

TI Designs: TIDA-01069

Advanced Motion Detector Using PIR Sensors Reference Design For False Trigger Avoidance



Description

This reference design is an analog front-end for an advanced motion detector based on two PIR sensors for false trigger avoidance, enabling machine learning. This TI Design has a standard BoosterPack™ pinout, uses Texas Instruments low-power components, and runs on one AAA alkaline battery cell.

Resources

TIDA-01069	Design Folder
OPA349	Product Folder
TLV369	Product Folder
TLV3691	Product Folder
ADS1114	Product Folder
TPS610981	Product Folder
HDC1010	Product Folder
OPT3002	Product Folder
TPD1E10B06	Product Folder

Features

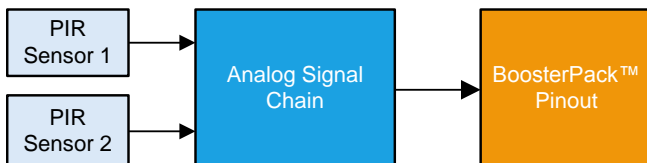
- Two PIR Sensors With Separate Area of Detection
- Sensitivity up to > 30 ft (≈ 9 m)
- Standard BoosterPack Pinout
- False Detection Avoidance
- Battery Based Low-Power Design
- Work With Different MCUs and DSPs
- Machine Learning Enabled

Applications

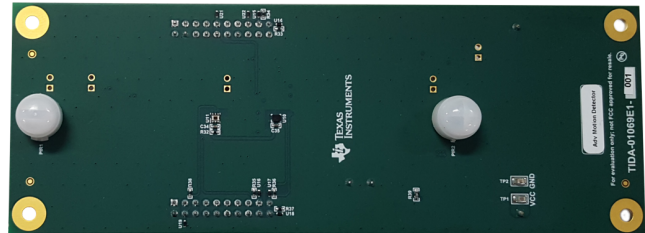
- Building Automation
- Motion Detection
- Intrusion Detection
- Occupancy Detector
- Room Monitors
- Pet Detection
- Fire Detection
- Falling Person Detection



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1 System Description

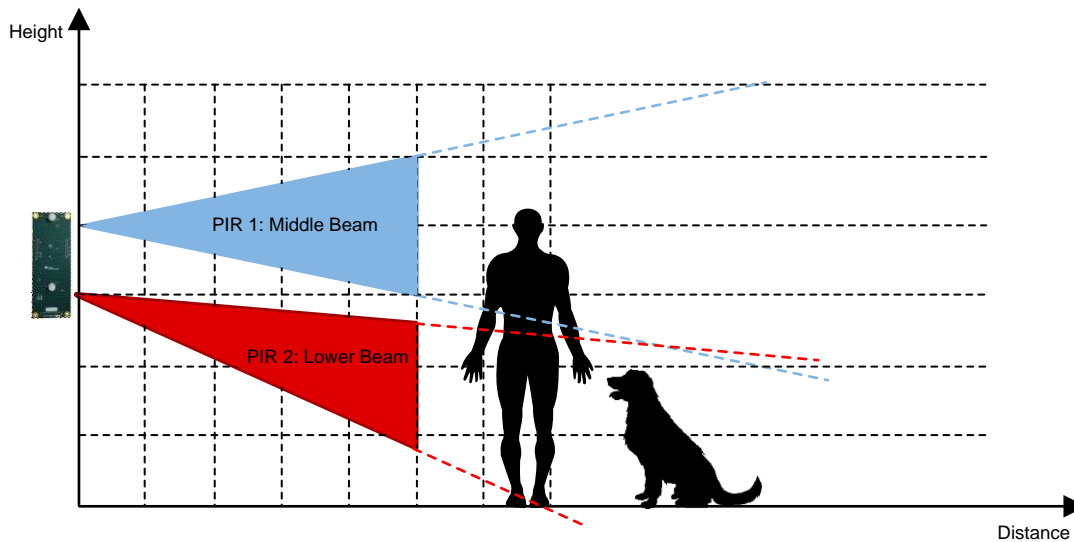


Figure 1. Operation Principle of System

Modern buildings are installing intelligence for energy and system efficiency through wireless sensor nodes. These sensor nodes must maintain a long battery life (up to 10 years preferably) while constantly monitoring key parameters such as temperature, humidity, occupancy. In building automation, PIR motion detectors are incorporated in an overall echo system, including comfort control to airflow control in heating, ventilation, and air conditioning (HVAC) systems as well as lighting, safety, and security. PIR motion detectors require just a PIR sensor and a few components around the sensor to make them work.

Motion detectors containing one PIR sensor, a Fresnel lens with a cone-type beam, and a binary output are very efficient for detecting any type of motion, including a human or pet. However, imagine a customer application based on this type of motion detector that sends a notification and switches on a light when any motion is detected. It could be very annoying to receive notifications and on and off the light, for example, when a pet is moving around in the house while the owner is outside. In addition to this, other false triggering can appear due to quick environment variation such a light or temperature variation.

In order to avoid false triggering, this reference design uses two PIR sensors instead of one, with two Fresnel lens covering distinctly the middle area and the lower area of detection (see [Figure 1](#)).

Enabled by Texas Instruments, at a high level this TI Design consists of an analog front-end with a [standard BoosterPack pinout](#) based on AAA alkaline cell battery, four low-power operational amplifiers (op amps), two nanopower comparators, two low-power ADCs, one digital light sensor, one digital temperature sensor, and two PIR sensors with analog signal output. Each PIR sensor is followed by an op amp forming an amplified bandpass filter with a high input impedance, which allows it to be connected directly to the sensor without loading it. The output of these two amplifiers goes in an another summing op amp with gain and a band-pass filter. The two comparators form a window comparator, which is used to compare the amplified AC sensors output at summer to fixed reference thresholds so that motion can be distinguished from noise. The two outputs of the window comparator can serve as interrupts to the MCU so that the MCU can operate in its lowest power sleep mode during times where there is no motion being detected and only wakes when motion has been detected on one of the two PIR sensors.

When any motion is detected through the windows comparator, the MCU switches the two ADCs from power down to operating mode and starts data acquisition of the amplified signals from the PIR sensors. In the meantime, data from the light sensor and temperature can be acquired for a better detection efficiency. Thanks to wavelet, it is possible to have a specific "signature" for different kind of motion in a time-frequency domain, allowing efficient motion detection and false triggering avoidance. Properly applied machine learning or artificial intelligence will open the door for new types of intelligent motion detectors. These motion detectors are able to adapt to different environments and detect more than just human motion.

This design guide addresses component selection, design theory, and the signal integrity results of this TI Design. The scope of this design guide gives system designers a head-start in integrating TI's low-power analog components and MCU platform. The following subsections describe the various blocks within the TI Design system and which characteristics are most critical to best implement the corresponding function.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Input power source	AAA alkaline cell battery (1.5-V nominal voltage)
Sensor type	Pyroelectric or passive infrared (PIR)
Average current consumption	21 μ A
Average current consumption with ADCs in Operating Mode	835 μ A
Standby-state duration	Around 1 minute and half of no motion detected
Motion sensing range	30 ft (9 m) nominal
Operating temperature	-18°C to 55°C (limited by AAA alkaline cell battery operating range)
Working environment	Indoor and outdoor
Form factor	55.88x152.44-mm rectangular PCB

2 System Overview

2.1 Block Diagram

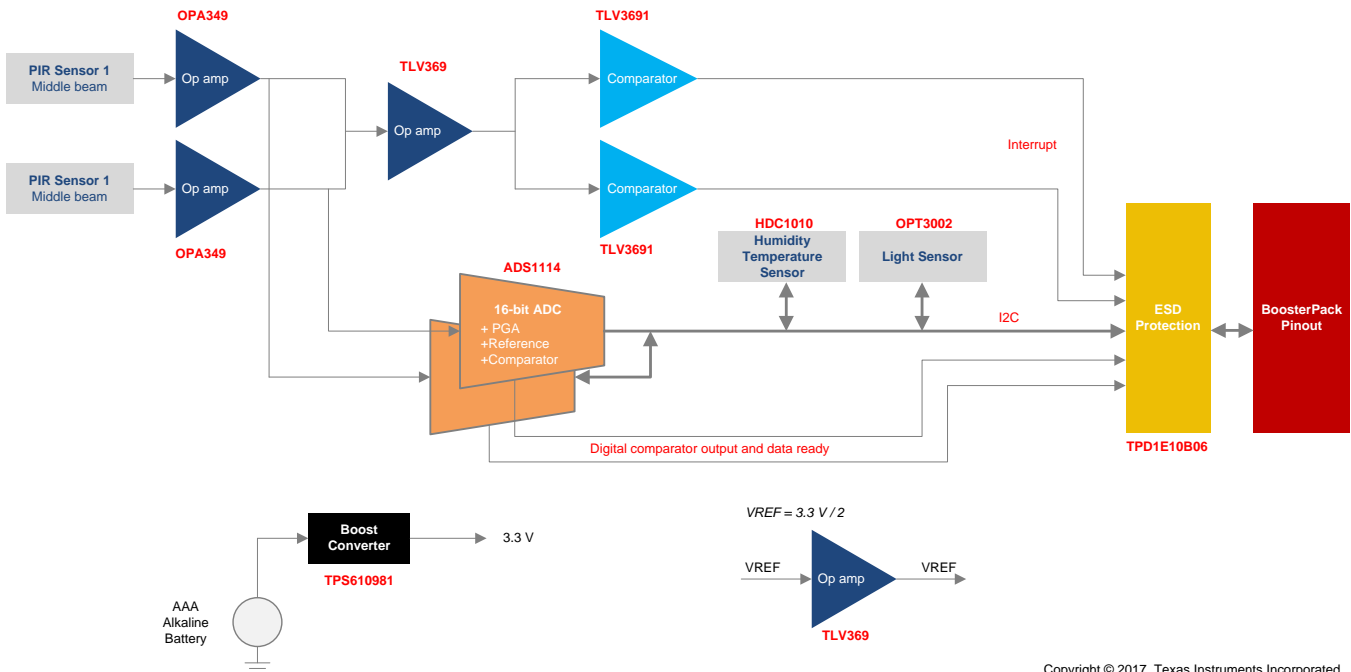


Figure 2. TIDA-01069 System Block Diagram

2.2 Design Considerations

2.2.1 Operational Amplifiers

In this TI Design, it is necessary to amplify and filter the signal at the output of the PIR sensor so that the signal amplitudes going into following stages in the signal chain are large enough to provide useful information.

Typical signal levels at the output of a PIR sensor are in the micro-volt range for motion of distant objects, which exemplifies the need for amplification. First, the filtering function is necessary to limit the noise bandwidth of the system before reaching the input to the window comparator. Second, the filtering function sets limits for the minimum and maximum speed at which the system will detect movement.

For a long battery life, this TI Design uses the OPA349 and TLV369 because of the low current consumption respectively of 1 μA and 800 nA (typical) per amplifier. Other considerations that make the OPA349 and TLV369 ideal for this TI Design are the low input voltage offset and low input bias current, which allows use of high value resistors and rail-to-rail operation on both input and output. Additionally, the OPA349 and TLV369 integrates EMI protection to reduce sensitivity to unwanted RF signals, which is useful for low-power designs because of their high impedance nodes.

2.2.2 Comparators

In this TI Design, it is necessary to convert the amplified and filtered version of the sensor output into digital signals, which can be used as inputs to the MCU or DSP. To accomplish this, a window comparator circuit is used.

The low current consumption of only 75 nA (typical) per comparator makes the TLV3691 in this TI Design ideal. Other considerations for the comparator in this reference design include its low input voltage offset and low input bias current. Additionally, the TLV3691 features a rail-to-rail input stage with an input common-mode range, which exceeds the supply rails by 100 mV, thereby preventing output phase inversion when the voltage at the input pins exceed the supply. This translates not only into robustness to supply noise, but also maximizes the flexibility in adjusting the window comparator thresholds in this TI Design.

2.2.3 Analog-to-Digital Converters

The main purpose of this motion detector reference design is to avoid false triggering. To accomplish this purpose, an intelligent signal processing and algorithm implementation is needed. Because the PIR sensors provide an analog output, the output needs to be converted from analog to digital for the MCU or DSP. In the meantime, the low power consumption for a battery-based design and low-cost solution are key criteria in this TI Design. In addition, the signal from the PIR sensor can be very small even after the amplification, for that a high-resolution ADC is preferred in order to have enough precision during data acquisition.

The ADS1114 is a 16-bit delta-sigma ADC that is an ideal solution for this TI Design with its integrated programmable gain amplifier (PGA), voltage reference, oscillator, and digital comparator, and it consume only 150 μ A during operating mode and 0.5 μ A during power-down mode.

This fully integrated solution reduces the cost, and the combination of the integrated PGA and the 16-bit resolution of the ADC allows for an accurate data acquisition for small signals.

2.2.4 Light and Temperature Sensors

To avoid false triggering due to quick environmental changes like temperature or light variations, additional sensors are required for better efficiency.

The HDC1010 is an ideal solution to avoid false triggering due to quick changes in temperature. This device is a digital temperature sensor, low power (1.3 μ A) and low-cost solution with an integrated humidity sensor that can be used for outdoor applications. The HDC1010 does not need external signal conditioning and it is ready to use through the I²C bus.

The OPT3002 is an ideal solution to avoid false triggering due to quick changes in light. This device is a digital light sensor, low power (1.8 μ A) and low-cost solution with a wide optical spectrum (300 to 1000 nm). The OPT3002 does not need external signal conditioning and it is ready to use through the I²C bus.

