- and 32-bit CRC accelerator, and a variety of high-performance analog peripherals such as one 12-bit, 1.68-MSPS analog-to-digital converter (ADC) with configurable internal voltage reference, one high-speed comparator with built-in reference digital-to-analog converter (DAC), two zero-drift zero-crossover operational amplifiers with programmable gain, one general-purpose amplifier, and an on-chip temperature sensor. These devices also offer intelligent digital peripherals such as four 16-bit general purpose timers, one windowed watchdog timer, and a variety of communication peripherals including two UARTs, one SPI, and two I 2Cs. These communication peripherals offer protocol support for LIN, IrDA, DALI, Manchester, Smart Card, SMBus, and PMBus.

The TI MSPM0 family of low-power MCUs consists of devices with varying degrees of analog and digital integration allowing for customers find the MCU that meets the needs of their projects. The architecture combined with extensive low-power modes are optimized to achieve extended battery life

MSPM0Gx MCUs are supported by an extensive hardware and software ecosystem with reference designs and code examples to get the design started quickly. Development kits include a LaunchPad™ Development Kit available for purchase and design files for a Target-Socket Board. TI also provides a free MSP Software Development Kit (SDK), which is available as a component of Code Composer Studio™ IDE desktop and cloud version within the TI Resource Explorer. MSPM0 MCUs are also supported by extensive online collateral, training with MSP Academy, and online support through the TI E2E™ support forums.

2.2.4 TPS26624DRCR

The TPS26624 is a high-voltage eFuse with a wide input range of 4.5 V to 60 V. The device comes with multiple built-in features such as OCP (Overcurrent protection), OVP (Overvoltage protection), Input Reverse Polarity protection, and Output reverse polarity protection. The integrated field-effect transistors (FET) provide a smaller footprint, and with a back-to-back FET topology, holdup time requirements can be met. In this design, this feature can protect the board in case of a rapid shutdown command, or other rapid shutdown scenario. The built-in current limit is adjustable by means of a resistor from 25 mA to 880 mA. In this implementation, a current limit of 500 mA was set.

2.2.5 LM5164QDDARQ1

The LM5164 is a synchronous buck converter designed to regulate over a wide input voltage range, minimizing the need for external surge suppression components. The input of the LM5164 can go down as low as 6 V, and up to a maximum input voltage of 100 V. The constant on-time (COT) control architecture provides nearly constant switching frequency with excellent load and line transient response. An additional feature of the LM5164 is the excellent quiescent current consumption.

2.2.6 TPS560430X3FDBVR

The TPS650430X3 is a fixed 3.3-V, 1.1-MHz switching synchronous step-down converter with a 600-mA maximum load current. Features built-in are cycle-by-cycle current limit, hiccup mode short-circuit protection and built-in thermal shutdown in case of excessive power dissipation. The device also comes in a small package (2.90 mm × 1.6 mm).

2.2.7 TMUX1204DGSR

The TMUX1204 is a modern complementary metal-oxide semiconductor analog multiplexer. The device comes in a 4:1 single ended (1-channel) configuration with a single supply from 1.08 V to 5.5 V. A low supply current of 10 nA makes this device an excellent choice for solar applications. All logic inputs have 1.8-V logic compatible thresholds, providing both TTL and CMOS logic compatibility when operating in the valid supply voltage range. Fail-safe logic circuity allows voltages on the control pins to be applied before the supply pin, protecting the device from potential damage.

2.3 Design Considerations

2.3.1 Modulator and Carrier Frequency Selection

A microcontroller is necessary to operate the TIDA-010935. From the microcontroller, the data requested can be sent across the power line by means of a modulator and a line driver. The TIDA-010935 uses a THVD8000 RS-485 transceiver with OOK modulation scheme as a modulator.
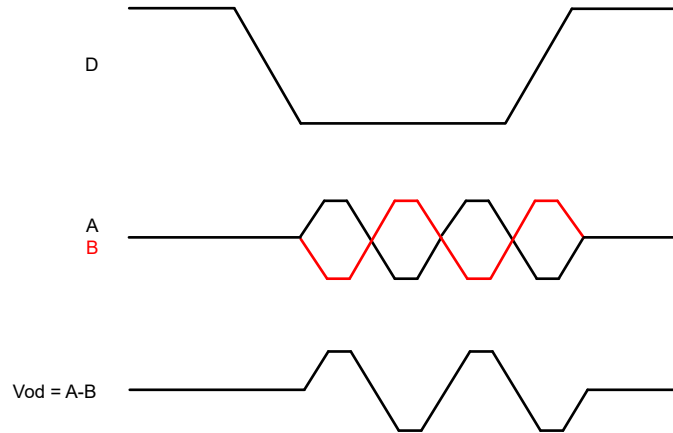
Modulation of the incoming data (**D**). Signal being produced is a differential signal, coming out of both A and B pins from the THVD8000. A logic high on the data pin results in a 0-V signal, whereas a logic low produces an oscillating signal seen at Vod.

Figure 2-2. OOK Mode

An additional feature of the THVD8000 is the *FSET* pin, which allows by means of an external resistor, to determine what carrier frequency to use for the modulation and demodulation scheme. The THVD8000 has carrier frequencies ranging from 125 kHz up to 5 MHz in set distances. To allow testing for multiple carrier frequencies in this system, 4 relevant carrier frequencies were selected and can be selected on the software side by means of setting the FSETB0 and FSETB1 values. Table 2-1 shows the available carrier frequencies for the TIDA-010935 and the corresponding resistor value necessary. Table 2-2 shows the necessary FSETB0 and FSETB1 values corresponding to the desired carrier frequency.

Table 2-1. Resistor Values vs Carrier Frequency

R_{F_SET} (kΩ)	OOK f_0 (kHz)
77	125
19	500
4.4	2000
1.5	5000

Table 2-2. FSET Values vs Carrier Frequency

FSETB0	FSETB1	OOK f_0 (kHz)
0	0	125
1	0	500
0	1	2000
1	1	5000

2.3.2 Power Consumption and Gain of the THS6222 Line Driver

With the selection of a carrier frequency, the modulated signal is fed into a line driver. The TIDA-010935 uses the THS6222 as a line driver, which boosts the incoming signal to 12 V. The THS6222 is a differential broadband buffer with a maximum sinking current of 328 mA.

Total power consumption is obviously dependent on the number of nodes attached on the PLC network with nodes describing individual TIDA-010935 module members. Node members are connected in series to the string inverter DC bus.

Nodes on a string. With the increasing number of members, the required sinking current needs to decrease to reach the signal 12-V peak.
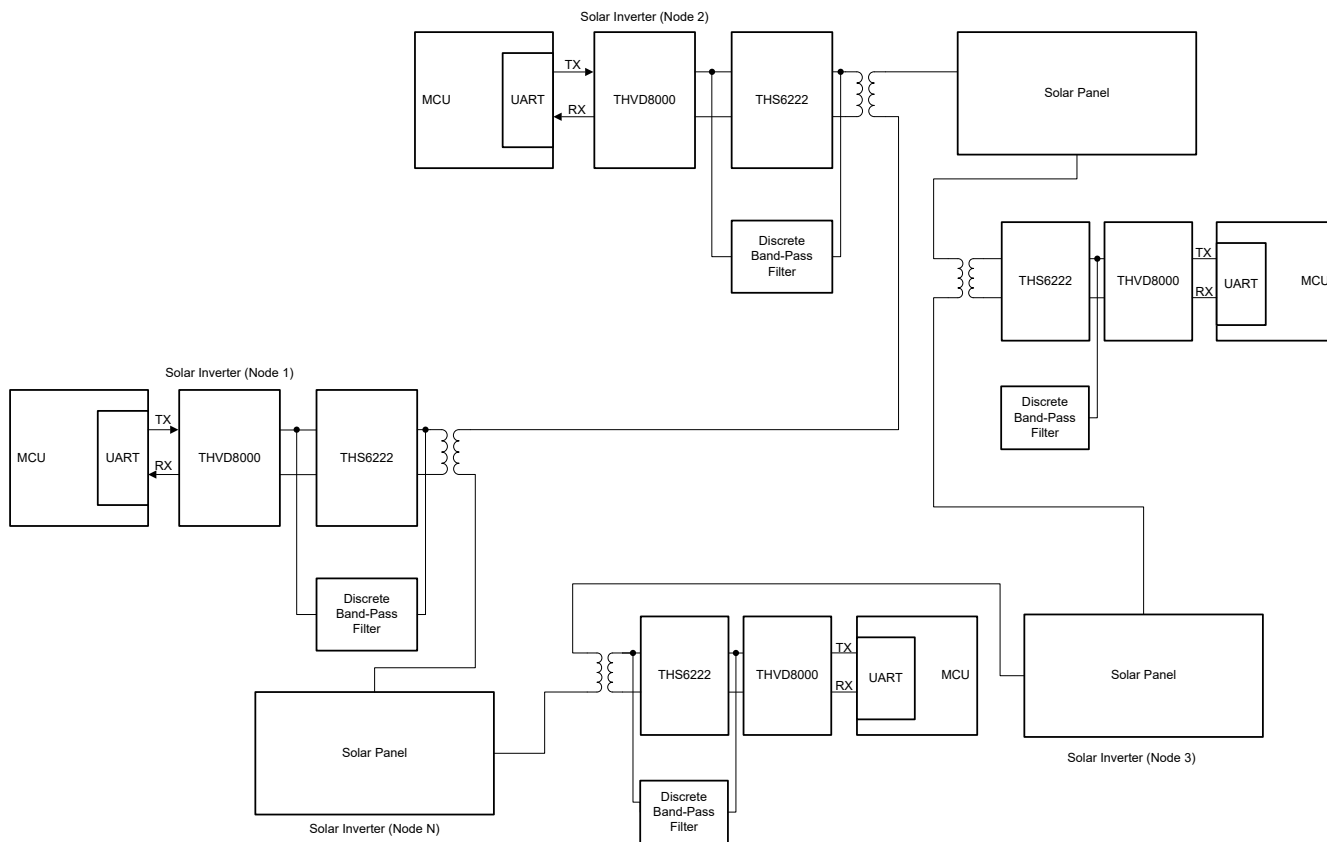

Figure 2-3. Application Example

Typically, multiple solar panels are attached on a string, each connected in series to reach the input voltage from a solar inverter. The required minimum sinking current is dependent on the total impedance on the PLC network and required signal peak voltage.

$$12 \text{ V } = I_{\text{sink}} \times Z_{\text{PLC, Net}} \tag{1}$$

$$I_{\text{sink}} = \frac{12 \text{ V}}{Z_{\text{PLC, Net}}} \tag{2}$$

The THS6222 features a bias setting input with 4 different modes. Table 2-3 lists all modes of the THS6222 in dependence of bias pin inputs with expected quiescent current consumption.

Table 2-3. Quiescent Current Consumption in Dependence of Bias Modes of the THS6222

BIAS1	BIAS2	MODE	QUIESCENT CURRENT AT 50 Ω AND 12-V SUPPLY
0	0	Off	1.1 mA
1	0	Low Bias Mode	10.4 mA
0	1	Mid Bias Mode	15 mA
1	1	Full Bias Mode	19.5 mA

Adjusting the bias setting of the TIDA-010935, allows for greater control over the overall efficiency of the TIDA-010935 or each node, more specifically. Ideally, this reference design is powered by a solar panel and efficiency is very important. The software included adjusts the bias between two modes, namely *OFF* and *TX-MODE*. During a transmit phase, the THVD8000 bias settings are set to the TX-MODE, which essentially determines which mode the device needs to use to amplify the modulated signal. After the message has been

successfully transmitted, the THVD8000 is shut off to increase efficiency. Additionally, if the device was not put in this mode during receiving a message, signal degradation occurred. This is because if the device is not put in high-impedance mode, or, *OFF*, a part of the signal current seeps into the device which reduces signal strength.