2.2.5 AAA Alkaline Cell

The power source for this TI Design is a AAA alkaline cell battery. The AAA alkaline cell battery as the power source was selected due to the ubiquity of that battery type, size, and the capacity over time compared to a coin-cell battery. The output voltage decreases linearly throughout the discharge life until the cell is nearly depleted (in the range of 0.8 to 1.0 V). When the cell is depleted, the output voltage drops off relatively quickly. The voltage characteristics of a AAA alkaline cell battery does not really matter because this TI Design uses a boost converter for a fixed output voltage at 3.3 V.

The temperature characteristics of the alkaline cells are inferior to lithium-ion batteries (coin cell battery) particularly at lower temperatures. The recommended operating temperature range for alkaline batteries is -18°C to 55°C . This range is still fairly enough for general motion detection applications. However, the AAA Alkaline cell battery is still the limiting component in terms of the operating temperature range; all of the integrated circuits and other electrical components are specified to operate at a wider temperature range than the battery. Therefore, the specified operating temperature range of the TI Design system is -18°C to 55°C . Given an appropriate weather-proof enclosure, this TI Design system is suited for both indoor and outdoor use.

This AAA alkaline cell battery is immediately followed by a low $R_{\text{DS_ON}}$ P-channel MOSFET. The P-channel MOSFET prevents damage to the hardware if cell battery is inserted backwards while minimizing the forward voltage drop in normal operation.

2.2.6 Boost Converter

The AAA alkaline cell battery used as power source for this TI Design has a nominal voltage at the beginning of life at 1.5 V and decreases linearly over time. The design is an analog front-end with a BoosterPack standard pinout, which means this reference design should plug on TI LaunchPad MCUs. The connection between this analog front-end and the MCU are digital and mostly uses the I²C bus. In order to avoid any damage due to voltage difference during the I²C communication between the MCU, the ADCs, and sensors and allow all the components to work correctly in the safe operating range, the power source must be fixed at 3.3 V.

For that the TPS610981 is an ideal solution for this TI Design. This booster converter with its operating input voltage from 0.7 to 4.5 V and ultra-low I_Q (300 nA) allow to have a power source at 3.3 V with high efficiency for low load.

2.2.7 PIR Sensors

This TI Design uses the Murata IRA-E700ST0 PIR sensor instead of the Murata IRS-B210ST01 PIR sensor (see the [TIDA-00489 design](#)) with the surface mount package because of the Fresnel lenses needed for this reference design.

While the test results collected for this TI Design are focused on a particular PIR sensor part number, it is expected that similar results can be obtained with any similarly specified PIR sensor that is available when the techniques and circuit designs demonstrated in this TI Design are applied.

As mentioned previously, this TI Design uses Fresnel lenses. In fact for any PIR sensor, it is necessary to use a lens in front of the sensor to extend the detection range by focusing the infrared energy onto the sensor elements. Using a Fresnel lens, the infrared image for the viewing area is spread across all of the sensor elements. Therefore, the lens shape and size determines the overall detection angle and viewing area. This TI Design uses the Murata IML-0635 lens for the middle area detection and the Murata IML-0636 for the lower area detection. Ultimately, the choice of lens is determined by the field of view angle and detection range required by the application.

2.3 Highlighted Products

The Advanced PIR Motion Detector reference design features the following devices:

- OPA349 ([Section 2.3.1](#)): 1- μ A, Rail-to-Rail I/O CMOS Operational Amplifier
- TLV369 ([Section 2.3.2](#)): Cost-Optimized, 800-nA, 1.8-V, Rail-to-Rail I/O Operational Amplifier With Zero-Crossover Distortion
- TLV3691 ([Section 2.3.3](#)): Nanopower, CMOS Input, Rail-to-Rail Input Comparator
- ADS1114 ([Section 2.3.4](#)): 16-Bit ADC With Integrated PGA, Comparator, Oscillator, and Reference
- TPS610981 ([Section 2.3.5](#)): Ultra-Low Quiescent Current Synchronous Boost With Integrated LDO/Load Switch
- HDC1010 ([Section 2.3.6](#)): Low-Power, High-Accuracy Digital Humidity Sensor With Temperature Sensor
- OPT3002 ([Section 2.3.7](#)): Light-to-Digital Sensor

For more information on each of these devices, see their respective product folders at www.TI.com.

2.3.1 OPA349

Features:

- Low supply current: 1 μ A
- Gain bandwidth: 70 kHz
- Unity-gain stable
- Low input bias current: 10 pA (max)
- Wide supply range: 1.8 to 5.5 V
- Input range: 200 mV beyond rails
- Output swings to 350 mV of rails
- Output drive current: 8 mA
- Open-loop gain: 90 dB
- Micro packages: SC70, SOT23-5, SOT23-8

Applications:

- Battery packs and power supplies
- Portable phones, pagers and cameras
- Solar-powered systems
- Smoke, gas, and fire detection systems
- Remote sensors
- PCMCIA cards
- Driving ADCs
- Micro power filters

The OPA349 and OPA2349 are ultra-low-power op amps that provide a 70-kHz bandwidth with only a 1- μ A quiescent current. These rail-to-rail input and output amplifiers are specifically designed for battery-powered applications. The input common-mode voltage range extends 200 mV beyond the power-supply rails and the output swings to within 350 mV of the rails, maintaining a wide dynamic range. Unlike some micropower op amps, these parts are unity-gain stable and require no external compensation to achieve wide bandwidth. The OPA349 features a low-input bias current that allows the use of large source and feedback resistors.

The OPA349 can be operated with power supplies from 1.8 to 5.5V with little change in performance, ensuring continuing superior performance even in low battery situations.

The OPA349 comes in miniature SOT23-5, SC70, and SO-8 surface-mount packages. The OPA2349 dual is available in SOT23-8 and SO-8 surface-mount packages. These tiny packages are ideal for use in high-density applications such as PCMCIA cards, battery packs, and portable instruments. The OPA349 is specified for 0°C to 70°C. The OPA2349 is specified for -40°C to 70°C.

2.3.2 TLV369

Features:

- Cost-optimized precision amplifier nanopower: 800 nA/Ch (Typ)
- Low offset voltage: 400 μV (typ)
- Rail-to-rail input and output
- Zero-crossover distortion
- Low offset drift: 0.5 $\mu\text{V}/^\circ\text{C}$ (Typ)
- Gain-bandwidth product: 12 kHz
- Supply voltage: 1.8 to 5.5 V
- Microsize packages: SC70-5, VSSOP-8

Applications:

- Blood glucose meters
- Test equipment
- Low-power sensor signal conditioning
- Portable devices

The TLV369 family of single and dual op amps represents a cost-optimized generation of 1.8-V nanopower amplifiers.

With the zero-crossover distortion circuitry, these amplifiers feature high linearity over the full common-mode input range with no crossover distortion, enabling true rail-to-rail input and operating from a 1.8- to 5.5-V single supply. The family is also compatible with industry-standard nominal voltages of 3.0 V, 3.3 V, and 5.0 V.

The TLV369 (single version) is offered in a 5-pin SC70 package. The TLV2369 (dual version) comes in 8-pin VSSOP and SOIC packages.

2.3.3 TLV3691

Features:

- Low quiescent current: 75 nA
- Wide supply:
 - 0.9 to 6.5 V
 - ± 0.45 to ± 3.25 V
- Micropackages: DFN-6 (1 mm × 1 mm), 5-pin SC70
- Input common-mode range extends 100 mV beyond both rails
- Response time: 24 μ s
- Low input offset voltage: ± 3 mV
- Push-pull output
- Industrial temperature range: -40°C to 125°C

Applications:

- Overvoltage and undervoltage detection
- Window comparators
- Overcurrent detection
- Zero-crossing detection
- System monitoring:
 - Smart phones
 - Tablets
 - Industrial sensors
 - Portable medical

The TLV3691 offers a wide supply range, low quiescent current of 150 nA (maximum), and rail-to-rail inputs. All of these features come in industry-standard and extremely small packages, making this device an excellent choice for low-voltage and low-power applications for portable electronics and industrial systems.

Available as a single-channel, low-power, wide supply, and temperature range makes this device flexible enough to handle almost any application from consumer to industrial. The TLV3691 is available in SC70-5 and 1-mm × 1-mm DFN-6 packages. This device is specified for operation across the expanded industrial temperature range of -40°C to 125°C .

2.3.4 ADS1114

Features:

- Ultra-small X2QFN package: 2 mm × 1.5 mm × 0.4 mm
- Wide supply range: 2.0 to 5.5 V
- Low current consumption: 150 μ A (continuous conversion mode)
- Programmable data rate: 8 to 860 SPS
- Single-cycle settling
- Internal low-drift voltage reference
- Internal oscillator
- I²C interface: Four pin-selectable addresses
- Four single-ended or two differential inputs (ADS1115)
- Programmable comparator
- Operating temperature range: -40°C to 125°C

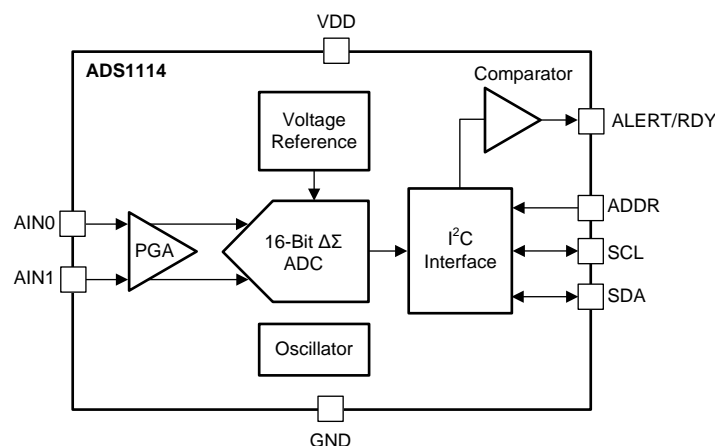
Applications:

- Portable instrumentation
- Battery voltage and current monitoring
- Temperature measurement systems
- Consumer electronics
- Factory automation and process control

The ADS1113, ADS1114, and ADS1115 devices (ADS111x) are precision, low-power, 16-bit, I²C compatible, ADCs offered in an ultra-small, leadless, X2QFN-10 package, and a VSSOP-10 package. The ADS111x devices incorporate a low-drift voltage reference and an oscillator. The ADS1114 and ADS1115 also incorporate a programmable gain amplifier (PGA) and a digital comparator. These features, along with a wide operating supply range, make the ADS111x well suited for power- and space-constrained, sensor measurement applications.

The ADS111x perform conversions at data rates up to 860 samples per second (SPS). The PGA offers input ranges from ± 256 mV to ± 6.144 V, allowing precise large- and small-signal measurements. The ADS1115 features an input multiplexer (MUX) that allows two differential or four single-ended input measurements. Use the digital comparator in the ADS1114 and ADS1115 for under- and overvoltage detection.

The ADS111x operate in either continuous conversion mode or single-shot mode. The devices are automatically powered down after one conversion in single-shot mode; therefore, power consumption is significantly reduced during idle periods.



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Figure 3. ADS1114 Block Diagram

2.3.5 TPS610981

Features:

- 300 nA ultra-low I_Q in low power mode
- Startup into load at 0.7-V input voltage
- Operating input voltage: 0.7 to 4.5 V
- Selectable output voltages Up to 4.3 V
- Minimum 350-mA switch peak current limit
- Integrated LDO and load switch
- Two modes controlled by MODE pin:
 - Active mode: Dual outputs at set values
 - Low power mode: LDO and load switch off; boost keeps on
- Automatic pass-through
- Up to 88% efficiency at 10- μ A load from 2- to 3.3-V conversion (low power mode)
- Up to 93% efficiency at 5- to 100-mA load from 2- to 3.3-V conversion
- 1.5 mm x 1.5 mm WSON package

Applications:

- Smart remote control
- *Bluetooth*[®] low energy tag
- Wearable applications
- Low-power wireless applications
- Portable consumer or medical products
- Single coin cell, single- or two-cell alkaline powered applications

The TPS61098x is an ultra-low-power solution for products powered by either a one-cell or two-cell alkaline, NiCd or NiMH, one-cell coin cell or one-cell Li-Ion or Li-polymer battery. It integrates either a low-dropout linear regulator (LDO) or a load switch with a boost converter and provides two output rails. The boost output VMAIN is designed as an always-on supply for a main system, and the LDO or load switch output VSUB is to power peripheral devices.

The TPS61098x has two modes controlled by MODE pin: active mode and low power mode. In active mode, both outputs are enabled with enhanced response performance. In low power mode, the LDO or load switch is disabled to disconnect peripherals. The TPS61098x consumes only a 300-nA quiescent current and can achieve up to 88% efficiency at a 10- μ A load in low power mode.

The TPS61098x supports automatic pass-through function. When input voltage is higher than a passthrough threshold, the boost converter stops switching and passes the input voltage to the VMAIN rail; when input voltage is lower than the threshold, the boost works in boost mode and regulates output at the target value. The TPS61098x provides different versions for different output set values.

The TPS61098x can provide up to 50 mA of total output current at a 0.7-V input to a 3.3-V output conversion. The boost is based on a hysteretic controller topology using a synchronous rectifier to obtain maximum efficiency at a minimal quiescent current.

The TPS61098x is available in a 1.5-mm \times 1.5-mm WSON package to enable small circuit layout size.