A proper gain resistor must be selected for the THS6222. The *detailed design procedure* section of the *TPS2662x 60-V, 800-mA Industrial eFuse With Integrated Input and Output Reverse Polarity Protection* data sheet describes which gain resistor to select to *not* bring the amplifier in saturation, if another value is desired. The gain resistor marked R9 is a 1.24-kΩ resistor giving a gain of 3. This way, a 3.3-V input signal does not drive the THS6222 into saturation as a higher gain goes beyond the input supply voltage, thus clamping can happen.

Figure 2-4 shows the schematic of the THS6222 line driver. The bias pins BIAS-1 and BIAS-2 determine the amount of current desired for current sinking. The R9 resistor determines the V/V gain. See the *THS6222* data sheet for the maximum possible gain and which resistor is required.
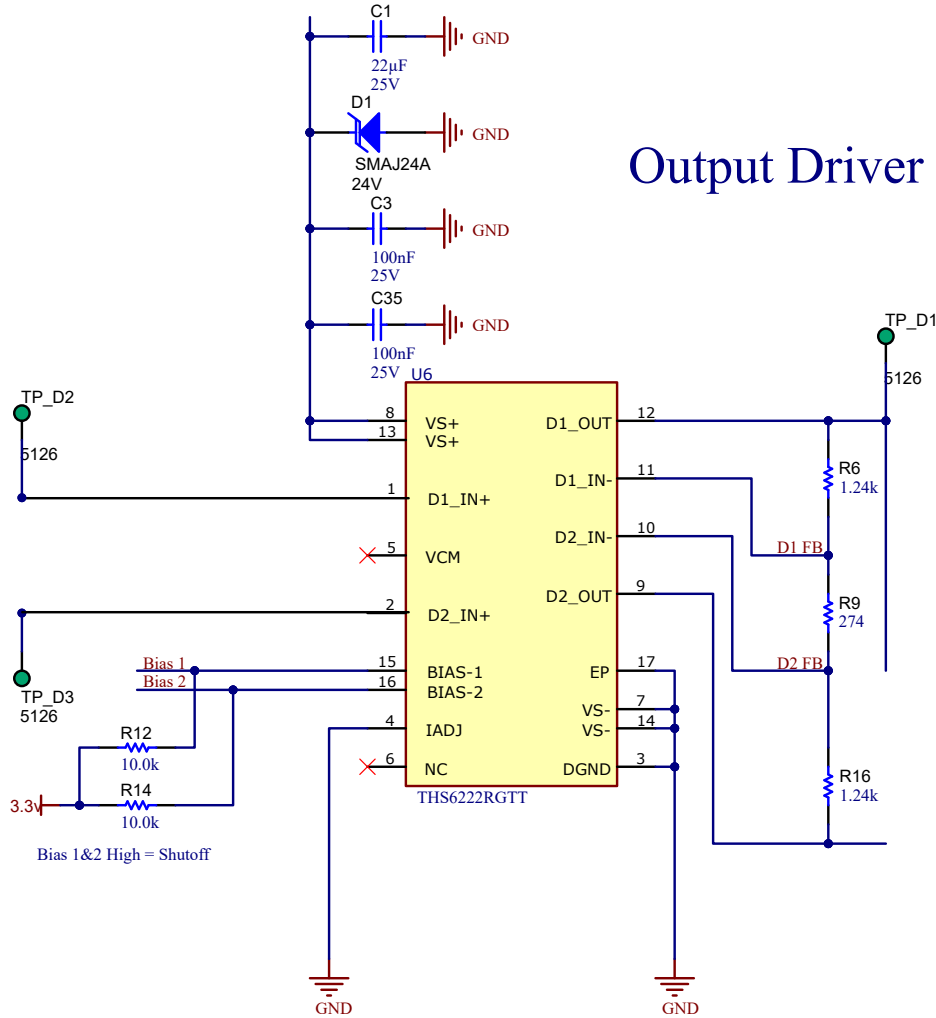
Figure 2-4. THS6222 Circuit

2.3.3 Front End and Discrete Filter

The THS6222 amplifies the signal coming from the THVD8000 RS-485 OOK transmitter. This signal is AC coupled into the DC bus, where all the power from the solar panels is injected, by means of an RF transformer.

Figure 2-5 illustrates a schematic of the signal front end. The signs "+" and "-" are the series connections into the DC bus.
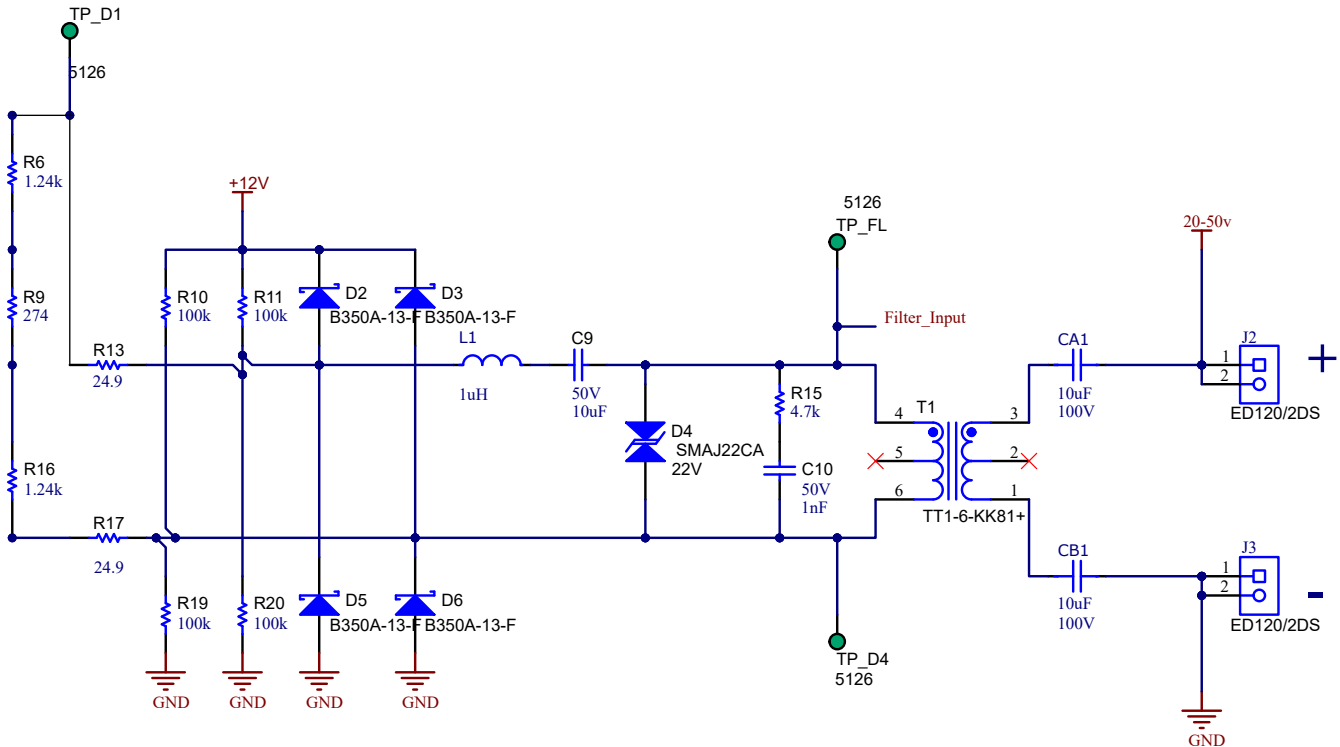
Figure 2-5. Front End

The resistors R13 and R17 are necessary for the out-of-band suppression to keep the data within a certain power level. Next to R13 and R17, are the required biasing resistors R10, R19, R11, and R20, as a signal can be sent out differentially; however, received quasi-single ended. These biasing resistors keep offset to a minimum between the A and B lines. Schottky diodes and TVS are put in place as PLC modules typically operate in harsh environments and suppress unwanted surges. A bandwidth-limiting filter comprised of L1 and C9 are included, as well as a snubber circuit R15 and C10 to avoid high-frequency switching noise being sent over.

As power lines voltage in this application is quite high, an appropriate coupling design has to be made. With higher current, thicker cables are necessary for the transformer if a DC current of > 10 A is expected. This makes a small footprint PCB practically impossible, if this DC current is not decoupled first since such a large transformer is required. CA1 and CB1 are there to reject the DC current, and allow the AC currents pass by which alleviates this problem.

A band-pass filter is implemented for received signals. Since this design supports 4 different carrier frequencies, a filter for each of them was designed.

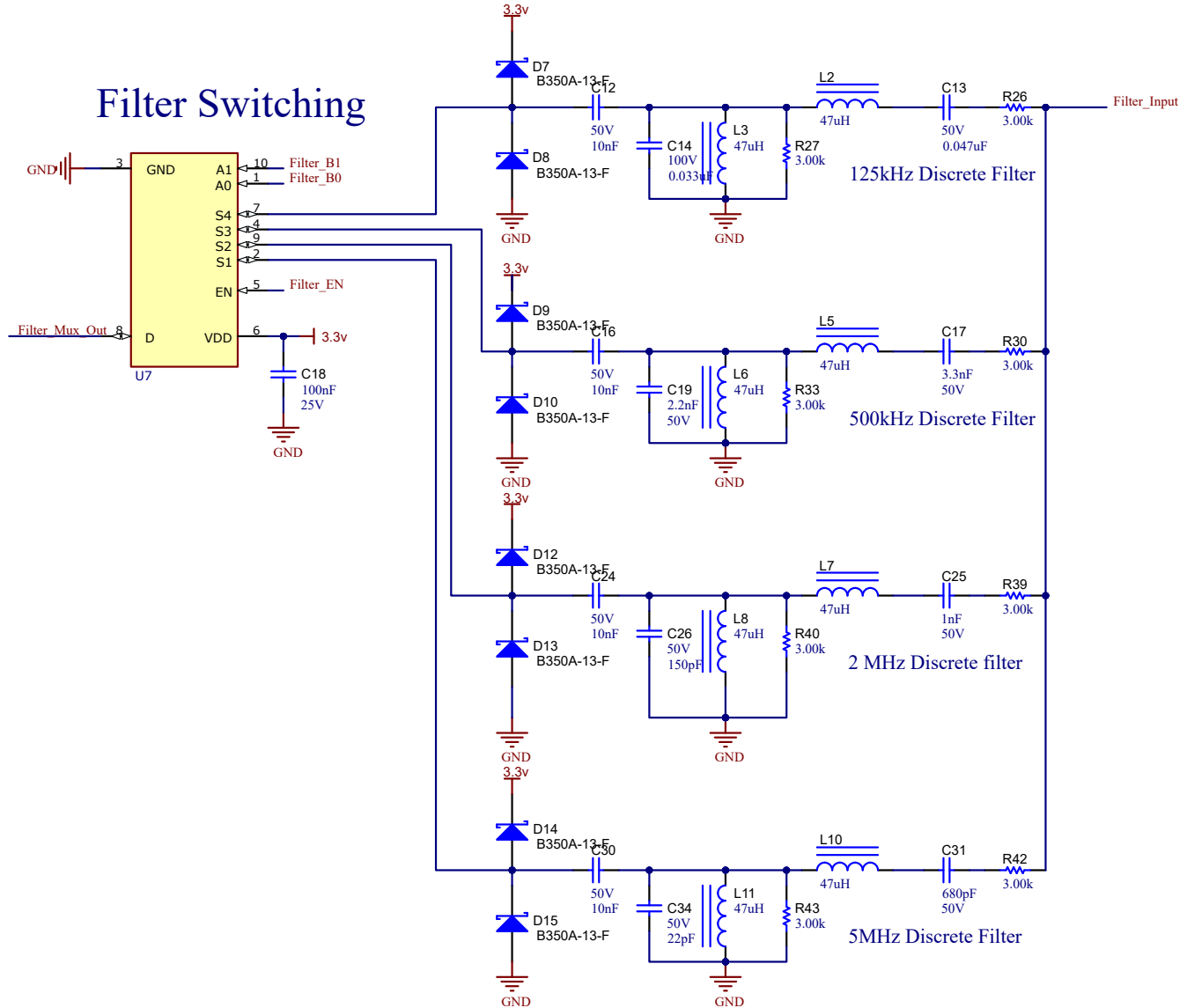Figure 2-6 shows the discrete filter for 4 different carrier frequencies.