2.3.6 HDC1010

Features:

- Relative humidity accuracy $\pm 2\%$ (typical)
- Temperature accuracy $\pm 0.2^\circ\text{C}$ (typical)
- Excellent stability at high humidity
- 14-bit measurement resolution
- 100-nA sleep mode current
- Average supply current:
 - 710 nA at 1 SPS, 11-bit RH measurement
 - 1.3 μA at 1 SPS, 11-bit RH and temperature measurement
- Supply voltage: 2.7 to 5.5 V
- Tiny 2-mm \times 1.6-mm device footprint
- I²C interface

Applications:

- HVAC
- IoT smart thermostats and room monitors
- Refrigerators
- Printers
- White goods
- Wireless sensor (TIDA-00374, TIDA-00484, and TIDA-00524) medical devices

The HDC1010 is a digital humidity sensor with integrated temperature sensor that provides excellent measurement accuracy at very low power. The device operates over a wide supply range, and is a low-cost, low-power alternative to competitive solutions in a wide range of common applications. The innovative Wafer Level Chip Scale Package (WLCSP) simplifies board design with the use of an ultra-compact package. The sensing element of the HDC1010 is placed on the bottom part of the device, which makes the HDC1010 more robust against dirt, dust, and other environmental contaminants. The humidity and temperature sensors are factory calibrated and the calibration data is stored in the on-chip non-volatile memory.

2.3.7 OPT3002

Features:

- Wide optical spectrum: 300 to 1000 nm
- Automatic full-scale setting feature simplifies software and configuration
- Measurement levels: 1.2 to 10 mW/cm²
- 23-bit effective dynamic range with automatic gain ranging
- 12 binary-weighted, full-scale range settings: < 0.2% (typ) matching between ranges
- Low operating current: 1.8 μ A (typ)
- Operating temperature: -40°C to 85°C
- Wide power supply: 1.6 to 3.6 V
- 5.5-V tolerant I/O
- Flexible interrupt system
- Small form factor: 2.0 mm \times 2.0 mm \times 0.65 mm

Applications:

- Intrusion and door-open detection systems
- System wake-up circuits
- Medical and scientific instrumentation
- Display backlight controls
- Lighting control systems
- Tablet and notebook computers
- Thermostats and home automation appliances
- Outdoor traffic and street lights

The OPT3002 light-to-digital sensor provides the functionality of an optical power meter within a single device. This optical sensor greatly improves system performance over photodiodes and photoresistors. The OPT3002 has a wide spectral bandwidth, ranging from 300 to 1000 nm. Measurements can be made from 1.2 up to 10 mW/cm², without the need to manually select the full-scale ranges by using the built-in, full-scale setting feature. This capability allows light measurement over a 23-bit effective dynamic range. The results are compensated for dark-current effects, as well as other temperature variations.

Use the OPT3002 in optical spectral systems that require detection of a variety of wavelengths, such as optically-based diagnostic systems. The interrupt pin system can summarize the result of the measurement with one digital pin. Power consumption is very low, allowing the OPT3002 to be used as a low-power, battery-operated, wake-up sensor when an enclosed system is opened.

The OPT3002 is fully integrated and provides optical power reading directly from the I²C- and SMBus compatible, two-wire, serial interface. Measurements are either continuous or single-shot. The OPT3002 fully-operational power consumption is as low as 0.8 μ W at 0.8 SPS on a 1.8-V supply.

2.4 System Design Theory

2.4.1 PIR Sensor

To better understand the circuit, the user must understand how the PIR motion sensor operates. The PIR motion sensor consists of two or more elements that output a voltage proportional to the amount of incident infrared radiation. Each pair of pyroelectric elements are connected in series such that if the voltage generated by each element is equal, as in the case of IR due to ambient room temperature or no motion, then the overall voltage of the sensor elements is 0 V. Figure 4 shows an illustration of the PIR motion sensor construction.

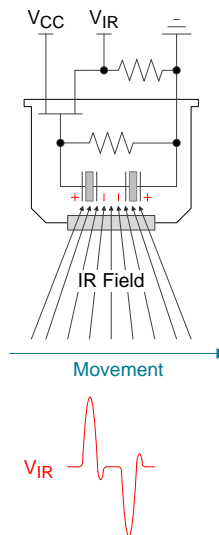


Figure 4. PIR Motion Sensor Illustration

The lower part of Figure 4 shows the output voltage signal resulting from movement of a body with a different temperature than the ambient parallel to the surface of the sensor and through the field of view of both sensor elements. The amplitude of this signal is proportional to the speed and distance of the object relative to the sensor and is in a range of low millivolts peak to peak to a few hundred microvolts peak to peak or less. A JFET transistor is used as a voltage buffer and provides a DC offset at the sensor output.

Because of the small physical size of the sensor elements, a Fresnel lens is typically placed in front of the PIR sensor to extend the range as well as expanding the field of view by multiplying and focusing the IR energy onto the small sensor elements. In this manner, the shape and size of the lens determine the overall detection angle and viewing area. The style of lens is typically chosen based on the application and choice of sensor placement in the environment. Based on this information, for best results, the sensor should be placed so that movement is across the sensor instead of straight into the sensor and away from sources of high or variable heat such as AC vents and lamps.

Also note that on initial power up of the sensor, it takes up to 30 seconds or more for the sensor output to stabilize. During this "warm up" time, the sensor elements are adjusting themselves to the ambient background conditions. This is a key realization in designing this subsystem for maximum battery life in that the sensor itself must be continuously powered for proper operation, which means power cycling techniques applied to either the sensor or the analog signal path itself cannot be applied for proper operation and reliable detection of motion.

2.4.2 Fresnel Lens

This TI Design needs two lenses with different areas of detection for each PIR sensor: One lens for PIR sensor 1 with middle detection area for a tall subject (like a human), and another one for PIR sensor 2 with lower detection area for a short subject (like a dog). The IML-0635 from Murata and IML-0636 was chosen for middle and lower detection, respectively.

Figure 5 shows the viewing angles of each lens.

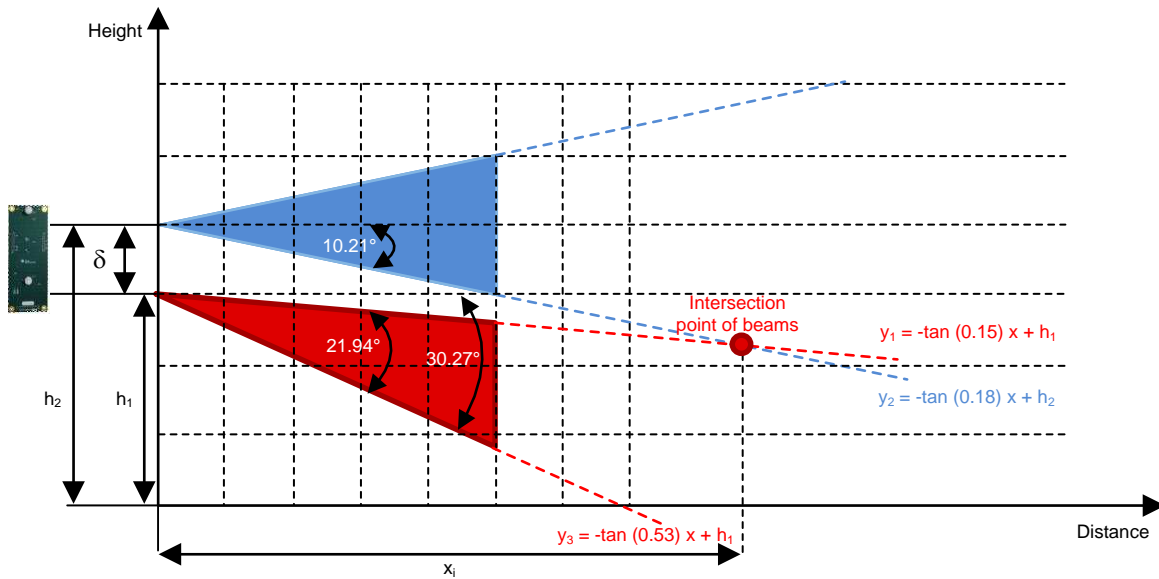


Figure 5. Fresnel Lenses View

Because the view angles are different for each lens, at a certain distance the beam of the middle and lower lens will cross each other. The distance x_i of this crossing point is given by Equation 1.

$$x_i = \frac{\delta}{\tan(0.18) - \tan(0.15)} \quad (1)$$

For this TI Design, δ is set at 10 cm, which is the distance between the center of the PIR sensor 1 and PIR sensor 2; for $\delta = 10$ cm, $x_i = 2.96$ m.

With this setting—according to the equations in Figure 5—the distance from the floor to the center of the PIR sensor 1 (h_2) should be around 1.70 m in order to receive enough IR radiation in PIR sensor 2 from a small subject like a pet. With h_2 too short, only PIR sensor 1 will sense IR radiation for the same range.

2.4.3 Analog Signal Path

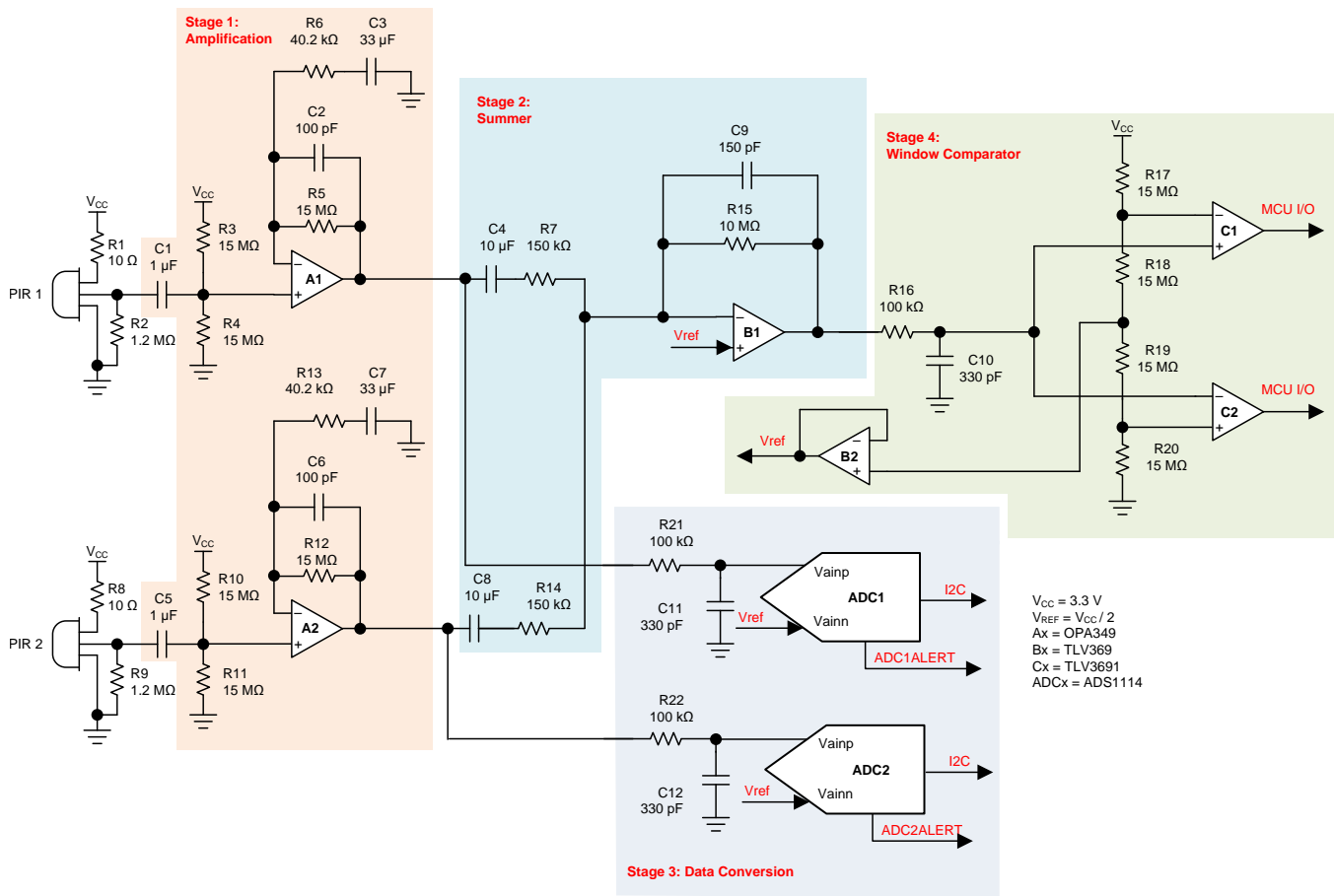


Figure 6. PIR Sensors Analog Signal Path Schematic

The typical signal chain for one PIR sensor consists of one or two stages of amplified filter followed by a window comparator (see the [TIDA-00489](#) design). This reference design uses two PIR sensors. Using the usual signal chain for one PIR sensor will double the power consumption and the cost of this TI Design. To avoid that, This TI Design is using a different analog architecture.

The analog signal conditioning section for this reference design is shown in the schematic in [Figure 6](#).

Stage 1 in [Figure 6](#) implements the amplified filter function for each PIR sensor, followed by stage 2, which implements the summer amplified filter function. Finally, stage 3 implements the window comparator design, and stage 4 implements two 16-bit ADCs for data conversion.

Resistors R2 and R9 set the bias current in the JFET output transistor of the PIR motion sensors. To save power, R1 and R9 are larger than recommended and essentially current starves the sensor. This comes at the expense of decreased sensitivity and higher output noise at the sensor output, which is a fair trade-off for increased battery lifetime. Some of the loss in sensitivity at the sensor output can be compensated by a gain increase in the filter stages. Due to the higher gain in the filter stages and higher output noise from the sensor, carefully optimize the placement of the high-frequency filter pole and the window comparator thresholds to avoid false detection.

Each component of the signal chain is powered by a boost converter. In order to reduce the noise due to the switching frequency of the boost converter, RC filters are used instead of just decoupling capacitors. Because each component consumes very low power, a value of 10 Ω for resistors is used for RC filters allowing negligible voltage drop.

2.4.3.1 Amplified Filter Design

Stage 1 in [Figure 6](#) is composed of two amplified filter functions after the PIR sensors. As both amplifiers have the same configuration, this design guide takes amplifier A1 as a reference for the rest of the description of stage 1.

The output of the PIR sensor consists of a very small AC signal (typically a few microvolts) when there is a motion with a DC offset depending on the environmental temperature.

The amplifiers and comparators being powered by a single power supply (V_{CC}). Set the bias point at $V_{BIAS} = V_{CC}/2$ in order to amplify symmetrically the signal in the full range of V_{CC} . For that, the C1 capacitor removes the DC component from the PIR sensor signal and the resistor divider set the V_{BIAS} point at $V_{CC}/2$ through the resistor R3 and R4.

The non-inverting configuration of the amplified filter provides a high impedance load, avoiding a voltage drop at the output of the resistor divider.

The output of stage 1 goes to stage 2 and stage 4. Because the signal is very small at the output of the PIR sensor, a high gain is required to have a significant signal amplitude in full scale range for the data conversion and maximize the motion sensitivity range. The gain was set at 374 (≈ 51 dB) through the resistors R5 and R6.

The filter section for stage 1 implements a second-order bandpass filter using simple poles. A typical bandwidth from 0.1 to 10 Hz is fairly enough to detect a human motion. This TI Design has a wider bandwidth to detect more than just a human walking motion (such as fire wiggling, for example). The chosen cutoff frequencies for the band-pass filter are set to 0.1 Hz and 106 Hz.

The low cutoff frequency is critical because it has a major effect on the system noise floor by limiting the overall impact of $1/f$ noise from the analog front-end as well as setting the minimum speed of motion that the system can detect; the high cutoff frequency is mostly for reducing broadband noise.

The OPA349 used for stage 1 has a unity gain bandwidth (UGBW) of 70 kHz, which means for a maximum gain of 374 (≈ 51 dB), the bandwidth is limited to 186 Hz. Taking into account the tolerances and variation of the components in the UGBW and the low I_Q , the OPA349 suits perfectly for stage 1.

[Equation 2](#) to [Equation 4](#) show the gain and cutoff frequencies for this stage:

$$|G_1| = \left| \frac{R5}{R6} + 1 \right| = \left| \frac{15 \text{ M}\Omega}{40.2 \text{ k}\Omega} + 1 \right| = 374 \quad (\approx 51 \text{ dB}) \quad (2)$$

$$f_{\text{Low}1} = \frac{1}{2\pi \times R6 \times C3} = \frac{1}{2\pi \times 40.2 \text{ k}\Omega \times 33 \text{ }\mu\text{F}} = 0.1 \text{ Hz} \quad (3)$$

$$f_{\text{High}1} = \frac{1}{2\pi \times R5 \times C2} = \frac{1}{2\pi \times 15 \text{ M}\Omega \times 100 \text{ pF}} = 106.1 \text{ Hz} \quad (4)$$

This reference design needs to trigger the windows comparator if there is any motion detected by PIR sensor 1 or 2. Stage 2 is arranged as an inverting summer gain stage and is AC coupled to stage 1. This allows the DC bias to be set to $V_{CC}/2$ easily by connecting the center point of the divider string in the window comparator to the non-inverting input of the op amp in this second stage. Because the peak-to-peak noise is present at the output of this stage, R15 is made as large as possible to minimize the dynamic current of the system. Similar to stage 1, stage 2 also implements a second-order bandpass filter with cutoff frequencies set to 0.1 and 106 Hz and the gain is set at 67 (≈ 37 dB) to maximize the motion sensitivity range. The gain and the cutoff frequency for both channel of the summer have been set same by having $R7 = R14$.

The TLV369 used for stage 2 has a UGBW of 12 kHz, which means for a maximum gain of 67 (≈ 37 dB), the bandwidth is limited to 180 Hz. Again taking into account the tolerances and variation of the component in the UGBW and the low I_Q , the OPA349 is ideal for stage 2.

Equation 5 to Equation 7 show the gain and cutoff frequencies for this stage:

$$|G_2| = \left| -\left(\frac{R15}{R4}\right) \right| = \left| -\left(\frac{10\text{ M}\Omega}{150\text{ k}\Omega}\right) \right| = 67 \quad (\approx 37\text{ dB}) \quad (5)$$

$$f_{\text{Low}2} = \frac{1}{2\pi \times R7 \times C4} = \frac{1}{2\pi \times 150\text{ k}\Omega \times 10\text{ }\mu\text{F}} = 0.1\text{ Hz} \quad (6)$$

$$f_{\text{High}2} = \frac{1}{2\pi \times R15 \times C9} = \frac{1}{2\pi \times 10\text{ M}\Omega \times 150\text{ pF}} = 106.1\text{ Hz} \quad (7)$$

The total circuit gain of stage 1 and stage 2 is given by $G1 \times G2 = 374 \times 67 = 25058$ (≈ 88 dB).

2.4.3.2 Window Comparator Design

The window comparator circuit shown in stage 3 of Figure 6 converts the analog output of the stage to digital signals, which can be used as interrupts for the MCU to tell it when motion has been detected on any PIR sensor. Composed of resistors R17 through R20, the resistor divider sets up the thresholds that determine a valid motion detection from the sensor. To save power, this resistor divider followed by the buffer B2 for impedance adaptation provides also the bias voltage to stages 2 and 4. The comparator chosen for this reference design is the TLV3691 due to its ultra-low supply current requirements. The TLV3691 comparator also has rail-to-rail input capability with an input common-mode range that exceeds the supply rails by 100 mV. This is not required for this TI Design, but it does allow the ability to maximize the adjustment range of the window comparator thresholds. The comparator outputs will be low when there is no motion detected. Typically, motion across the sensor will generate a high pulse on one comparator output followed by a high pulse on the other comparator, which corresponds to the amplification of the S-curve waveform shown in the lower part of Figure 4.

Equation 8 and Equation 9 show the threshold values:

$$V_{\text{ref_low}} = \frac{R17}{R17 + R18 + R19 + R20} \times V_{\text{CC}} = 0.25 \times V_{\text{CC}} \quad (8)$$

$$V_{\text{ref_high}} = \frac{R17 + R18 + R19}{R17 + R18 + R19 + R20} \times V_{\text{CC}} = 0.75 \times V_{\text{CC}} \quad (9)$$

There is also a constraint that $R17 + R18 = R19 + R20$ so that the $V_{\text{CC}}/2$ bias level is maintained at the center tap of the divider for use as the bias for the second stage of the filter. The thresholds chosen for this TI Design are a balance between sensitivity and noise immunity. Widening of the window improves noise immunity but reduces sensitivity. Making the window too small can lead to false triggers due to the peak-to-peak noise seen at the input to the window comparator. The low-pass filter made by R16 and C16 is used to prevent again false triggering due to peak-to-peak noise.

2.4.3.3 Data Conversion Design

In order to implement an intelligent signal processing and algorithm to avoid false triggering, the amplified signal from the PIR sensors needs to be converted from analog to digital. For that, this TI Design uses two ADS1114 devices, low-power 16-bit delta-sigma ADCs. The reasons to use two external 16-bit ADC are:

- The signal at the output of the PIR sensor decreases exponentially in function of the distance between the PIR sensor and the moving object. Depending on the distance and the moving object, the signal can not fill the full scale range of the 10- or 12-bit ADC, causing a loss of precision. But a 16-bit ADC in this application has enough resolution at 3.3 V ($3.3 / 2^{16} = 5 \times 10^{-5}$ V) to acquire with good precision a signal amplitude from 10 mV to 3.3 V, even if the full-scale range is not used. In addition, the integrated PGA in the ADS1114 allows the device to rescale small signals and use efficiently the full-scale range by setting input ranges from ± 256 mV to ± 6.144 V.
- Using an external ADC instead of an integrated ADC in an MCU gives more flexibility to the customer for the final choice of the MCU or DSP depending on the needs.
- The ADS1114 has a programmable data rate from 8 to 860 SPS. The higher detectable frequency of a motion can go up to 100 Hz. A minimal suitable data rate for this higher frequency according to Nyquist-Shannon criteria and the programmable data rate value of the ADS1114 is 250 SPS. The ADS1115 is same as the ADS1114 with an integrated multiplexer. It is possible to use one ADS1115 instead of two ADS1114 devices, but it means the data rate for the ADS1115 in multiplex mode should be at least 475 SPS in order to sample the signal from both PIR sensors for 100 Hz as a higher frequency. But up to a 250-SPS sampling data rate, there is a loss of precision due to RMS noise. In order to avoid that, two ADS1114 devices are used in parallel and it is also a way to acquire signal data from PIR sensors 1 and 2 at the same time. However, one ADS1115 can be used in multiplex mode instead of two ADS1114 devices if there is no need for a wide bandwidth of motion detection.

The ADS1114 also includes an integrated voltage reference, oscillator, digital comparator, and PGA, which allows to reduce the cost and use efficiently the full-scale range of the ADC.

Both ADS1114 devices in this TI Design are used in common-mode; the VAINP input of the ADC is used for the signal input, and the VAINN input is set at $V_{CC}/2$ for the full-scale range, with $V_{IN} = (V_{AINP} - V_{AINN})$. The buffer B2 is specially used to adapt the impedance between the resistor divider and the VAINN input whose impedance varies between 3 to 100 M Ω in common-mode input. The low-pass filter made by R21,C11 and R2,C12 are used to improve signal-to-noise ratio.

The ADS1114 communicate and send data through the I²C bus. In this design the address of ADC1 is set at (0x49) by connecting the ADDR pin to 3.3 V and the address of ADC2 is set at (0x48) by connecting the ADDR pin to GND.

The ADC1ALERT respectively ADC2ALERT pins can be used:

- To know when the data conversion for 1, 2, or 4 samples are ready
- As an output of the integrated digital comparator, which can be a traditional comparator or a window comparator

The threshold values of the comparator can be in the Lo_thresh register (0x02) and Hi_thresh register (0x03).

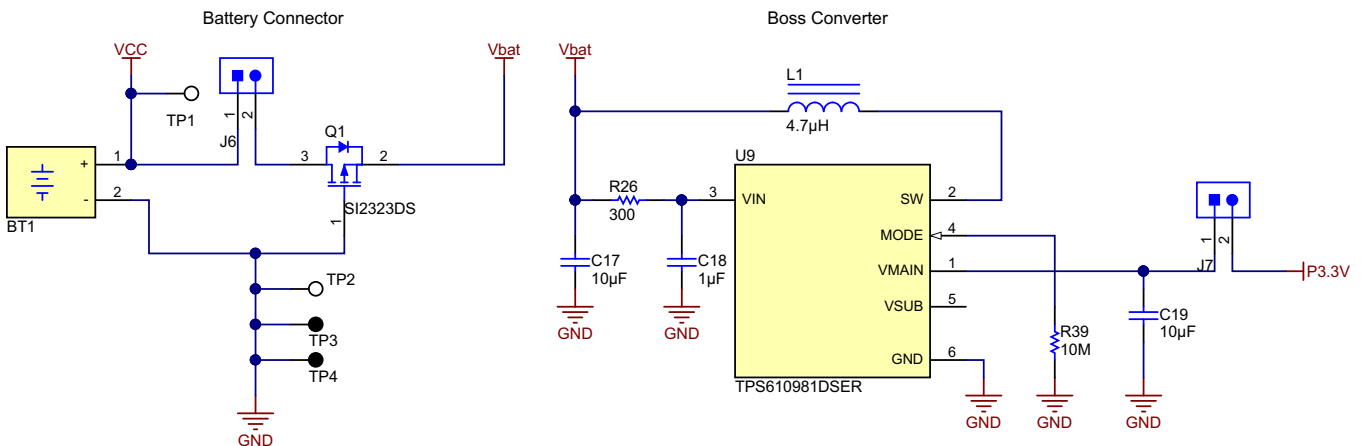
2.4.4 Light Sensor

A quick variation of light may cause a false triggering for the motion detection. In order to avoid that, the digital light sensor OPT3002 is used with a wide optical spectrum (300 to 1000 nm). Power consumption is very low, allowing the OPT3002 to be used as a low-power in a battery-based design. The sensor communicates through the I²C bus, and in this TI Design the address of the OPT3002 is set at (0x44) by connecting the ADDR pin to GND.

2.4.5 Temperature Sensor

A quick variation of temperature due to air conditioner or heater may cause a false triggering for the motion detection. In order to avoid that, the digital temperature sensor HDC1010 is used. This sensor also includes a humidity sensor, which can be used for outdoor applications. Power consumption is very low, allowing the HDC1010 to be used as a low-power in a battery-based design. This sensor communicates through the I²C bus, and in this TI Design the address of the HDC1010 is set at (0x40) by connecting the ADR0 and ADR1 pins to GND.

2.4.6 Power Supply Design



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Figure 7. Power Supply Schematic

This TI Design is based on a AAA alkaline Battery (1.5 V) for a high battery capacity compared to a coin-cell battery. A PMOS transistor is used in place of the traditional Schottky diode for reversed battery protection, followed by a boost converter for a fixed 3.3-V output. In this TI Design, the power supply for the circuit must be fixed at 3.3 V in order to work in the safe operating area and avoid any damage due to voltage difference during the I²C communication between the MCU, the ADCs, and sensors.

The TPS610981 has two outputs: VMAIN and VSUB. VMAIN is the output of the boost converter and gives a 3.3-V fixed output for an input voltage range from 0.7 to 4.5 V and can deliver up to 50 mA. VSUB can be used for a 3.0-V output from the integrated LDO for very low output noise when the MODE input is high. This reference only uses VMAIN for the 3.3-V power output, while the MODE pin is connected to ground for maximum efficiency.