Figure 2-6. Discrete Filter

After the discrete filter, another TMUX1204 device is used to connect the correct filter to the THVD8000, according to which carrier frequency was selected. The TMUX1204 has a leakage source off current of 75 nA, and a drain off leakage current of 200 nA (see the electrical characteristics (V_{DD} = 5 V ±10%) section of the *TMUX1204 5-V, 4:1, General Purpose Analog Multiplexer* data sheet. This makes the device an excellent choice in our application as a very minimal leakage current increases overall efficiency of the system. The analog MUX routes the signal back to the THVD8000, where the devices switch from a transmit state to the receive state, demodulates the signal, and feeds the signal back to the MCU, per UART.

To control the TMUX1204, two-selection pins FILTER_B0, FILTER_B1 and one enable pin FILTER_EN are provided. Accordingly to the combination of those 3 pins it is possible to select the correct demodulating frequency.

Table 2-4. Demodulating Frequency Selection

FILTER_EN	FILTER_B0	FILTER_B1	FREQUENCY_OUT (kHz)
0	X	X	Transmitting phase, no demodulation
1	0	0	125
1	0	1	500
1	1	0	2000
1	1	1	5000

2.3.4 THVD8000 Schematic

Figure 2-7 shows the schematic overview of the THVD8000.
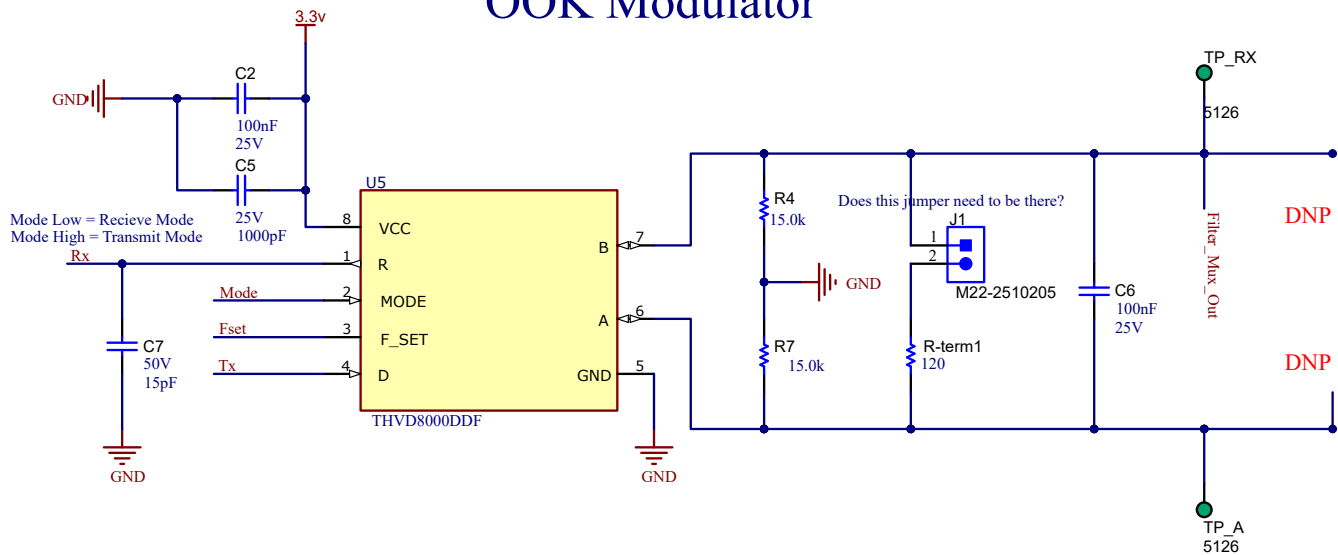
Figure 2-7. THVD8000 Schematic

The selection between transmitting and receiving phase is handled by the THVD8000 as depicted in Figure 2-7. The FSET pin provides the carrier frequency, chosen by the TMUX between 125 kHz, 500 kHz, 2 MHz, and 5 MHz.

The MODE pin is responsible of setting the receiving (set low) and the transmitting (set high) phase, if the TX phase is active the signal is taken as input from the pin D, if the RX phase is active the R pin is taken as output.

2.3.5 Board Pinout

Table 2-5 provides descriptions of the pins.