The values of the components and placement in the PCB were set according to the EVM design [TPS610981EVM-674](#). A high value of the inductor is used to reduce the peak current.

The TPS610986—another version of TPS610981—can be used to improve the total power consumption efficiency with its integrated switch (with VSUB = 3.3 V) to supply the ADCs, the sensors, and the pullup resistors.

3 Hardware, Testing Requirements, and Test Results

3.1 Required Hardware

Figure 8 and Figure 9 show the hardware for the Advanced Motion Detector Using PIR Sensors Reference Design For False Trigger Avoidance. The printed circuit board (PCB) is in a 55.88x152.44-mm rectangular form.

All the integrated circuits, the battery holder of the AAA alkaline cell and the BoosterPack pinout are located on the bottom side of the PCB. On the top of the PCB are all the sensors (PIR, Light, Humidity, and Temperature).

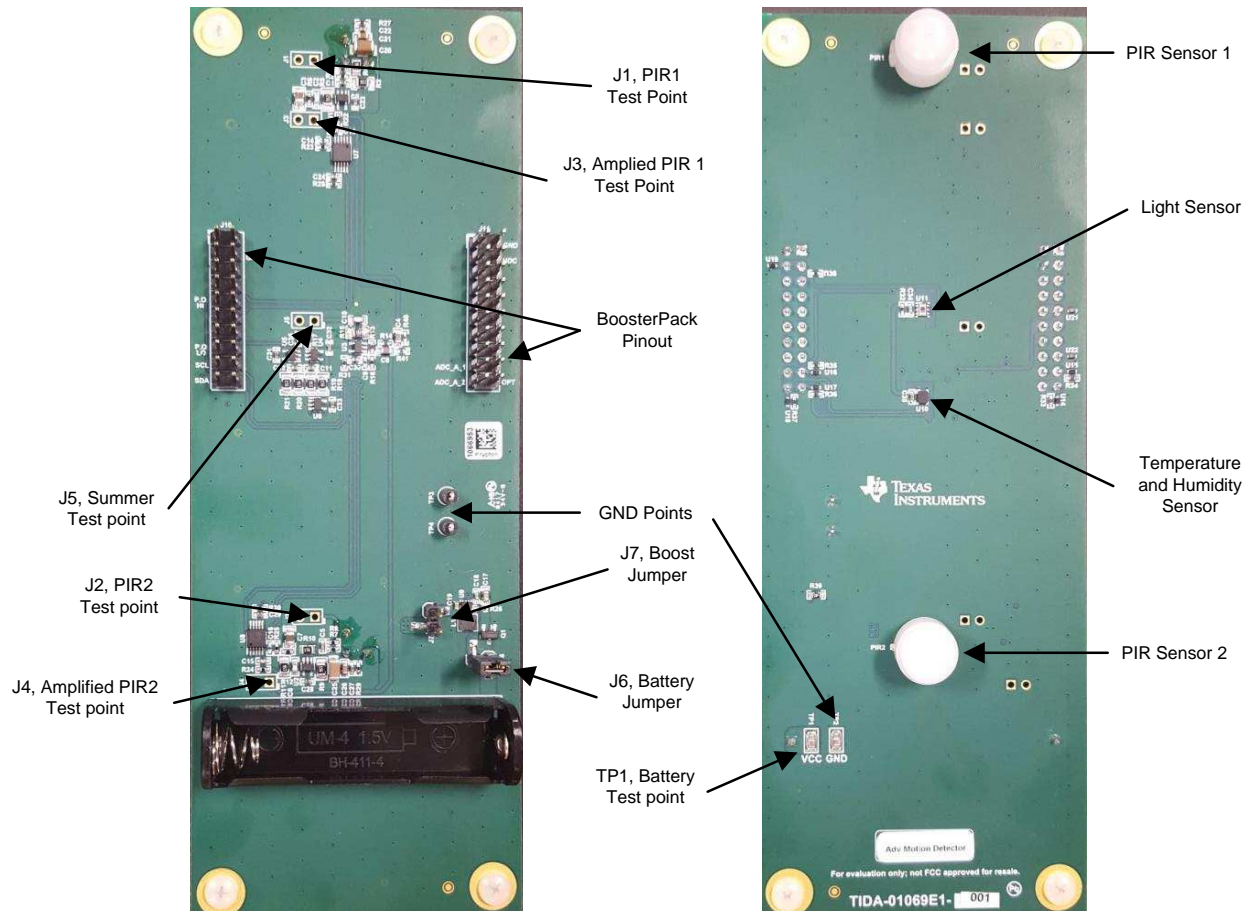


Figure 8. Advanced PIR Motion Detector Reference Design Hardware Description

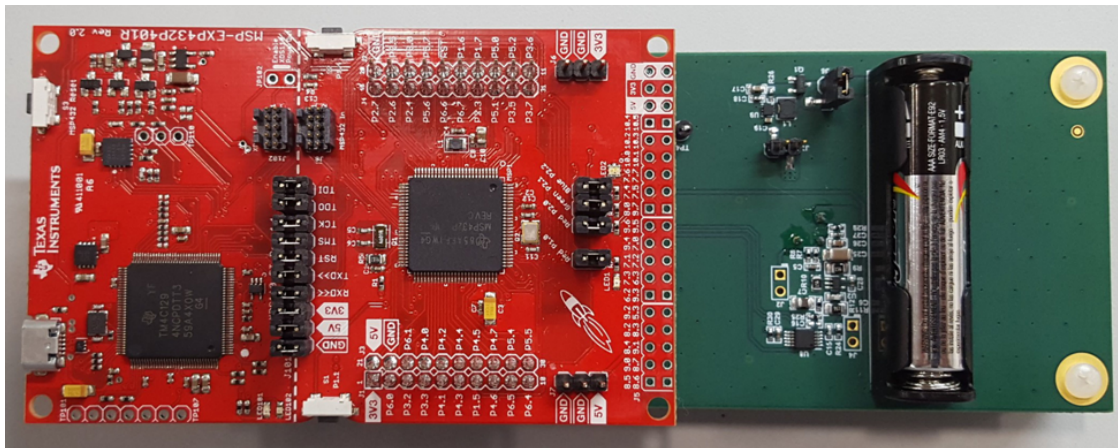


Figure 9. Plugged LaunchPad Example

3.1.1 Jumper Configuration

To facilitate power consumption measurement and debugging in this reference design, two jumpers J7 and J6 were included. Jumper J6 is used to measure current from the battery and J7 measures from the boost converter. To properly operate this TI Design, both jumpers must be shorted.

3.1.2 Test Point Description

To facilitate debugging for a different analog stage in this reference design, jumpers J1 to J5 were included to allow these measurement. These jumpers are not populated in the design to avoid any noise in the signal if a jumper acts like a antenna. A Barrel probe can used for better measurements results.

The following is a brief description of these test points:

- J1: Output of PIR Sensor 1
- J2: Output of PIR Sensor 2
- J3: Output of the amplification stage for PIR Sensor 1
- J4: Output of the amplification stage for PIR Sensor 2
- J5: Output of the summer stage

The outputs of the windows comparator can be measured on the BoosterPack pinout with pins named by PIR_OUT_HI and PIR_OUT_LO.

3.1.3 BoosterPack Pinout Standard

To make this analog front-end work properly a MCU must be used to take data from the ADCs and the sensors. In order to give more flexibility for the choice of the MCU a standard BoosterPack pinout was selected. With this standard, any 40-pin LaunchPads, depending on the needs, can be plugged on this reference design.



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Figure 10. BoosterPack Pinout for TIDA-01069

The following is a brief description of the BoosterPack pins in this TI Design:

- PIR_OUT_HI: Output of the windows comparator for high threshold
- PIR_OUT_LO: Output of the windows comparator for low threshold
- SDA and SLA: I²C bus pins
- ADC1ALERT: Can be used as output of the integrated digital comparator or as a data ready pin for ADC 1
- ADC2ALERT: Can be used as output of the integrated digital comparator or as a data ready pin for ADC 2
- OPT3002_INT: Interrupt pin from the light sensor; can be used to wake up an MCU if the light crosses a threshold level
- HDC1010_DRDY: Data ready pin from the sensor

3.1.4 I²C Addresses

Table 2 lists the I²C address values of the ADCs and sensors.

Table 2. I²C Addresses

DEVICE	ADDRESS
ADC 1 (ADS1114)	0x49
ADC 2 (ADS1114)	0x48
Light Sensor (OPT3002)	0x44
Humidity and Temperature Sensor (HDC1010)	0x40

3.1.5 Fresnel Lens Placement

The Fresnel lenses used for this TI Design are fixed on the PIR sensors by friction. The correct placement of those lenses on the PIR sensors are critical to detect correctly a motion. Indeed, the lenses shape the area of detection.

Figure 11 shows how to place the lenses.

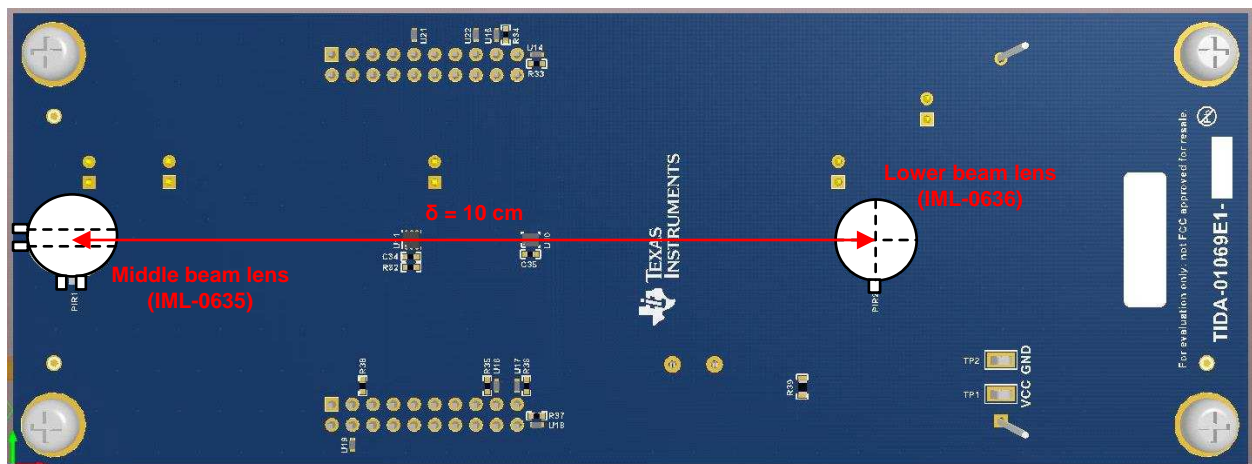


Figure 11. Fresnel Lenses on TIDA-01069

3.2 Testing and Results

3.2.1 Test Setup

3.2.1.1 Power Consumption Test Setup

This TI Design uses low-power components, and the whole system runs on one AAA alkaline battery. This section shows the setup for the average current consumption measurement of the whole system.

Because the ADCs are the most consuming parts of this design when running, there are mainly two modes of operation:

- When there is no motion, the ADCs are in power-down mode.
- When there is a motion, the ADCs are in operating mode (continuous-conversion mode)

The measurements results of these two modes of operation are shown in [Section 3.2.2.1](#).

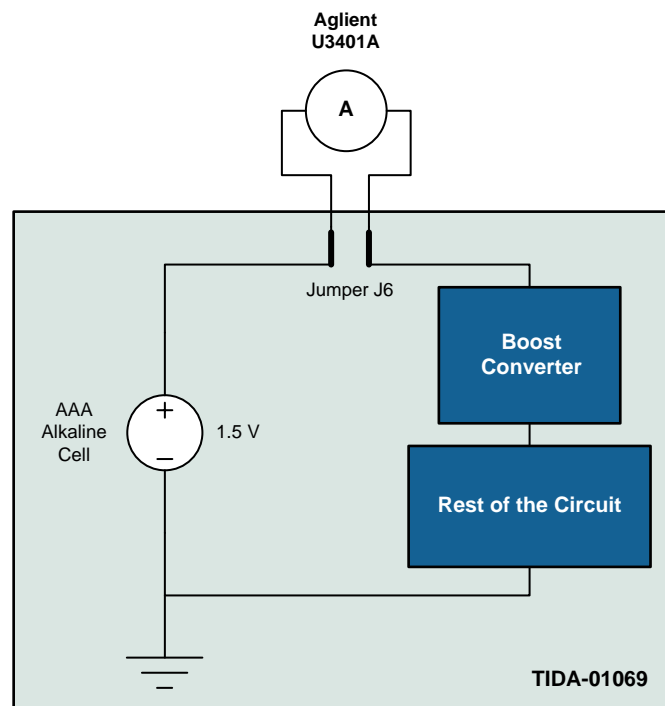


Figure 12. Test Setup for Measuring Battery Current

3.2.1.2 Signals Integrity Test Setup

The main goals of this TI Design as an analog front-end of an advanced motion detector is signal conditioning and data conversion.

This section shows the setup for the output signal of PIR sensors 1 and 2 after data conversion of 20 seconds of an adult human walking perpendicularly at different distances.

The motion detector was placed such that the distance between the floor and the PIR 1 is 1.70 m (see [Figure 13](#)).