Table 2-5. Pinout Table

PIN NUMBER	PIN NAME	DESCRIPTION
1	3.3V	3.3-V power supply
3	RX	Receiver pin
4	TX	Transmitter pin
5	SHDN	Shutdown pin, set high to enable the communication
8	MODE	Mode pin, set high for enabling transmitting phase, low for receiving phase
11	FLT	FLT pin, if set high the device is off, if low the device can work
20	GND	Ground connection
22	GND	Ground connection
31	FILTER_B1	TMUX pin for filter selection
32	FILTER_B0	TMUX pin for filter selection
33	FSET_B1	Modulation frequency selection pin
34	FSET_B0	Modulation frequency selection pin
35	FILTER_EN	Enable pin for activating TMUX and demodulation
39	BIAS_1	Current consumption selection pin
40	BIAS_2	Current consumption selection pin

3 Hardware, Software, Testing Requirements and Test Results

For testing the TIDA-010935, MSPM0G3507 LaunchPad Development Kit are used to change the GPIOs in real time for board configuration and data exchange.

To automatically test that the correct value is received, two different programs are loaded to the tho communication nodes (each consisting of a TIDA-010935 and a MSPM0G3507 LaunchPad:

- *External loopback*: The first data package is sent through the TIDA-010935 configuring the correspondent GPIOs to allow data transmission. After the data is sent, the configuration changes in receive mode to wait for the data to be sent back

- *Echo interrupt* : First configured in receive mode after some data arrives, switches in transmitting mode and sends the data back, after the transmission returns back in receive mode.

As soon as the transmission is started by the external loopback software, it transmits the first byte of data. After the data is received and sent back by the echo interrupt software, the external loopback software checks if the received data is equal to the sent data. If so, the data sent is incremented and the loop starts again.

This is a way to automatically check correct transmission of data between both nodes for preservation of data integrity. Connect the 2 microcontrollers to different PCs and the 2 TIDA reference designs to different power supplies, to avoid ground loops.

The software automatically changes GPIO values so that both boards can receive and transmit. In Code Composer Studio debug mode it is possible to change the modulation and demodulation frequency from the 4 possible choices, that is, 125 kHz, 500 kHz, 2 MHz, and 5 MHz by adjusting the according variables.
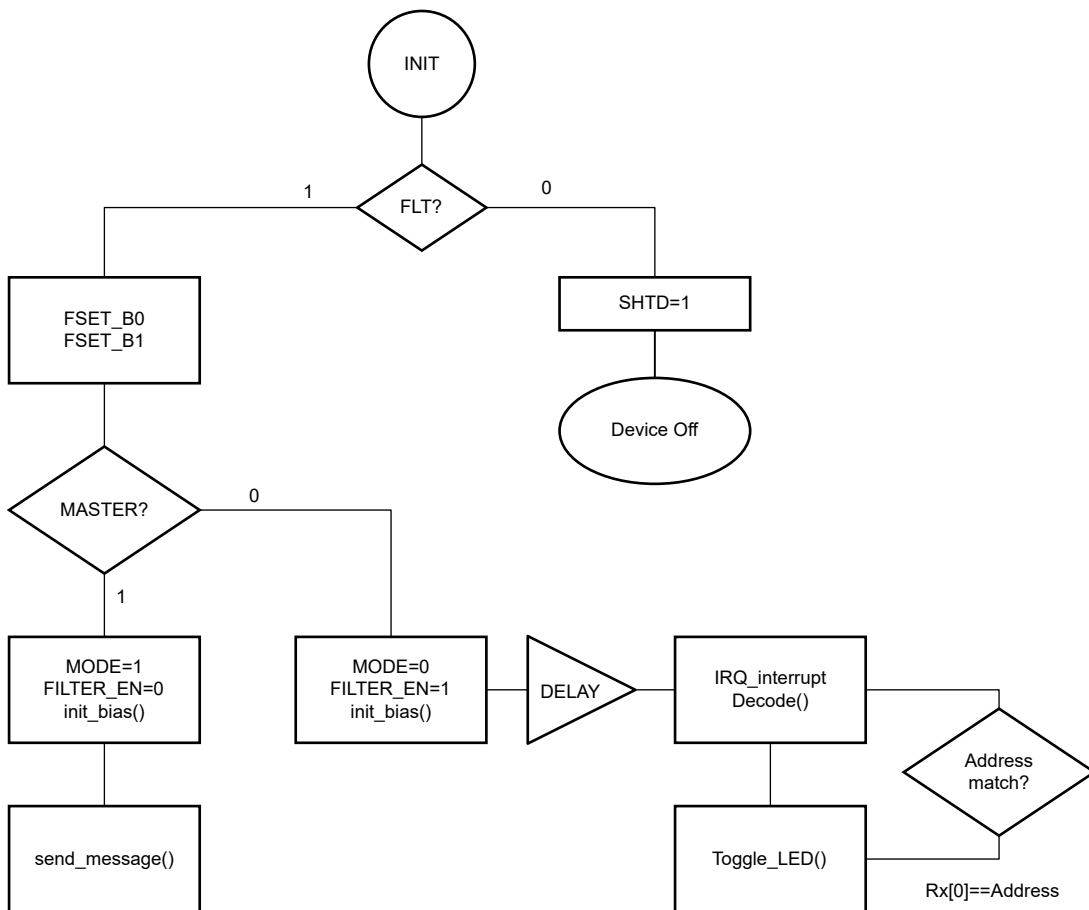

Figure 3-1. Flow Chart for the Built-in Software Implementation Using UART

3.1 Test Setup

In this project, the LP-MSPM0G3507 LaunchPad Development Kit was used to drive the TIDA-010935, the pin disposition was designed to superimpose the TIDA to the LaunchPad. Alternatively, jumpers can be used to connect TIDA pins to the GPIOs of a generic microcontroller using the information in Table 2-5.

The board is then connected to a power supply between 13.5 V and 50 V. Best design practice includes keeping the two boards isolated using different supplies. The 2 TIDA designs are connected to each other through jumpers J2 and J3 with two resistors that have the same value.

The connection between the two TIDA designs was made with two 15-Ω resistors, but also 20-Ω and 100-Ω were tried.

3.1.1 Powering the TIDA-010935

Powering the TIDA-010935 requires an input voltage ranging from 13.5 V to 50 V. This is done to match the varying output voltage from a solar panel as it is possible that the output power is not constant. Supplying the TIDA-010935 with solar power is done by connecting the DC cables coming from the solar panel according to the poles described at the J2 and J3 headers. J2 is the positive pole while J3 is the negative pole. To power the board from these connectors, jumper J4 needs to be populated.

Alternatively, the board can be powered by an auxiliary supply connected to the AUX_Supply connector. The same input voltages can be used and the polarity is marked on the board. In this case, do not populate jumper.
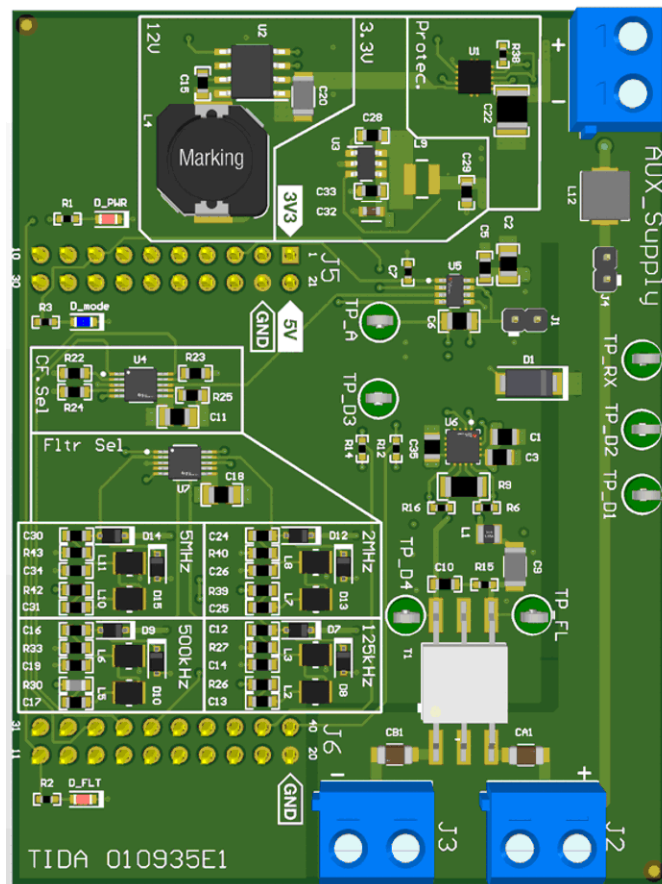
Figure 3-2. Board AUX Supply

3.2 Test Results
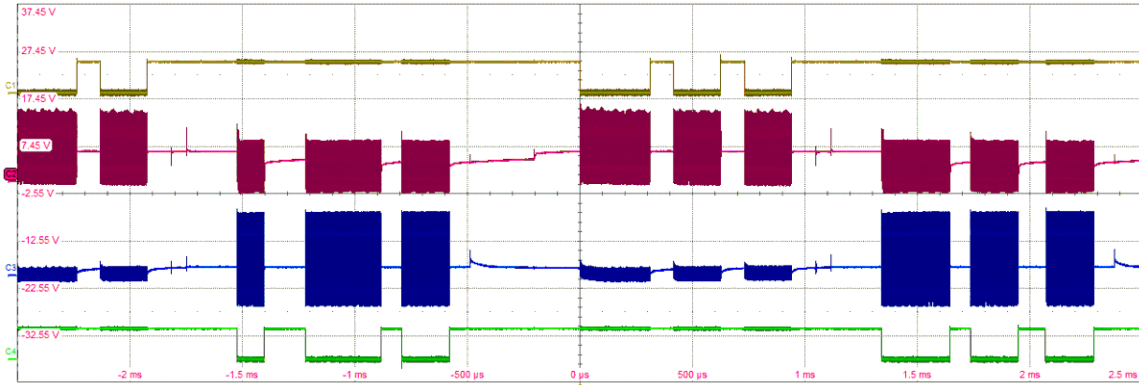
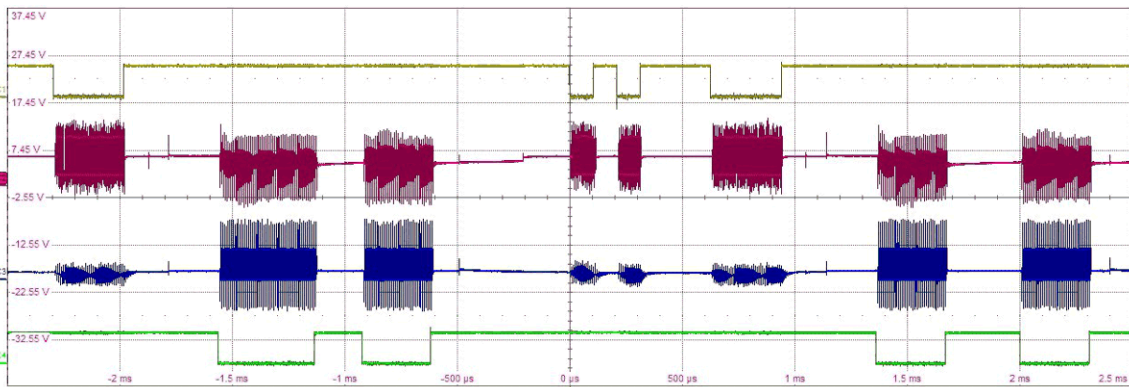**Figure 3-3. Signal Chain Waveforms at 5 MHz**