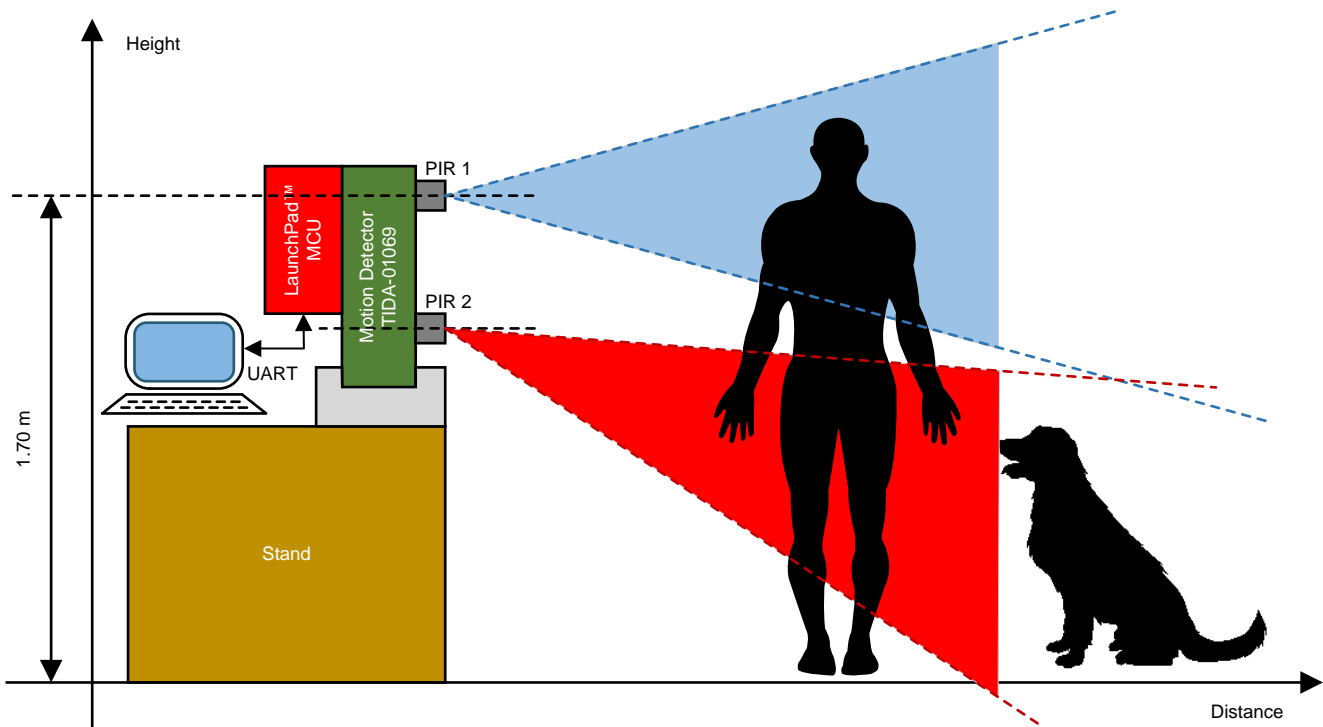


Figure 13. Test Setup for Measuring Signal Integrity (Side View)

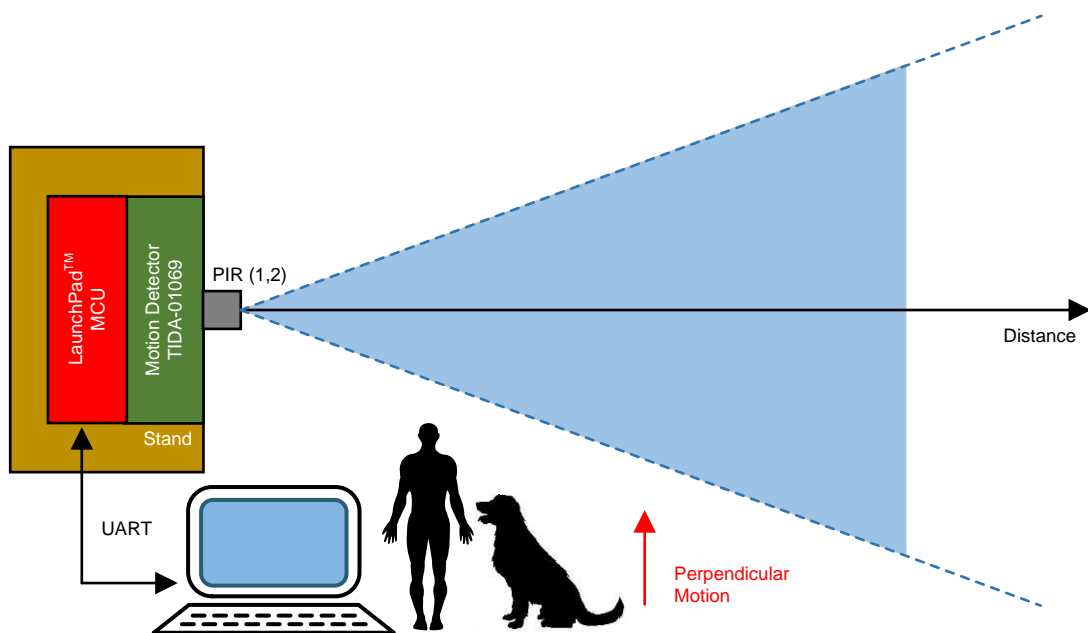


Figure 14. Test Setup for Measuring Signal Integrity (Top View)

3.2.2 Test Results

NOTE: The test data in the following sections were measured with the system at room temperature.

3.2.2.1 Power Consumption Results

Table 3 shows the current consumption results for two modes of operation of this TI Design.

Table 3. Power Consumption Results

MODE	BATTERY VOLTAGE (V)	AVERAGE CURRENT CONSUMPTION (μ A)
No motion with ADC1 and ADC2 in power-down mode	1.47	21
Motion with ADC1 and ADC2 in operating mode (continuous-conversion mode)	1.47	835

For more details about power characterization for motion detectors, see Section 8.1 of the TIDA-00489 design guide (TIDUAAU1).

3.2.2.2 Signals Results

In Section 3.2.2.2.1, signal integrity results are shown with this TI Design and only for an adult human walking. However, with an initial prototype, many measurements were done with different subjects, motions, and distances. Some relevant measurements results are shown in Section 3.2.2.2.2.

The measurements results consist of PIR 1 and 2 signal form after amplification and data conversion followed by the Fast Fourier Transform (FFT) and Continuous Wavelet Transform (CWT) of these signals.

NOTE: To compute FFT and CWT, MATLAB 2016b was used and the wavelet toolbox is needed in order to use the CWT function. Two parameters were used for CWT function, x and F_s , where x is the signal to transform and F_s the sampling frequency of the signal x . For more information, go to <https://fr.mathworks.com/products/wavelet.html>.

3.2.2.2.1 TIDA-01069 Signal Integrity Results

The subject for these measurements was an adult human walking perpendicularly to the motion detector.

The characteristic of the subject are:

- Height: 1.87 m (\approx 6 ft 2 in)
- Weight: 80 kg (\approx 176 lbs)

The sampling frequency of the ADCs was set at 64 SPS. The full-scale range used through the integrated PGA and the distances between the subject and the motion detector are indicated in the title of the following figures.