Figure 3-4. Signal Chain Waveforms at 125 kHz

Figure 3-3 show the signal chain waveforms, taken from different points on the boards, from top to bottom:

- Yellow: TX pin taken on the board that is transmitting the data
- Red: Differential signal taken at the test points TP_FL and TP_D4, after the THS6222 and before the transformers that deliver the signal from one board to the other
- Blue: Differential signal taken at the test points TP_RX and TP_A, on the receiver board before the THVD8000 demodulation
- Green: TX pin taken on the board that is receiving data

Observe that the 2 waveforms in the middle of each waveform image also have some signal oscillations when the board is not transmitting any data, due to the fact that the line is used on both directions of communication receiving and transmitting.

The delay between the TX and RX pin is composed by 2 different contributions: a fixed software delay is purposefully placed to ease all the signal chain waveforms visualization and a propagation delay which depends from the demodulating frequency chosen and decrements with the increase of the frequency, which is equal for both falling and rising edges.

Pins FSET0 and FSET1 are responsible for selecting the frequency and the corresponding propagation delays are shown in Table 3-1, the filter response in frequency is shown, with the selected pins FSET0 and FSET1, in Figure 3-5.

Table 3-1. Delay Input-Output Depending on the Chosen Frequency

FSET0	FSET1	DELAY (µs)	FREQUENCY (kHz)
0	0	32	125
0	1	8.7	500
1	0	2.5	2000
0	1	1.2	5000
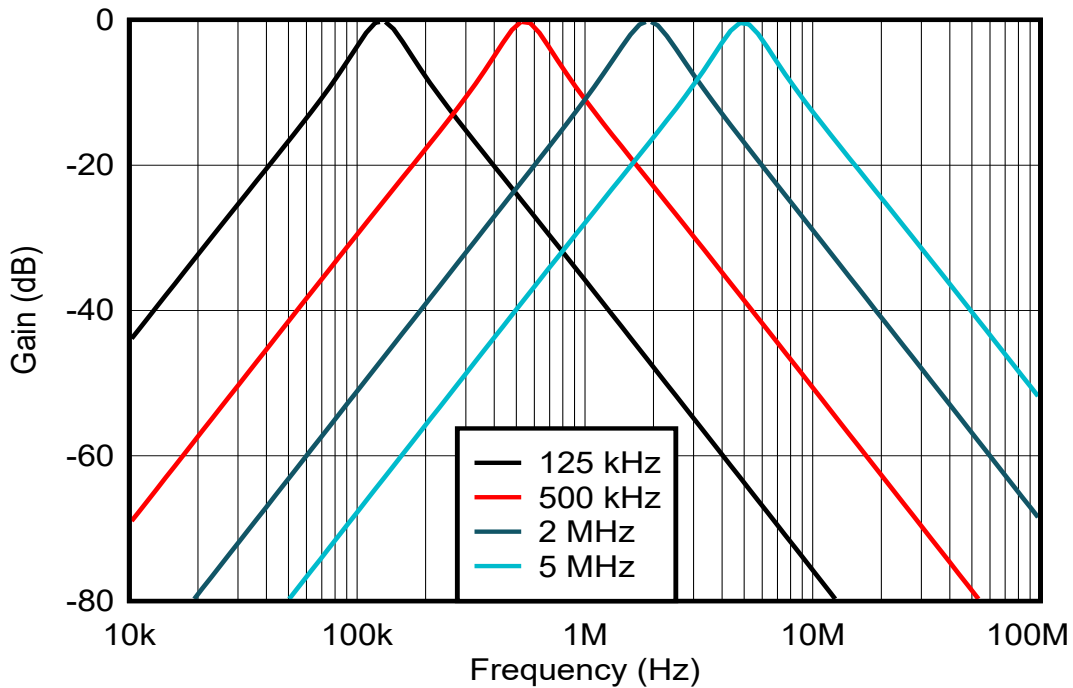
Figure 3-5. Frequency Response of the 4 Selectable Passive Filters

4 Design and Documentation Support

4.1 Design Files

4.1.1 Schematics

To download the schematics, see the design files at TIDA-010935.

4.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010935.

4.2 Documentation Support

1. Texas Instruments, *TPS2662x 60-V, 800-mA Industrial eFuse With Integrated Input and Output Reverse* data sheet
2. Texas Instruments, *LM5164-Q1 100-V Input, 1-A synchronous buck DC/DC converter with ultra-low I$_Q$* data sheet
3. Texas Instruments, *TPS560430 SIMPLE SWITCHER® 4-V to 36-V, 600-mA Synchronous Step-Down Converter* data sheet
4. Texas Instruments, *THVD8000 RS-485 Transceiver with OOK Modulation for Power Line Communication* data sheet
5. Texas Instruments, *THS6222 8 V to 32 V, Differential HPLC Line Driver with Common-Mode Buffer* data sheet
6. Texas Instruments, *TMUX1204 5-V, 4:1, General Purpose Analog Multiplexer* data sheet
7. Texas Instruments, *MSPM0G3507 LaunchPad Development Kit (LP-MSPM0G3507)* user's guide

4.3 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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5 About the Author

ANDREAS LECHNER is a Systems Engineer working in the Systems Team for Grid Infrastructure and Renewable Energy at Texas Instruments. Andreas earned his master's degree in electrical engineering from the University of Applied Sciences in Landshut, Germany.

6 Revision History

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

Changes from Revision * (November 2023) to Revision A (February 2024)   **Page**
- Changed labels on the NC pin from 7 to 6, and the Vs- pin from 6 to 7 in Figure 2-4.......................................6

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