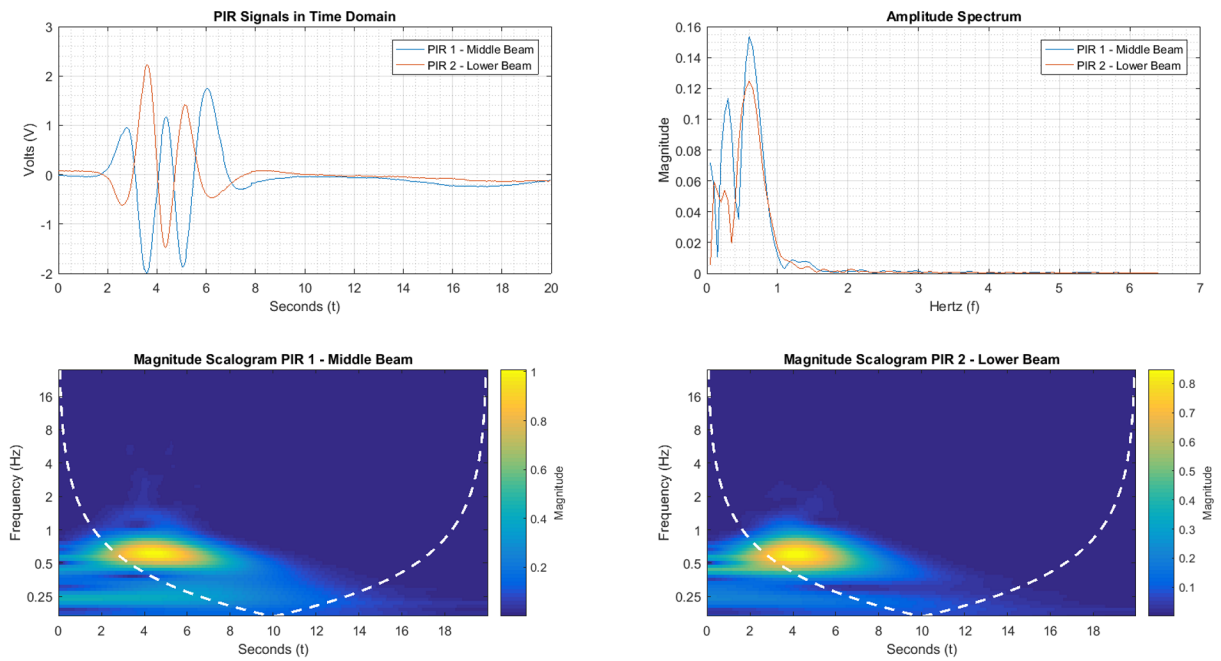


Figure 15. Human Walking 3 m With FSR = ± 2.048 V

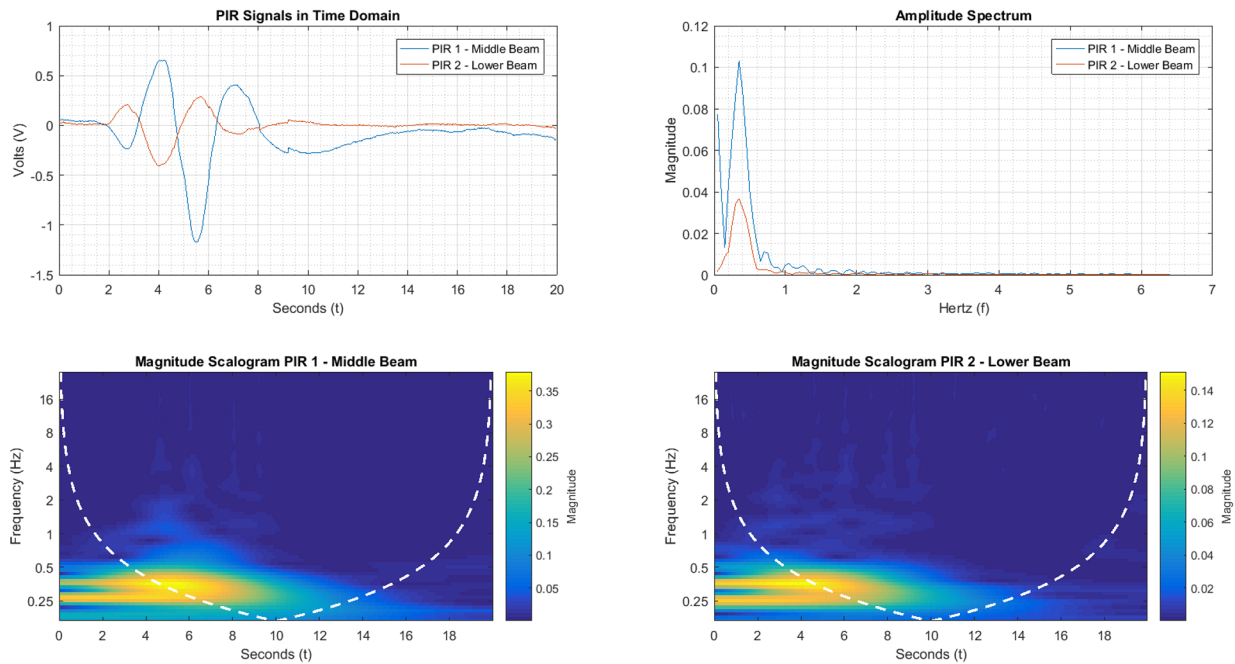


Figure 16. Human Walking 6 m With FSR = ± 2.048 V

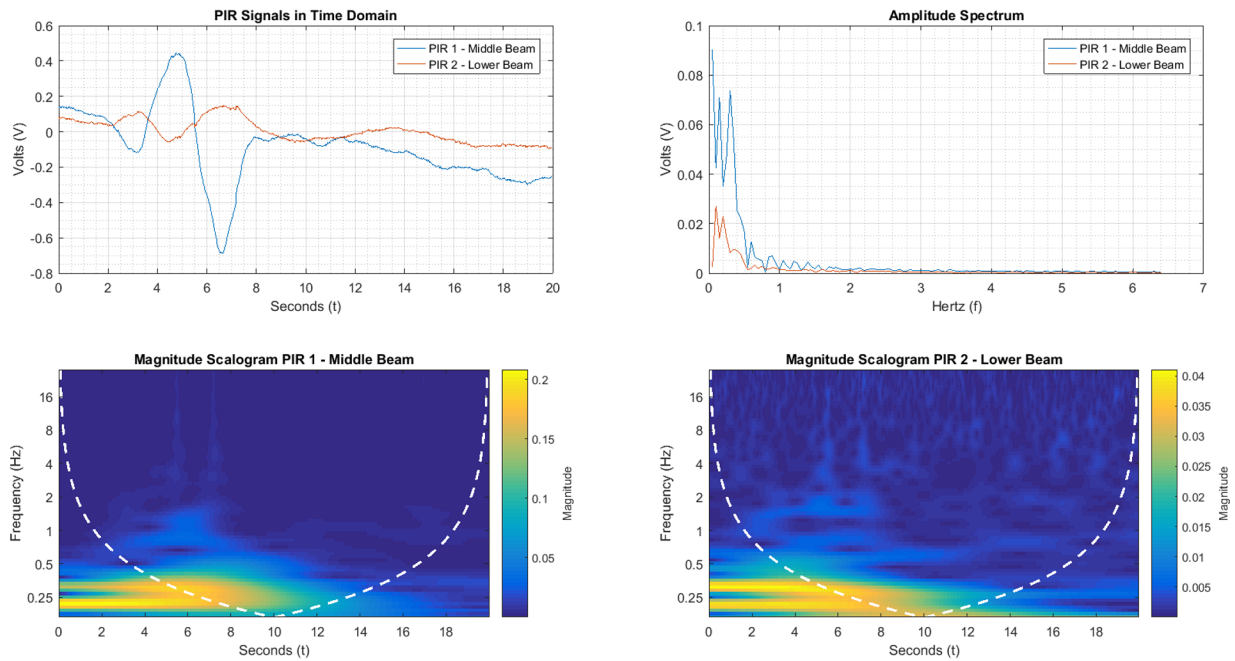


Figure 17. Human Walking 9 m With FSR = ± 2.048 V

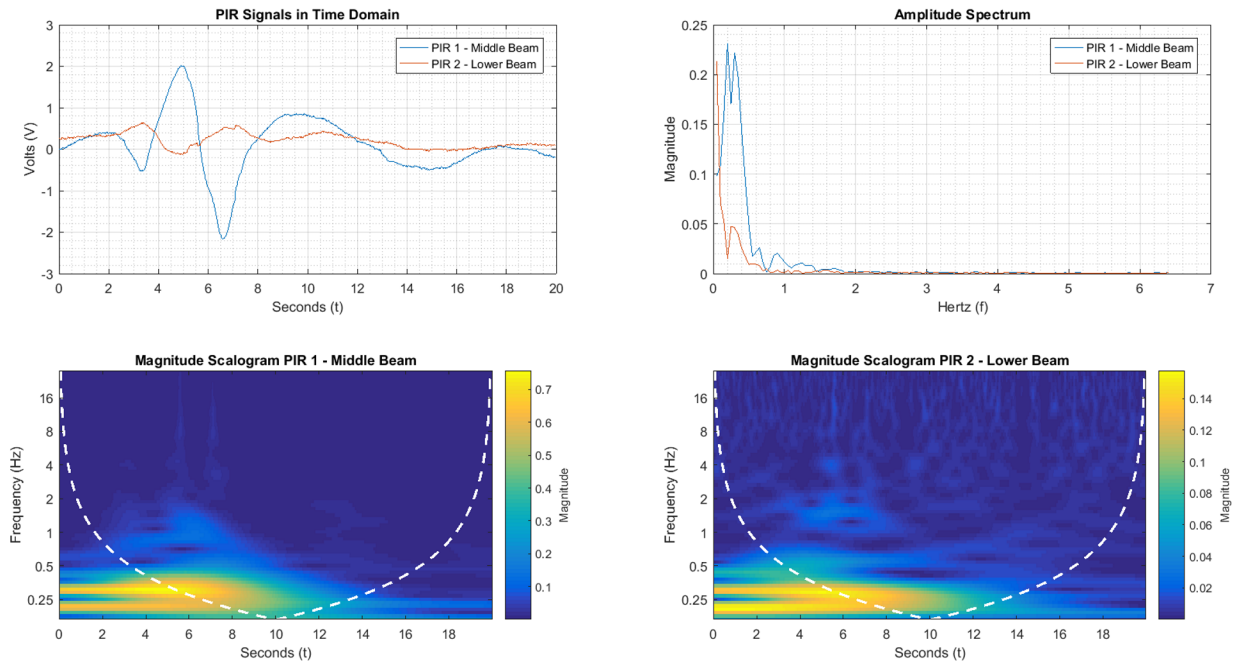


Figure 18. Human Walking 9 m With FSR = ± 0.512 V

These results show a good signal integrity of the signal with a good SNR until the distance of 6 m. These signals can be used without any filtering.

At the distance of 9 m with an FRS = ± 2.048 V or ± 0.512 V, the signals are noisy but still exploitable for useful information.

3.2.2.2 Others Motions Results

The main goal of the results in this section is to show the form of the signals for different kind of motion and especially the signature obtained through the wavelet transform of those signals.

Figure 19 shows different subject used for the measurements and their characteristics.

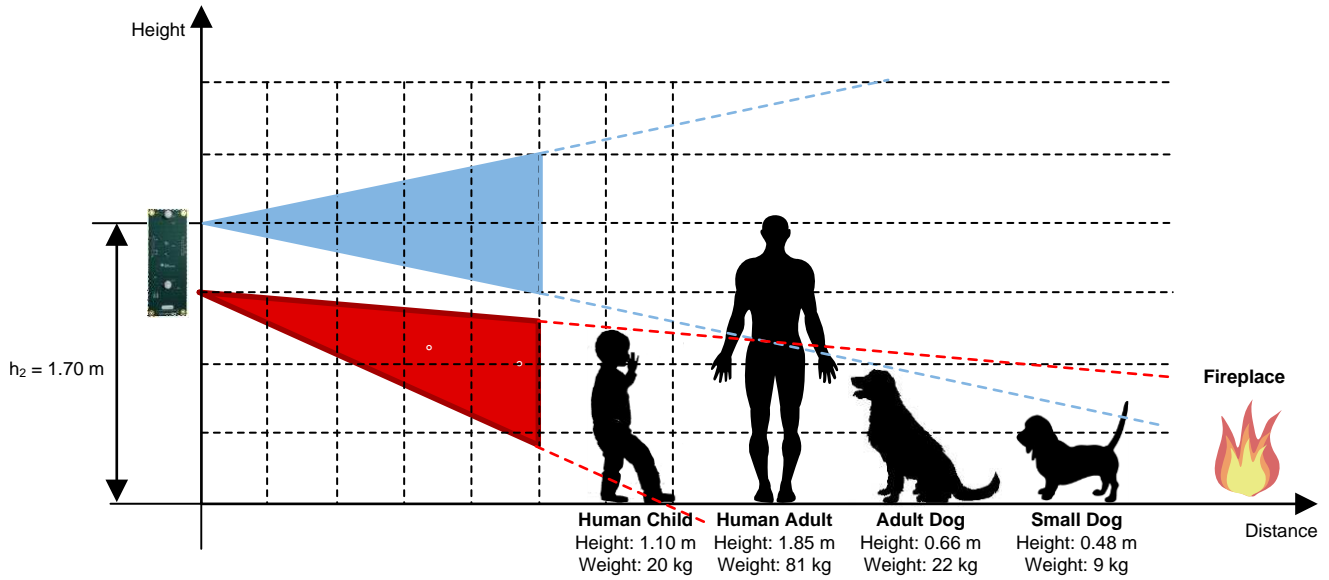


Figure 19. Moving Subjects Characteristics

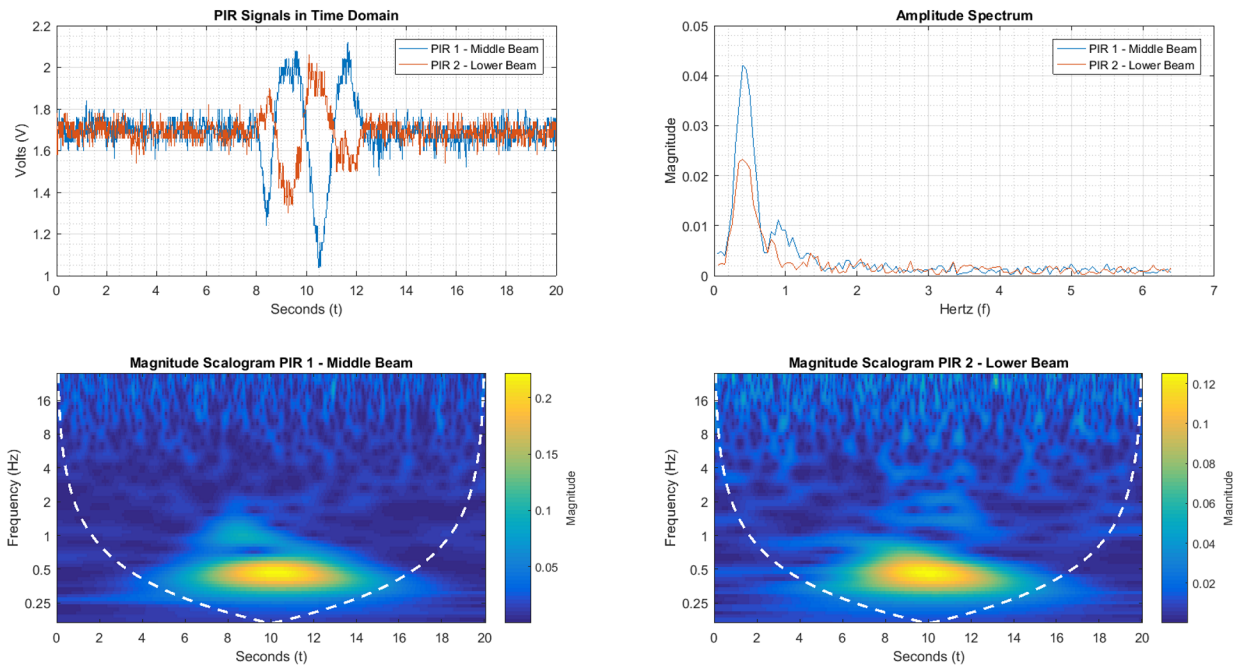


Figure 20. Adult Human Walking 6 m

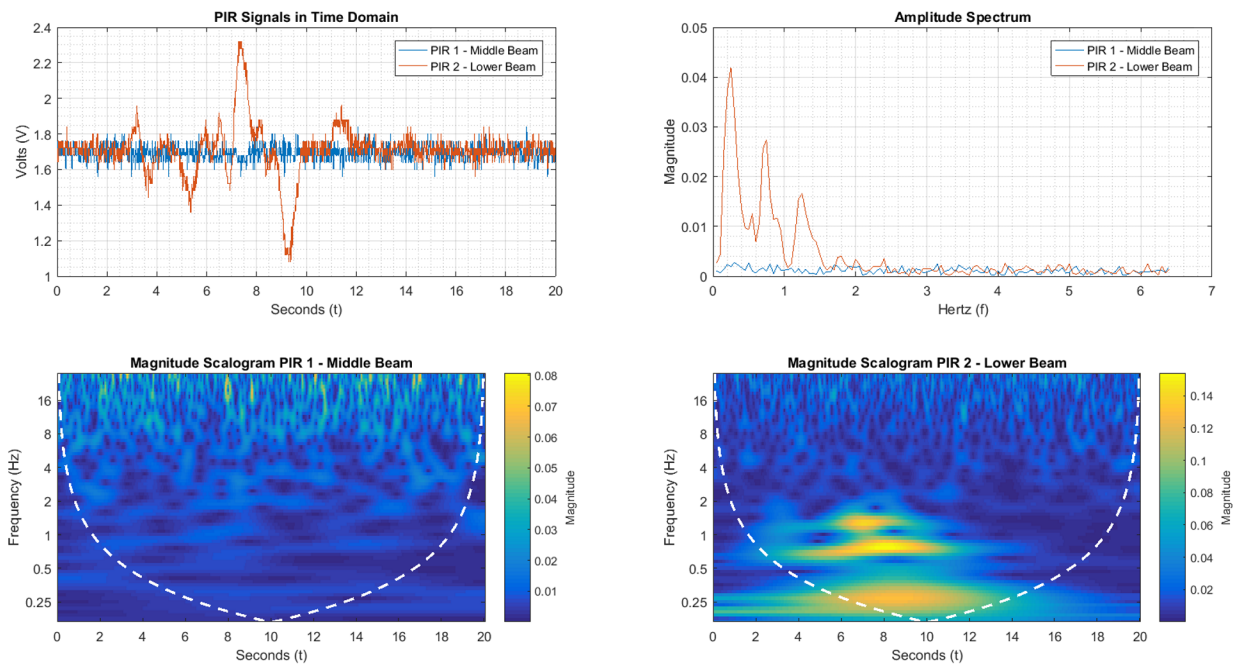


Figure 21. Adult Human Rolling on Floor for 3 m

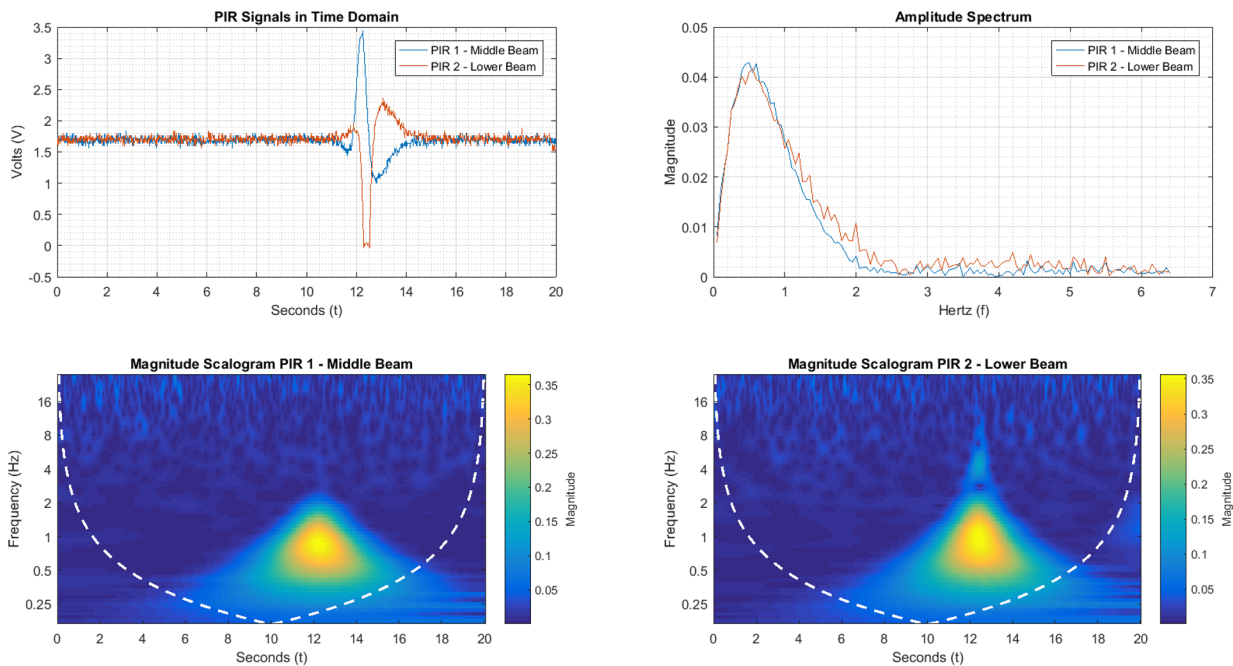


Figure 22. Adult Human Instantly Falling 3 m

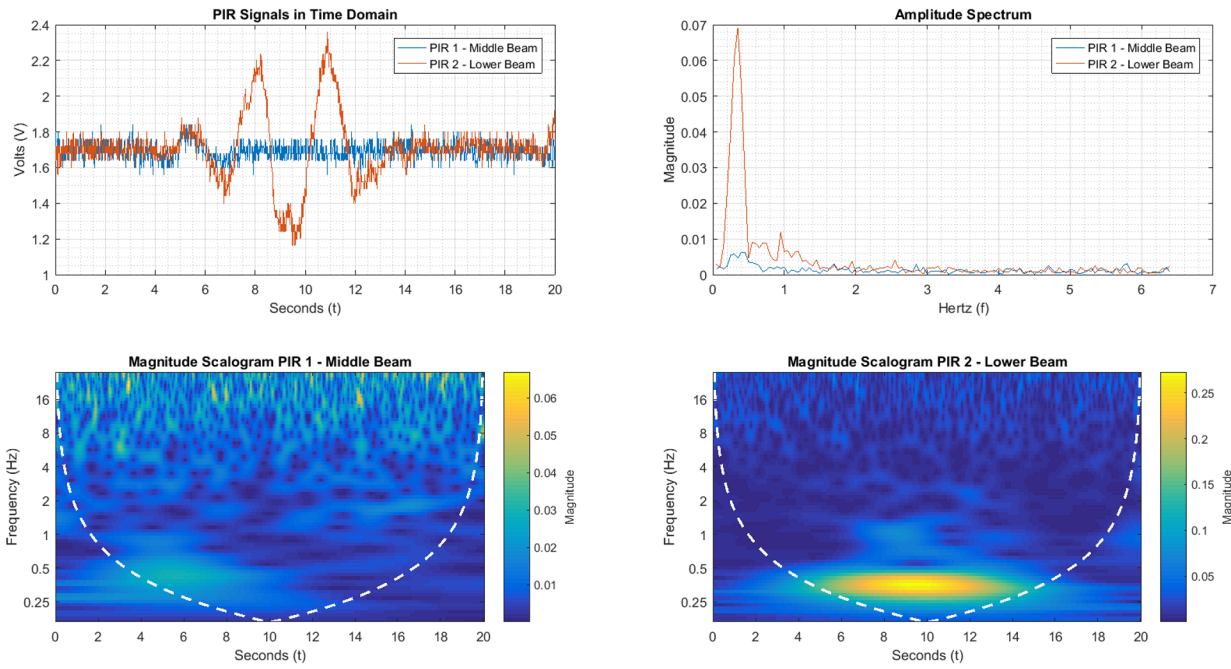


Figure 23. Adult Dog Moving 4 m

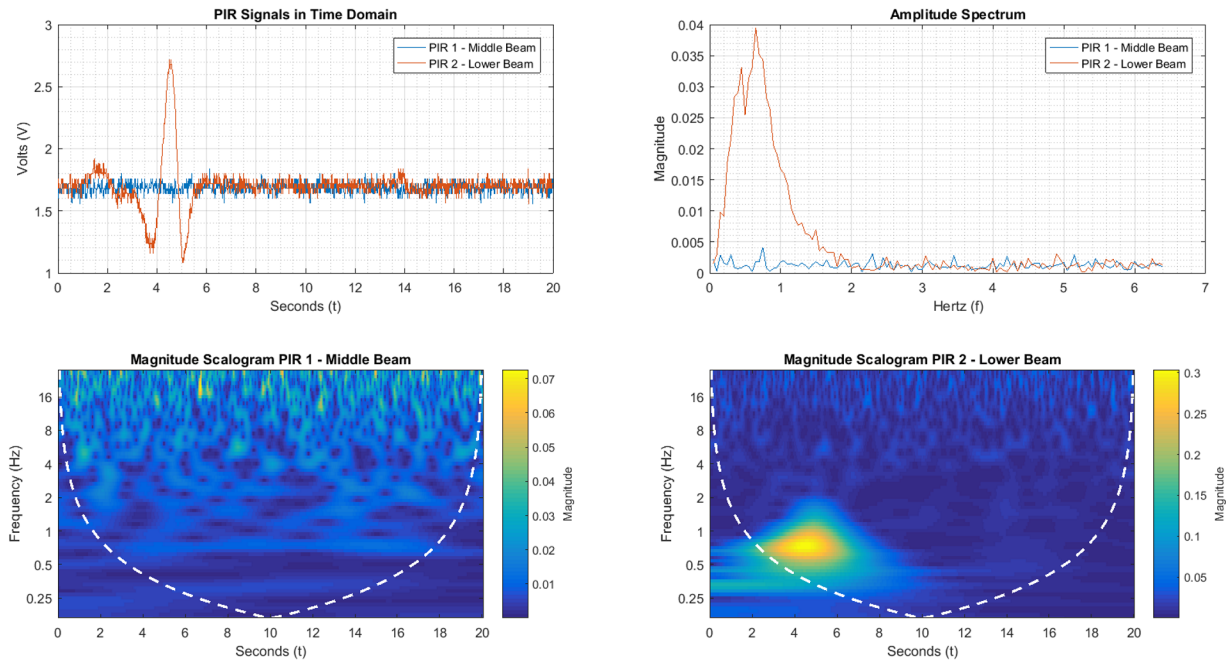


Figure 24. Small Dog Moving 4 m

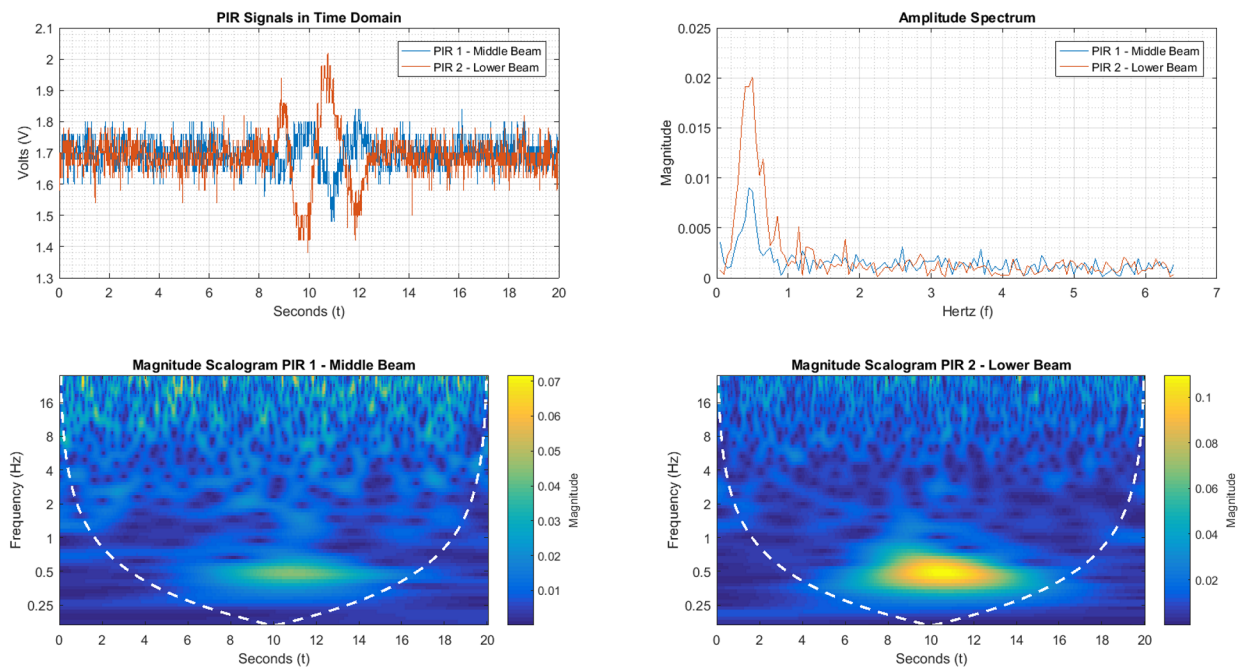


Figure 25. Human Child Walking 6 m

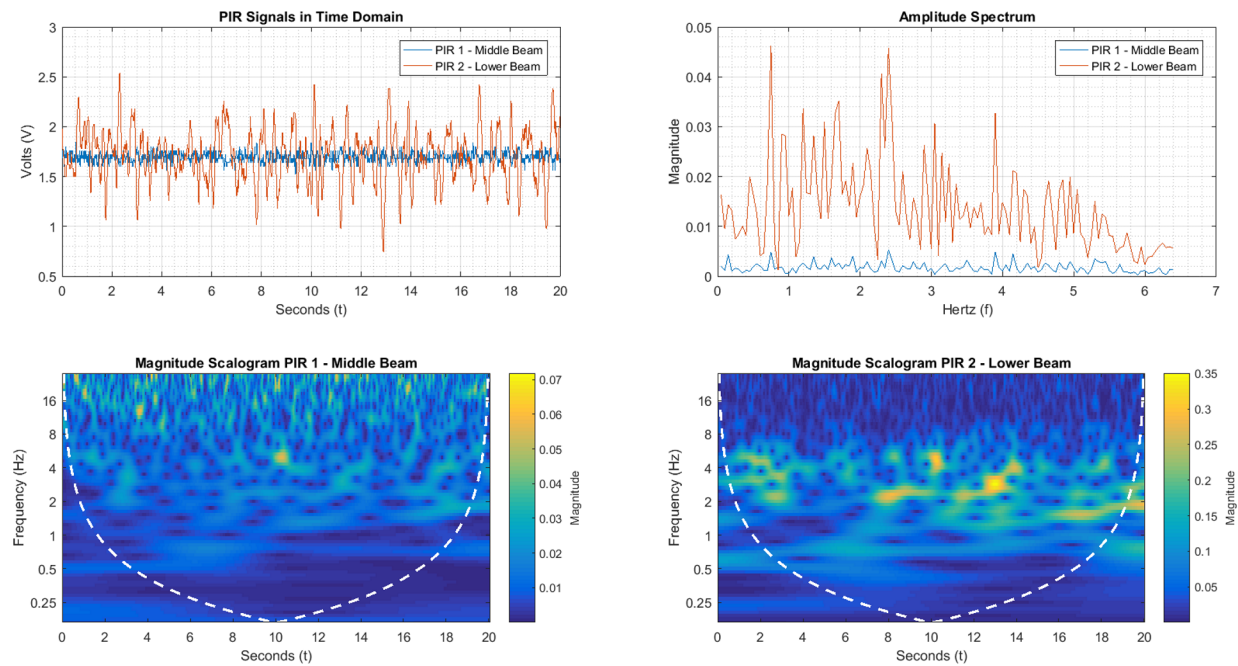


Figure 26. Fireplace at 6 m

Thanks to a wavelet transform, an analysis of the time-frequency domain gives more information about the signal. It is possible to have a signature for different kinds of motion. Visually, it is easy to see one or many clusters in the scalogram, depending on the type of motion. From the wavelet transform data, one can easily apply a classification algorithm and detect different kinds of movement very efficiently.

This same design as an analog front-end with a wavelet transform and algorithm implementation in an MCU or DSP LaunchPad can be used for other types of detection such as:

- Human adult walking
- Human child walking
- Pet moving
- Falling person
- Person moving or rolling on the floor
- Background fire
- External sunlight changes

Properly applied machine learning or artificial intelligence will open the door for new types of intelligent motion detectors through this TI Design. This motion detector will be able to adapt to different environments and detect more than just human motion

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01069](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01069](#).

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01069](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01069](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01069](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01069](#).

5 Software Files

To download the software files, see the design files at [TIDA-01069](#).

6 Related Documentation

1. Texas Instruments, [Low-Power PIR Motion Detector With Sub-1GHz Wireless Connectivity Enabling 10-Year Coin Cell Battery Life](#), TIDA-00489 Design Guide

6.1 Trademarks

BoosterPack is a trademark of Texas Instruments.
Bluetooth is a registered trademark of Bluetooth SIG.
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Revision History

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

Changes from A Revision (April 2017) to B Revision	Page
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• Changed R3 to R6 in Equation 3	17

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